Tangled Up and Blue: Evaluating Alternatives to Reduce Whale Entanglements in Commercial Dungeness Crab Fishing Gear

Kaitlin Marie Lebon

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Ryan Kelly

Dave Fluharty

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Abstract

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Kaitlin Marie Lebon

Chair of the Supervisory Committee:
Assistant Professor, Ryan Kelly
School of Marine and Environmental Affairs

Since 2014, the U.S. West Coast has experienced a sudden increase in reported whale entanglements with commercial fishing gear. The increase has been particularly acute in reported entanglements between Humpback whales (*Megaptera novaeangliae*) and commercial Dungeness crab gear. The current rate of entanglements is alarming and could trigger consequences for the responsible fisheries under the Marine Mammal Protection Act (MMPA) and Endangered Species Act (ESA); it seems likely that some change in the social-ecological status quo will be necessary to avoid significant harm to either the fishing community or the whales. Here, I compare several gear modifications and management alternatives to reduce entanglements, thereby reducing conflicts between whales and fishermen, scoring policy alternatives according to estimated cost to fishermen, likelihood of the alternative to reduce whale entanglements, and anticipated reaction of fishermen in response to the change. The intent

of this study was to create a decision-aid tool for managers and policy makers to use when contemplating changes to the West Coast commercial Dungeness fishery. A small number of policy options consistently ranked high in a multi-criteria decision analysis; these included the use of Galvanic Timed Releases, which minimize the time that crab-pot lines are in the water and thus reduce the likelihood of entanglement. In addition, I include potential regulatory and non-regulatory pathways for implementing changes to the commercial Dungeness fishery, thereby providing both a substantive and procedural roadmap for reducing fishery-whale conflict.

Introduction

Fishing lines, traps, and other equipment generally target particular commercially important species, but also have the potential to entrap marine mammals and other bycatch species of policy importance. Whales, in particular, are often ill-equipped to deal with the obstacles fishing gear pose. Whales may come into contact with fishing equipment because of unfamiliarity with the gear, difficulties detecting certain shapes or materials in the water column, or because health and oceanographic conditions inhibit their sensory abilities (Hofman, 1990; Kot et al., 2012). Entanglement is a routine event for some whale populations; nearly 72% of North Atlantic right whales on the East Coast of the United States bear scars from past entanglements (Johnson et al., 2005). Even populations in remote Arctic waters show impacts, with ten percent of bowhead whales taken by subsistence harvesters bearing rope scars from pot or trap fishing equipment (Citta et al., 2014).

Entanglements therefore pose a real threat to whales, especially those species and populations recovering from the past intensive whaling activities. Ropes wrapped around a whale can cause lacerations, often leading to infection and subsequent death (Moore & Hoop, 2012). Whales unable to immediately break free from gear may drown or remain entangled and slowly die from starvation over a period of months (Moore & Hoop, 2012). Line from fixed gear may become embedded in a whale's baleen plates, disrupting water flow patterns and general feeding ability (Moore & Hoop, 2012). In addition to scarring from lacerations, entanglement creates drag that drains a whale's energy. In females, the high energy costs of entanglement can delay reproduction by months or years (J. van der Hoop, Corkeron, & Moore, 2017; J. M. van der Hoop et al., 2016). Similar to other areas around the world, the commercial Dungeness crab fishery along the West Coast of the United States reported whale entanglements.

The Current Trend in Whale Entanglements

The U.S. West Coast has experienced a sudden increase in reported whale entanglements with commercial fishing gear, especially in entanglements between Humpback whales (*Megaptera novaeangliae*) and fixed-gear fisheries like Dungeness crab (Figures 1 and 2, NMFS, 2016).

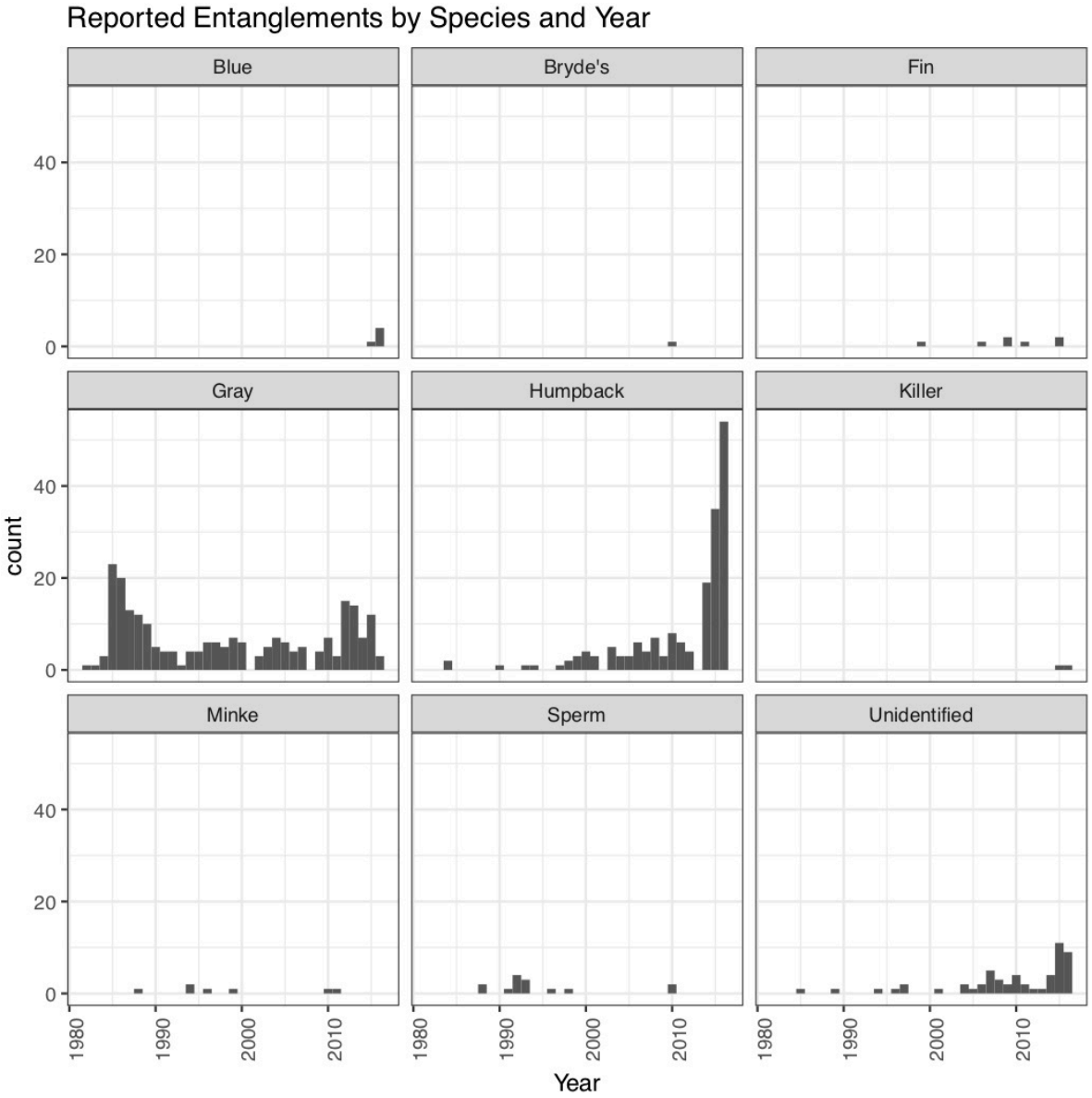

Figure 1: Reported West Coast whale entanglements by species and year.

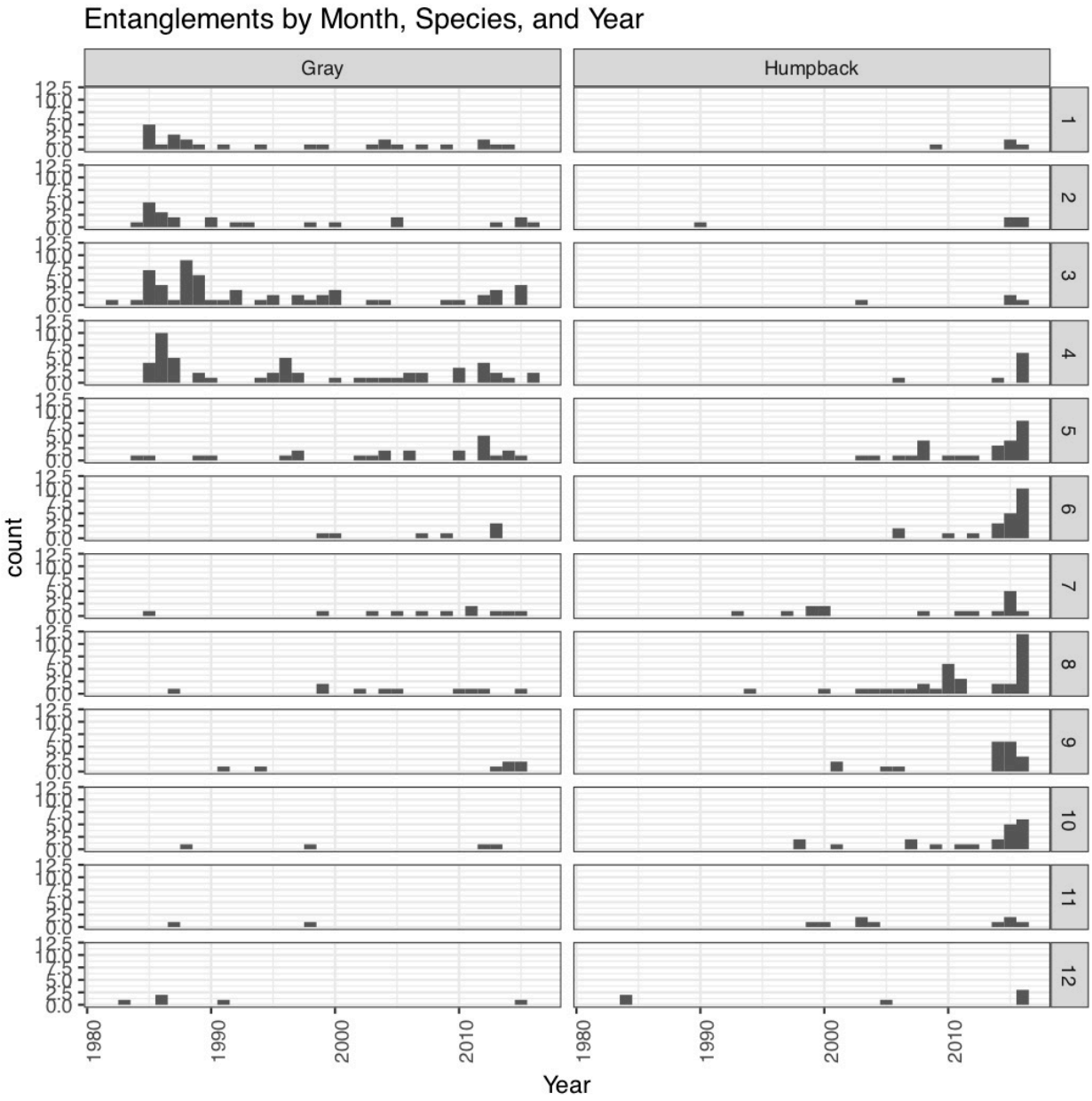

Figure 2: Reported West Coast whale entanglements by species, and year for humpback and gray whales. Figure illustrates the transition in entanglement trends from mostly gray whales – reported entangled January-March, mainly in the 1980s – to the current set of entanglements, in which humpback whales are reported predominantly in the warmer months, but throughout the year.

Annual reported Humpback entanglements have increased significantly in recent years (1984-2012 vs. 2014-2106; Wilcoxon test; $p = .007$; no data available for 2013). Several non-exclusive factors may account for this increase, including (1) an increase in the per-capita rate of entanglements, (2) a greater percentage of whale entanglements being reported as information on whale entanglement reporting procedures becomes easily accessible, or (3) a static per-capita rate of entanglements with an increasing whale population. Whether a growing problem or simply the increasing awareness of an existing one, a continuation of current entanglement trends can potentially trigger federal regulations under the Endangered Species Act (ESA) or Marine Mammal Protection Act (MMPA) which may affect fishing industry practices and raise industry concerns.

The MMPA mandates a moratorium on the take and importation of marine mammals, with some exceptions for incidental take in commercial fisheries (16 USC § 1371). Section 2 of the MMPA, however, dictates that marine mammal species numbers should not be permitted to fall below their optimum sustainable yield level, requiring immediate actions to replenish failing marine mammal populations (16 USC § 1361 (2)). For commercial fisheries, in particular, incidental bycatch of marine mammals is permitted so long as it does not rise to a level that would "compromise the ability" of the species (stock) to reach its optimum sustainable population (16 USC § 1387); where an individual fishery accounts for more than 10% of a stock's potential biological removal rate, that fishery may have a take reduction plan, created by a Take Reduction Team (16 USC § 1387 (f)). As such, humpback entanglements in recent years have threatened to force federal intervention in the Dungeness fishery, first by creating a Take Reduction Team, and ultimately by the loss of authorization for incidental take of marine mammals. Similarly, Section 9 of the ESA prohibits the take of an animal that is listed as

endangered or threatened (16 USC § 1538). Therefore, entangling whales listed under the ESA is a violation of the Act subject to fines or, if done intentionally, criminal sanctions. The México population of humpbacks is listed as a threatened Distinct Population Segment (DPS) following a 2016 NOAA realignment of humpback ESA listings (81 FR 62259, 2016); these whales feed along the west coast of the United States and consequently are likely to be among those entangled by the Dungeness fishery.

Similar interactions between whales and fisheries have led to Take Reduction Teams, directed by NOAA's National Marine Fisheries Service (NMFS) as mandated by the Marine Mammal Protection Act (MMPA, 1972). These Take Reduction Teams, created by NMFS, occur when a fishery exceeds the given Potential Biological Removal for a strategic stock of marine mammals. Strategic stocks, as defined by the MMPA, are a marine mammal population that is either listed as endangered or threatened under the ESA, likely to be listed under the ESA, or a marine mammal stock that has human-caused mortality exceeding the Potential Biological Removal threshold (16 USC § 1362 (19)). Pursuant to the MMPA, Teams are appointed to develop Take Reduction Plans to help prevent the additional depletion of a strategic stock interacting with a fishery that takes more than 1% of the Potential Biological Removal Rate of that stock (16 USC § 1387 (f)). In an attempt to address the problem of entanglement several fisheries have experimented with whale deterrents, including acoustic noisemakers ("pingers") in California drift gillnets (Appendix A, B; Kraus et al, 2014; Jefferson & Curry, 1996). Others have reductions the length of line used for pots and traps or have changed the seasons of their fisheries like in East Coast pot or gillnet fisheries (Appendix A, B; Knowlton et al., 2012; Moore & Hoop, 2012).

Conflicts between North Atlantic right whales and fixed-gear fisheries in the Atlantic provide an easily comparable situation to current entanglement conditions along the Pacific Coast. In an effort to alleviate growing conflict between fisheries and endangered North Atlantic right whales, NMFS created the Atlantic Large Whale Take Reduction Plan (ALWTRP) in 1997 (Kraus, Brown, Caswell, & Clark, 2005; 62 FR 39157, 1997). Since its induction, the ALWTRP has focused on furthering research on methods to reduce entanglements, disentanglement efforts, timed area closures, and gear modifications (62 FR 39157, 1997). Regulations suggested in Take Reduction Plans like the ALWTRP are approved and promulgated by the Secretary of Commerce and implemented by NMFS as mandated by the MMPA (16 USC § 1387). Fisheries observers are often used to monitor for implementation of Take Reduction Plan regulations, like with the use of pingers in gillnets under the Harbor Porpoise Take Reduction Plan in the Northeast United States (Young, 2001). Take Reduction Teams have had mixed success in the past, often struggling to meet deadlines for developing draft plans, publishing final plans, and failing to reduce bycatch levels in strategic stocks (Mcdonald, Lewison, & Read, 2016; United States Government Accountability Office, 2008).

A summary of current ALWTRP regulations for trap and pot gear and gillnets can be found in Appendix A and B. Splitting the Atlantic Coast into Northeast, Mid-Atlantic, and Southeast Regions, the ALWTRP has published gear guides for trap and pot fisheries and gillnet fisheries independently. These reports are recirculated as updates to recommended gear practices and area closures are enforced. The reports include information such as coast-wide gear requirements, regional and local area closures, and existing exemptions (Appendix A, Appendix B). For example, all trap and pot gears are required to use sinking ground lines, and buoy lines must be attached by a weak link with a breaking strength specified by its management area

(Appendix A). Similarly, gillnet gear cannot have excess floating line at the surface, and fishermen are encouraged to voluntarily reduce the number of knots occurring in their lines from the gear tying process by using other splicing techniques (Appendix B).

Recent years have seen dramatic increases in reported entanglements on the West Coast (Figure 1). Entanglements on the West Coast have transitioned from involving mostly gray whales in net fisheries gear to humpback whales interacting with commercial Dungeness gear (Figure 3). There were 71 cases of reported entanglements in 2016 (NMFS, 2017). Of those, 48 were confirmed by NOAA and 22 were identified as involving commercial Dungeness gear (NMFS, 2017). Additionally, a majority of these entanglements occur in California waters around Monterey Bay, with 73% of 2016 entanglement reports originating from central California (NMFS, 2017).

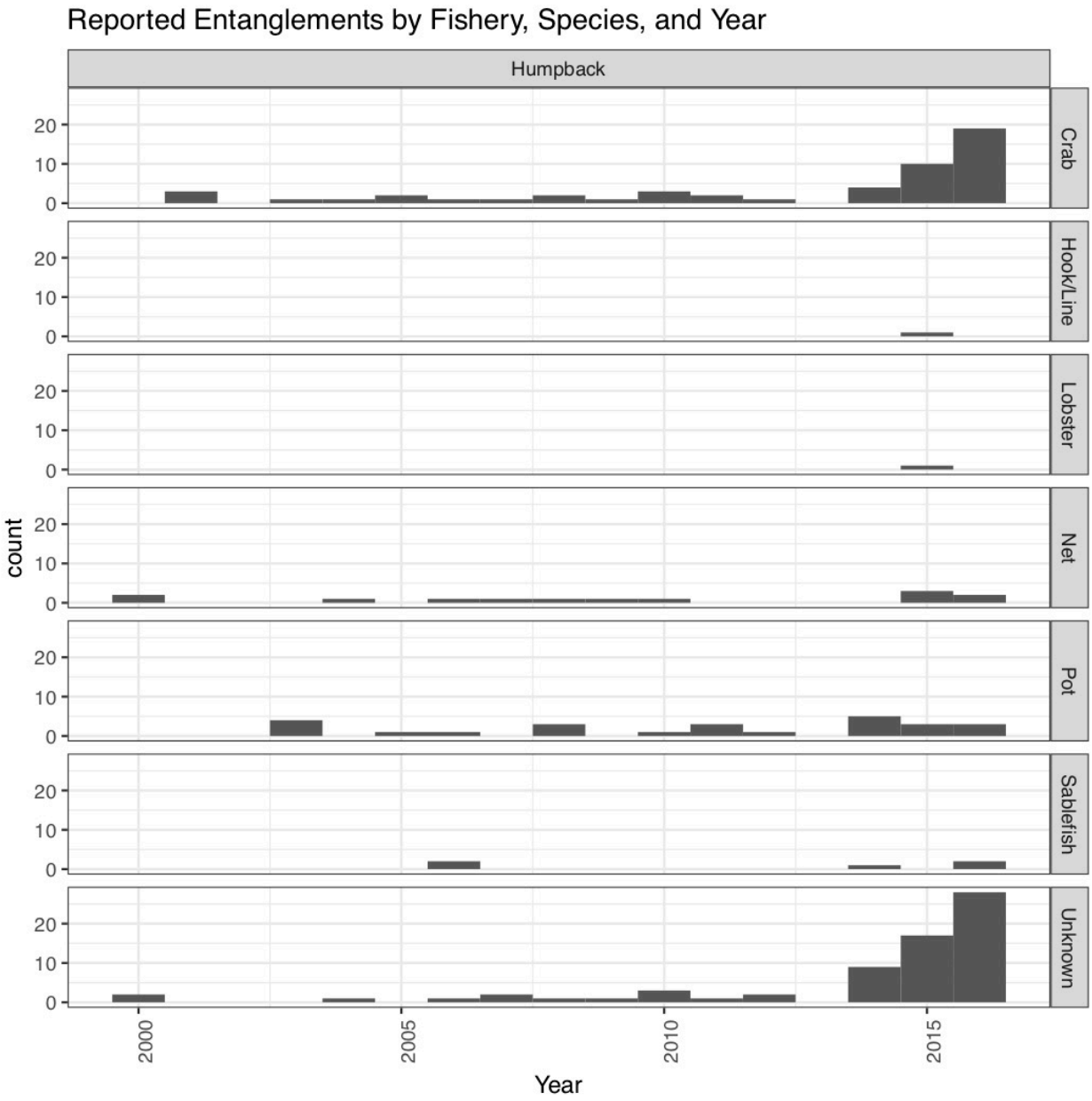

Figure 3: Reported West Coast whale entanglements by fishery for humpback whales. Next to unidentifiable fishing gear, commercial crab fishing gear is most frequently involved in humpback whale entanglements.

Commercial Dungeness Crab Fisheries of the U.S. West Coast

The modern West Coast Dungeness crab fishery began in 1848 in San Francisco (Hankin & Warner, 2001). California, Oregon, and Washington have permanent authority to manage their

individual Dungeness crab fisheries apart from federal agencies as part of the Tri-State Agreement with the Pacific States Marine Fisheries Commission (Public Law 115-49). California State Legislature has regulated California's Dungeness fishery beginning as early as 1895 (Hankin & Warner, 2001). The Dungeness commercial crab fishery is one of the most important fisheries along the West Coast. Fishermen can catch upwards of 85 million pounds of crab, often worth up to $109-$245 million annually in landing value (NMFS Commercial Fishing Landings, 2016). The California Dungeness crab fishery can land more than 20 million pounds of crab a year worth $41-$88 million to fishermen as first sale (NOAA Fisheries, n.d.). Dungeness crab fishing is the basis of many people's livelihoods: In California, 73% of commercial fishermen report that more than 40% of gross income is derived exclusively from Dungeness crab (Dewees, Sortais, Krachey, Hackett, & Hankin, 2004).

Commercial crab fishermen use crab pots to capture and collect their harvest. Each crab pot is set with an individual buoy attached to a float line. Dungeness crab can be found in waters ranging from intertidal depths down to 750 feet, although commercial crabbers typically place their pots in 18 to 92 meters of water (Hankin & Warner, 2001; Oregon Department of Fish and Wildlife, 2018). Pots are brought back to the surface using a winch (Oregon Department of Fish and Wildlife, 2018). In 2017 there were an estimated 534 individuals/vessels in the California Dungeness fishery, 433 individuals/vessels in the Oregon fishery, and 228 in the Washington coastal fishery (NOAA Fisheries, 2018). Washington, Oregon, and California are limited entry fisheries with a maximum of 500 pots allocated to license holders depending on historical landings (14 CCR § 132.1; OAR 635-005-0405; WAC 220-340-430). The normal crabbing season start dates range from mid-November to early December through August or September

depending on the management area. This helps fishermen avoid contact with crab during peak molting or mating periods, reducing potential damage to the crab (Hankin & Warner, 2001).

However, various factors can influence the fishery and result in variable season start dates. Harmful algal blooms along the West Coast have caused closures and delays in the Dungeness fishing season because of the resulting domoic acid in the crab (Du, Peterson, Fisher, Hunter, & Peterson, 2016). Delays and closures in California as a result of domoic acid outbreaks caused a federal declaration of fishery disaster in both Dungeness and rock crab fisheries for the 2015-2016 season (81 FR 6919, 2016). Additional season setbacks might occur if crabs are too soft for harvest, or if there are price disputes between fishermen, unions, and buyers. For example, the 2017-2018 fishery in Oregon was delayed almost a month because crab were not fully grown, and then further delayed as a result of price negotiations between fishermen and processors (Frankowicz, 2018; Oregon Department of Fish and Wildlife, 2017). With these delays the start dates are later in the season than normal. Whales, moving to follow their food sources, overlap with the fishermen working later in the season (Goldbogen et al., 2013). Additionally, many whales like the West Coast humpback stocks, are increasing in population and therefore increasing potential for conflict (Carretta et al., 2017). The Dungeness crab fishery, with a single vertical line-per-pot in the water column and variable season start dates, has a high potential to entangle large marine mammals. Many of the recent entanglements, however, occur in summer and extend through early fall, when a majority of the fishing is already completed (Figure 2).

Although methods for reducing negative interactions between humans and marine mammals exist, there have been limited investigations into best practices for fixed-gear fisheries like Dungeness crab on the Pacific Coast. This analysis compares several gear modifications and

management alternatives that may help reduce entanglements, thereby reducing conflicts between fishermen and whales. I reviewed relevant regulations for West Coast Dungeness crab fisheries and estimated feasibility for each prospective solution. This report reviews these alternatives, highlighting the relative strengths and weaknesses of each option.

Potential Alternatives

Gear modifications and other alternatives are ways for the West Coast Dungeness crab fishery to alleviate increasing reported whale entanglements before federal intervention is required by either the MMPA or the ESA. A number of methods have already been implemented in response to similar challenges around the world. I summarize common options below, categorized by gear modifications, social interventions, and regulatory changes. This list is not an exhaustive record of potential solutions but is an attempt to cover the most likely interventions.

Gear Modifications

Pingers and other Acoustical Deterrents

Whale pingers placed on lines or nets work by emitting noises at frequencies intended to alert or warn whales away from where gear has been set (Werner, Kraus, Read, & Zollett, 2006). Acoustic harassment devices are intended to deter whales from approaching, although they emit sounds at high levels that can potentially impair the hearing of nearby marine mammals (Werner et al., 2006). Pingers are employed in some pot and gill net fisheries but have had limited success in deterring whales. Depending on the frequency and duration of the sound, whales will show no response in directionality, speed, or other

behaviors when pingers are present (Pirotta et al., 2016). Humpback whales have, however, shown some response to tones from 2.0 to 2.1 kHz at certain durations and intervals (Harcourt, Pirotta, Heller, Peddemors, & Slip, 2014). In the California drift gillnet fishery, pingers were so effective that they became mandatory (Carretta, Price, Petersen, & Read, 2004). Despite some uncertainty in their effectiveness, whale pingers are a whale-deterring method readily available on the market and implemented in various fixed-gear fisheries in Canada, Australia, and the United States (Harcourt et al., 2014).

Line Material/Strength

Some fisheries have experimented with changing either composition or breaking strength of rope in hopes of more easily freeing whales that become entangled. Lobster fisheries on the East Coast use sinking line to decrease the opportunity for slack line to loop in the water column and create entanglement risks, but this line is more expensive than traditional floating line (Cavatorta, Starczak, Prada, & Moore, 2005). However, it is floating line made with polypropylene that generates the smallest amount of friction with baleen plates, thus reducing risk of entanglement (Cavatorta et al., 2005). Rope breaking strength is another modification that can allow whales to break free after a certain amount of pressure has been applied (Knowlton et al., 2016). Rope breaking in response to whale entanglements, however, will result in the loss of pots and the need for fishermen to replace lost equipment. Reducing the breaking strength of ropes to 1700 lbsf or less can significantly reduce whale entanglements (Knowlton et al., 2016), but presumably comes at a cost of increased false-positive breakages, and therefore an overall increase in lost gear.

Line Color

Initial studies on marine mammal eyesight suggest they are L-cone monochromats, implying color-blindness especially in poor light conditions (Peichl, Behrmann, & Kröger, 2001). This means common rope colors, including yellow, green, or blues may be challenging for a whale to see in the marine environment until the whale is close up to the gear. Changing rope colors to best stand out in the poor lighting conditions of ocean environments like white, black, or black and white striped line may aid in reducing entanglements by allowing the whale to see the gear before they collide with it (Kot et al., 2012). Changing line color is a relatively simple change for fishermen in comparison to other methods in this list, as it would not require reconfiguration of trap placement or retrieval methods. However, regulations requiring immediate line color changes could force fishermen to replace the entirety of the line they use, perhaps before the line has lost its functionality.

Weak Links

In an effort to reduce North Atlantic right whale entanglements, East Coast fixed gear fisheries currently employ weak links. Weak links are connectors between vertical lines and buoy systems designed to break free at a set pressure threshold, theoretically improving the chance of releasing a whale that is entangled and freeing it from the pot attached below (Knowlton, Hamilton, Marx, Pettis, & Kraus, 2012). These weak links are already widely employed and easily obtained. There are, however, mixed results on the effectiveness of weak links (Levesque, 2009; Vanderlaan, Smedbol, & Taggart, 2011). Depending on how a whale encounters the gear the links may not work as designed. If a

whale hits gear straight-on, the whale should generate enough force to break the weak link; if the whale simply brushes up alongside the gear then the link may not break before the whale becomes entangled (Salvador, Kenney, & Higgins, 2003). As with line material or strength (above), presumably there is a necessary calibration to optimize tradeoffs between false-negative and false-positive breakage. There is the additional cost to fishermen of having to replace gear lost following a whale entanglement.

Galvanic Timed Releases (GTRs)

Fixed gear fisheries in Australia and New Zealand employ GTRs, but they are not commonly used in pot or trap fisheries on the US Gulf of Mexico or East Coast (Salvador, Kenney, & Higgins, 2006). Metal anodes on the GTRs erode when in contact with saltwater, eventually releasing the submerged vertical float line (Salvador et al., 2006). GTRs are inexpensive and help to keep vertical float lines out of the water column until fishermen can feasibly retrieve their pots. Keeping floats and float lines at the bottom near the pots until ready for pickup eliminates the possibility of whales encountering the lines while swimming through an area where multiple pots have been placed. NOAA Fisheries tests of GTRs revealed they accurately release within the manufacturer's given erosion time (Salvador et al., 2006). GTRs can be developed to erode over assorted timeframes, providing greater flexibility for fishermen. There is the potential for occasional erosion failure, resulting in gear replacement costs for fishermen and derelict gear in the environment.

Timed Line Cutting Device

Timed tension line cutters (TTLCs) work as a link between vertical line and traps on the ocean floor, cutting the line when a set pressure is maintained for longer than it normally takes fishermen to haul in their gear (Werner et al., 2006). Thus, when a whale becomes entangled and puts pressure on the line for a sustained period of time, the TTLC will cut the line and free the whale. In NOAA Fisheries tests, TTLCs performed in controlled settings with no noted failures in their mechanisms, obtaining no cracks in the housings or leaks in the internal components (Salvador, Kenney, & Higgins, 2008). Many of these devices are still in development phase and are not widely available to the public. As such, there is limited information on how much TTLCs would cost to employ. Models may be reset after gear has been retrieved, eliminating the need to frequently replace the TTLC if the cutting function has not been triggered. As with many of these changes or modifications, there is the potential expense of having to replace pots and other gear after an entanglement or false-positive trigger.

Social Intervention

Seafood Certification

Eco-labels can educate consumers about the impacts products have on the environment, inducing a change in the purchasing behavior of harmful products (Teisl, Roe, & Hicks, 2002). The Marine Stewardship Council has one such certification program, although some environmental groups claim the Council certifies fisheries with less-than-pristine records (Moore & Hoop, 2012). The American tuna industry faced a similar certification

change in the 1990s, when the Dolphin Protection Consumer Information Act required that tuna products be labeled as dolphin safe only if dolphins were not harmed while fishing (Teisl et al., 2002). Seafood certification can be given to Dungeness crabbers using one or more of the entanglement reduction methods discussed in this list as an additional component of certification requirements. Consumers may choose to only purchase Dungeness crab that has been certified, making it difficult for fishermen who are not using entanglement reduction methods to sell their product. This puts financial pressures on fishermen to implement strategies that eliminate conflicts with whales. The Oregon commercial Dungeness crab fishery has been MSC certified in the past, however this certification has since expired (Vincent & DeAlteris, 2014). This method is dependent on the participation of consumers to be effective as well as on stringent certification requirements.

Boycotts

Consumer boycotts can be a powerful tool to force industries to alter their behaviors. Environmental groups like the NRDC are pushing for US consumers to look more harshly on imported lobster from foreign fisheries that frequently endanger North Atlantic right whales (Smith, Gilroy, Eisenson, Schnettler, & Stefanski, 2014). Tuna fisheries have experienced several boycotts. Consumers in the 1980s after hearing about tuna's negative impacts on dolphins, significantly reduced the demand for tuna by boycotting the industry. Boycotts can garner significant public attention; one study showed nearly 78% of interviewed subjects having taken part in the tuna boycott (Wright, 2000). In 2008, WWF campaigned for consumers to join with several stores boycotting

the Mediterranean bluefin tuna fishery as a result of their views on unsustainable harvesting practices (Schoemburg, 2008). Consumers, upset over conflicts between crabbers and whales, could chose to forgo purchasing Dungeness crab in favor of another seafood to avoid contributing to the entanglement problem. This has the potential to be financially debilitating for fishermen if consumers are not buying their product and could be a motivation to employ gear in a way that reduces potential for entanglements. However, as with seafood certification, boycotts are only successful if enough consumers actively participate.

Regulatory Changes

Shorter Fishing Season

Possibly one of the most direct methods to reduce entanglements is to decrease the amount of fishing gear in the water while whales are present through seasonal closures (Vanderlaan et al., 2011). East Coast lobster fisheries in Maine, for example, could use seasonal closures to restrict their fisheries, reduce their fishing intensity and increase their fishing effectiveness while still landing the same amount of lobster at decreased risks to right whales (Groom & Coughran, 2012; Myers et al., 2007). West Coast Dungeness crab seasons could close in late spring or summer when whales are more prevalent in fishing locations. This would remove vertical lines from the water and reduce the potential for entanglement. However, shortening the fishing season has the potential to anger stakeholders. Fishermen may be unable to increase their fishing effectiveness and lose money as a result of the shortened season. If the season has a rigid end date to avoid the presence of whales, there could be financial losses for fishermen if the season opening is

delayed because of the presence of domoic acid or because the crabs have not adequately filled out.

Temporary Area Closures

Short-term closures on a seasonal or multi-year level are already employed as a method to reduce whale entanglements by the ALWTRP along the Atlantic Coast (Table 1, 2). Managers can close areas in response to timely observations of current whale locations. This can allow fishermen to continue fishing nearby and for closed areas to open up quickly once whales have vacated the area. Temporary area closures can be an alternative to more permanent closures like Marine Protected Areas (MPAs), since short-term closures are more adaptive to the fluid nature of whale habitat needs and difficulties in defining terms of more permanent protection measures (Hoyt, 2011). Fishing grounds in Monterey Bay, California, for example, could be temporarily closed to crab fishing when whales are reported in the area, removing the potential for conflicts between whales and gear. Downsides to temporary area closures include the need for increased communication between fishermen and management to alert fishermen to where crabbing is currently closed, and increased monitoring costs to ensure area closure compliance.

Permanent Area Closures or Marine Protected Areas (MPAs)

As with shortening the length of the fishing season, the designation of marine protected areas where whales are prevalent may also mitigate entanglements. The designation of a marine protected area in New Zealand prohibiting gillnetting fisheries successfully reduced the bycatch of Hector's dolphins (Gormley et al., 2012). MPAs can be effective

if they consider the right variables, including being the optimal size and location, if threats to marine mammals are reduced, and if no new threats are introduced (Slooten, 2013). Permanent area closures along the West Coast could provide whales with sanctuaries perpetually free of pots and float lines. It can, however, be challenging to predict the exact habitat needs for whales in a MPA because of migration patterns or movement of food sources (Hoyt, 2011). MPAs can take a long time to implement and may cut off fishermen from important fishing areas.

Catch Shares

Catch shares can change the way a fishery functions. Catch shares give each fisherman his/her own secure quotas, eliminating the competition to catch fish before other fishermen do and encouraging collaboration and communication amongst fishermen as opposed to competition (Hsueh & Kasperski, 2018). This management system allows fishermen to be more flexible and to use more sustainable fishing methods to avoid the bycatch or entanglement of unwanted species like marine mammals (Hilborn, 2007; Hsueh & Kasperski, 2018). Catch shares may have the potential to allow fishermen the adaptability to avoid fishing for crab when or where whales are present along the West Coast in the absence of a derby-style fishery. West Coast states already have trap allocation systems set up based on historical landings, and all three states have a limited-entry permit system that helps limit the number of pots and the number of permits actively fishing each year (14 CCR § 132.1; OAR 635-005-0405; WAC 220-340-480). Catch shares, although reducing the competition between fishermen, may spread the fishing effort throughout the season (Hsueh & Kasperski, 2018). This may lead to more

pots being placed later in the season – and therefore more entanglements – rather than the traditional front-loading of fishing effort for economic reasons when whales are not as prevalent.

Shortening Rope Length/Float Line Length

Shorter line-length and the tighter setting of gear is already recommended in Dungeness fisheries, particularly in California. The California Dungeness Crab Fishing Gear Working Group, through the California Ocean Protection Council, has published a best-practices guide to help fishermen set their gear in ways that might reduce whale entanglements (California Dungeness Crab Fishing Gear Working Group, 2017a). Suggestions include float line lengths of between 18-30 ft depending on the depth of water the traps are set in (California Dungeness Crab Fishing Gear Working Group, 2017a). This eliminates extra float line in the water forming loops that whales may become trapped in. Using shorter float line lengths is a voluntary change for fishermen to implement. However, current recommendations from working groups provide little to no incentive to employ the changes. Shorter rope lengths can be effective in reducing whale entanglements only if all or a majority of fishermen are making the change.

Multiple Pots-per-Line

It is currently illegal to attach more than one trap by a common line in West Coast Dungeness fisheries (FGC Sec 9012; OAR 635-005-0485; WAC 220-340-435). However, changing commercial fishing regulations to allow multiple pots per line would reduce the number of vertical float lines in the water column that can potentially entangle

whales without restricting or reducing the number of traps that fishermen are allowed to use. This would entail changes in current commercial fishing regulations for Washington, Oregon, and California. Additionally, it might require fishermen to change fishing methods, particularly with how they retrieve or deploy pots. This can include costly updates to vessel winch systems (Pacific States Marine Fisheries Commission, 2017). There is also the potential for increased instances of fishermen overlapping their gear with pots already placed in the water (Pacific States Marine Fisheries Commission, 2017). However, fishermen would presumably be able to increase fishing effort in a single location without having to deploy several pots independently.

Cooperation Among Fishermen

Cooperation among fishermen can be as simple as commercial fishing fleets sharing information in real time about the presence of whales in common fishing areas (Werner et al., 2006). Fishermen can then avoid placing traps where the whales are. This, however, requires the fishermen to voluntarily communicate, potentially causing conflict with those who wish to keep their fishing locations private. Communication may also include fishermen attending and actively participating in workshops aimed at developing methods to reduce entanglements. At these workshops, like the one held by Pacific States Marine Fisheries Commission in 2017, fishermen can learn steps to reduce the chances of entanglement as well as give input on strategies considered by managing entities (Pacific States Marine Fisheries Commission, 2017). Fishermen cooperation can be beneficial because it allows fishermen to feel involved in the decision-making processes, which in turn can increase participation with and acceptance of new regulations. Costs of

cooperation might include travel expenses and the investment of time to participate in meetings or attend entanglement workshops.

Methods

I employed a form of Multi-Criteria Decision Analysis (MCDA) to rank each of the above policy alternatives over several qualitative categories in a systematic and replicable manner. MCDA is a methodology combining factors such as stakeholder views and cost/benefit information to rank proposed alternatives for decision makers (Huang, Keisler, & Linkov, 2011). Because of its ability to quantify quantitative and qualitative considerations into easily comparable numbers, MCDA is a rapidly growing method of investigation, particularly in the environmental field (Huang et al., 2011; Ishizaka & Lusti, 2006; Linkov & Moberg, 2012). MCDA has evolved to include specific algorithms designed to fit the analytical needs of several decision-making scenarios (Huang et al., 2011). One such method in environmental decision analysis is the Analytic Hierarchy Process (AHP). AHP creates scores for each alternative, breaking down decision making problems into a hierarchy considering aspects such as goals and decision criteria via pairwise comparisons (T. L. Saaty, 1977, 1980; Zhang, 2016). The hierarchy is built by comparing each of the decision criteria against each other to determine relative weights, and then subsequently comparing all of the alternatives against each of the decision criteria (Linkov and Moberg, 2012). AHP simplifies the decision making process by relying on the idea that humans are better able to accurately evaluate two alternatives than all alternatives in a decision at once (Franek & Kresta, 2014; T. Saaty, 2008). This approach to a decision analysis provides guidance as to which alternatives best fit the criteria and importance of criteria for a particular situation (Mu & Pereyra-Rojas, 2017).

Table 1: Alternatives renamed with letter designations for analysis in AHP.

Alternative	Letter Designation
Galvanic Timed Releases	A
Float/Trailer Line Length	B
Seafood Certification	C
Catch Shares	D
Rope Material/Breaking Strength	E
Rope Color	F
Cooperation Among Fishermen	G
Temporary Area Closures	H
Permanent Area Closures or MPAs	I
Shorter Fishing Season	J
Weak Links	K
Line Cutter Device	L
Multiple Traps Per Line	M
Boycotts	N
Whale Pingers	O

Following a literature review, I selected 15 alternatives that are already implemented or frequently discussed in fisheries from around the world encountering entanglement issues with marine mammals (Table 1). I chose decision criteria that incorporated common considerations for regulatory changes, including potential solutions to the problem, and the identities and reactions of groups involved (McCubbins, Noll, & Weingast, 1987). For this study, those considerations translated into the following criteria (1) *Cost*, an estimation of how financially burdensome an alternative would be to fishermen, (2) *Effectiveness,* an alternative's relative ability to successfully reduce whale entanglements, and (3) *Response,* how likely an alternative is to be readily accepted by commercial Dungeness crab fishermen. Alternatives were scored for each of the three decision criteria using a Saaty scale (Appendix C; Figure 4; Saaty, 1980). I used information obtained from literature reviews, historical data, management plans, NOAA gear tests, minutes from entanglement workshops, discussions with experts, and other relevant reports and documents as the basis of ranking the alternatives with respect to the three decision criteria.

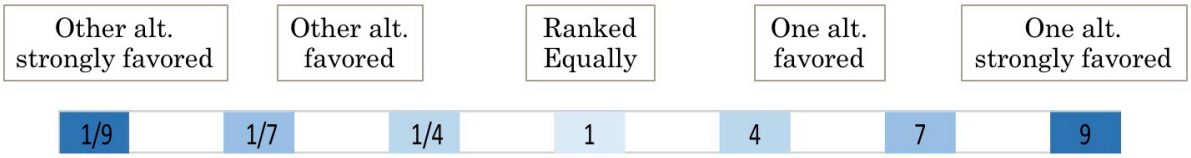

Figure 4: Saaty scale used to determine scores to pairwise rankings adapted from Saaty, 1980.

Not all decision criteria will have the same significance, so it is important to consider criteria priorities with respect to one another (Mu & Pereyra-Rojas, 2017) Weights were altered to simulate scenarios where decision makers and managers might consider certain factors to be of higher importance than others (Table 2). Presenting decision makers with several alternatives of interest in MCDA can help them to make the choice that best meets their goals (Kaddani, Vanderpooten, Vanpeperstraete, & Aissi, 2017). After scoring alternatives, AHP analyses were done in R version 3.4.3 using the Analytic Hierarchy Process package version 0.2.12 (Glur, 2018; R Core Team, 2017).

Table 2: Scoring matrix used in weighting scenarios for the decision criteria using a Saaty Scale (Saaty, 1980). Cost/Effectiveness compares *Cost* versus *Effectiveness*. Cost/Response compares *Cost* versus *Response*. Effectiveness/Response compares *Effectiveness* versus *Response*.

Weighted Scenario	Cost/Effectiveness	Cost/Response	Effectiveness/Response
1	1	1	1
2	1/7	1	7
3	7	6	3
4	4	4	1
5	1	1/7	1/7
6	1/7	1	1/7
7	1/3	4	4
8	1/3	2	2
9	4	3	4
10	4	1/3	1/4

Results

When all three decision criteria are weighted equally GTRs are the highest-ranking alternative, collectively outscoring the other alternatives in each criterion (Figure 5). Galvanic Timed Releases were estimated to have low one-time purchasing costs, reduce whale entanglements, and to be met with little resistance in the fishing community. Options like reducing float trailer line length and seafood certification programs also ranked high (Figure 5). Alternatives such as decreasing fishing season length and allowing multiple traps per line scored lower, largely because of anticipated negative reactions from crab fishermen. The lowest scoring alternatives generally had negative predicted responses from fishermen. Lower ranked alternatives also tended to have unclear demonstrated abilities to reduce whale entanglements, either from experiences in other fisheries or from an absence of physical tests and trails with the gear. Whale pingers, for example, were ranked low based on their high estimated implementation cost, low likelihood of success in reducing whale entanglements, and potentially high levels of resistance from fishermen.

Altering the weight given to each criterion did little to change the outcome of alternative scores (Figure 5). For example, Alternatives A, B, and C consistently ranked high regardless of the variations in weighting decision criteria. Alternatives like changing rope material or cooperation among fishermen scored lower in weighting scenarios where emphasis was placed on the importance of cost for fishermen. Where effectiveness was considered most important, alternatives like GTRs, catch shares, and temporary area closures scored highest.

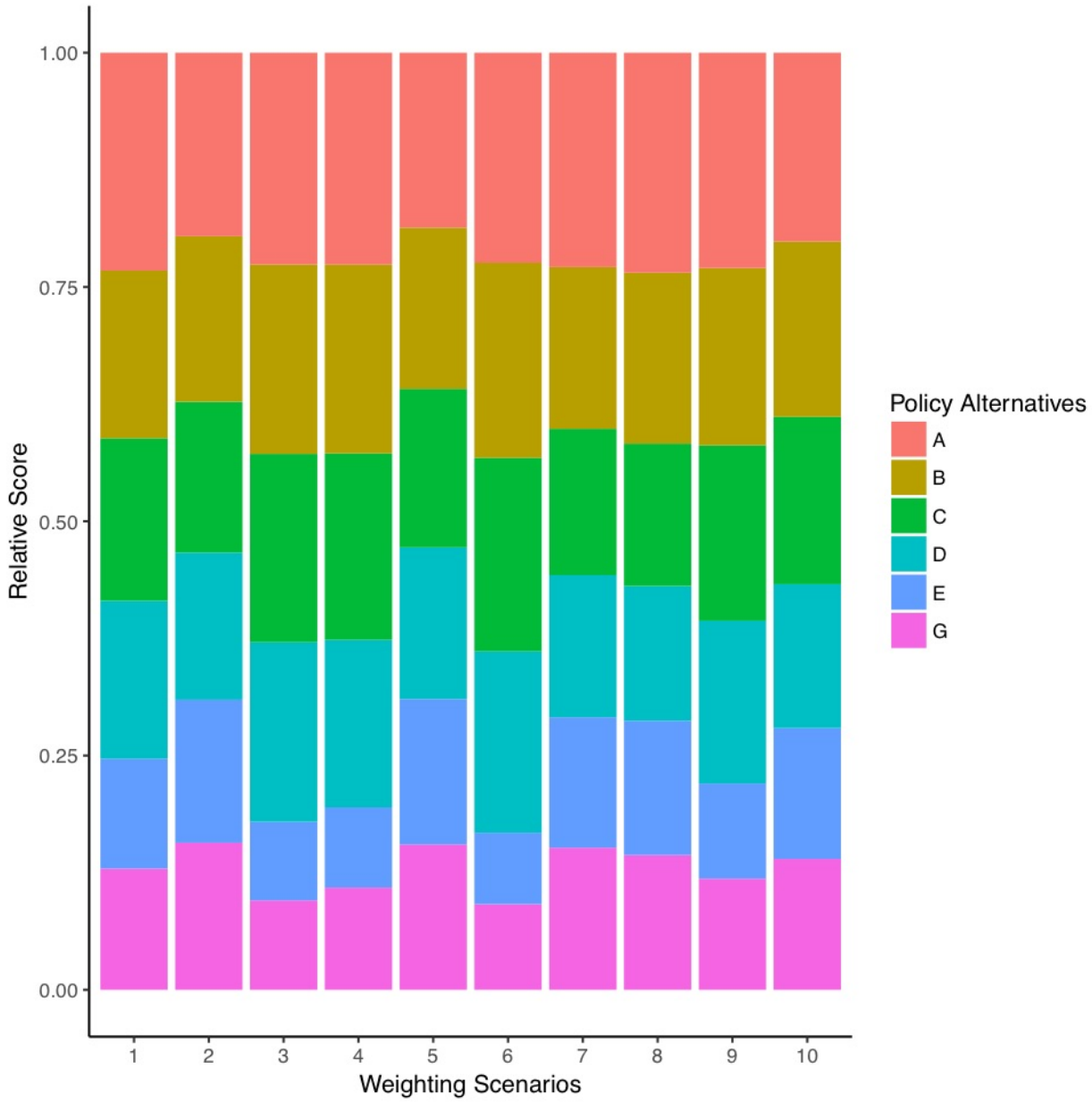

Figure 5: Scores for top-ranking alternatives evaluated across ten weighting scenarios. Alternative scores represent an alternative's overall rank summed across all three decision criteria. For ease of comparison across weighting scenarios, here these top-ranking policy alternatives are scaled so that their scores sum to one in each weighting scenario.

Discussion

I found that a few policy options – namely, GTRs, catch shares, and seafood certification programs – consistently ranked highly according to my criteria; different weighting schemes had

little effect on this outcome. This result suggests that there are a few alternatives that stand out from the others as being likely choices for policy makers and managers implementing changes to the West Coast commercial Dungeness fishery. It can be difficult to offer a solution when the exact causes of whale entanglements are unknown, however these alternatives could offer a way to reduce whale entanglements without generating untoward financial constraints on fishermen.

Through a form of MCDA, this study investigates the cost, performance and preferences of alternatives and transferred this assessment into a repeatable, clear, and formal assessment that can be transparent to both managers and stakeholders (Saaty, 1977, 1980; Zhang, 2016). Fifteen alternatives were scored using the Analytic Hierarchy Process; these categories included cost to fishermen, anticipated response from fishermen, and how likely the alternative was to reduce whale entanglements. Over several scenarios, alternatives such as whale pingers consistently scored low, while alternatives like GTRs scored high.

Implementing any these or other policy alternatives will require some action via regulatory or non-regulatory pathways (Appendix D, E, F). Any policy change surrounding commercial Dungeness fisheries is unlikely to occur unless the benefits of action outweigh the costs of inaction. As reflected in the policy alternatives I evaluated here, motivation for change can come from regulatory requirements or through incentivized voluntary action. Managers can implement regulatory changes by creating new regulations or rolling back existing ones. Implementing GTRs in Washington State, for instance, would require Washington Department of Fish and Wildlife to undergo the rulemaking process to change current regulations for crab pots or buoys such as WAC 220-340-435 or WAC 220-340-430. A list of pertinent commercial crabbing regulations for Washington, Oregon, and California can be found in Appendix E. Similarly, fishermen who opt to voluntarily use GTRs could be rewarded with incentives like

additional derelict crab pot retrieval permits. Decision makers could also incentivize actions within a fishery by providing fishermen exemptions from unpopular regulations in return for employing entanglement reduction methods in their fishing practices.

Although exact causes for the recent surge in reported West Coast whale entanglements have not been identified, the current rate of entanglement and associated mortality of whales is unsustainable and damages the public image of the West Coast Dungeness crab fishery. Therefore, it is necessary to examine alternatives that may resolve this problem. The goal of this analysis was not to suggest a single solution for reducing whale entanglements in West Coast Dungeness crab gear, but rather to provide managers or policy makers with a tool to use when considering how to reduce entanglements. These scores can then allow managers or policy makers to select a method that can effectively reduce entanglements while maintaining low costs to fishermen or considering other variables of importance.

This analysis revealed several options that are strong candidates for aiding the West Coast commercial Dungeness crab fisheries in reducing whale entanglements. Regardless of weighting scenarios, some alternatives ranked high because of their potential for reducing whale entanglements, as well as anticipated low costs and their likelihood to be accepted by the fishing community. GTRs, for example, cost $1.75 to $2.50 per unit depending on desired corrosion release length ("Galvanic Timed Releases," n.d.). GTRs can effectively reduce the amount of time whales can interact with gear by keeping gear out of the water column until necessary and are already employed by fixed-gear fisheries in Australia and New Zealand (Salvador et al., 2006). Reducing float line length, similarly, would contribute no additional costs to fishermen, and reduce the potential for line to slack and form loops in the water column. Entanglement groups on the West Coast have already developed best-practices guides for voluntary line length

suggestions (California Dungeness Crab Fishing Gear Working Group, 2017a). These alternatives will likely be the easiest for managers to initially implement in commercial Dungeness fisheries.

If managers are primarily concerned with only selecting options that may successfully reduce whale entanglements, then plausible alternatives will be GTRs, catch shares, temporary area closures, permanent area closures, or shorter fishing seasons. Some of these alternatives may be met with more resistance, however, because of the potential for more dramatic changes to the fishery. Temporary area closures, permanent area closures or MPAs, or shortening the length of the fishing season could all negatively impact fishing effort. Implementing catch shares would require restructuring the fishery.

Potential weaknesses in this type of analysis include scarcity of data for the relative ability of alternatives to reduce whale entanglements. For other alternatives, there can be a wide range of possible outcomes depending on the situation. Although these alternatives have all been suggested as ways to reduce whale entanglements for fixed gear fisheries, some alternatives are better than others in their demonstrated ability to reduce interactions with whales. Other alternatives could create excess financial burdens for fishermen. Whale pingers can have one-time purchase costs in excess of $70 per pot, driving costs for fishermen working with 500 pots upwards of $35,000 ("3kHz Whale Pinger," n.d.). Pingers also displayed limited to no success in several studies involving whales and the most frequently employed frequencies (Dunlop & Dunlop, 2013; Harcourt et al., 2014; Pirotta et al., 2016). Boycotts scored low, largely due to their variability in effectiveness, and uncertainty in the costs it would bring to fishermen. West Coast commercial Dungeness fishermen anticipate that a consumer boycott of their fishery could potentially be problematic (Pacific States Marine Fisheries Commission, 2017). Boycotts are

largely out of the hands of managers or fishermen and could happen as a result of consumers becoming unhappy with the continuation of whale entanglements involved with the Dungeness fishery.

Conclusion

Whale entanglements warrant serious consideration from a fisheries management standpoint. The West Coast Dungeness crab fisheries, and California in particular, will face federal intervention if current entanglement rates continue. This study can help managers to focus future entanglement reduction efforts on methods most likely to make the most significant impact on entanglements while avoiding unnecessary repercussions to fishermen. Preemptive action may save the profitable West Coast Dungeness fishery, and the fishermen who depend on it for a large portion, if not all, of their livelihoods from potentially restrictive federal interference.

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Appendix A: Pot/Trap gear requirements and management areas under the Atlantic Large Whale Take Reduction Plan

Region	State Waters	Trap/Pot Gear Regulations	Trap/Pot Sub-Region Regulations	Exemptions
Northeast	Maine New Hampshire Massachusetts Rhode Island Connecticut Federal Waters	- No buoy line floating at the surface - Gear must be hauled at least once every 30 days - Fishermen are encouraged to keep knot-free buoy lines - Groundlines must be sinking line - Trawls with <= 5 traps may only have 1 buoy line, MA state waters 3 traps or less must have 1 endline - Anything attached to the buoy line must be attached with a weak link with breaking strength as defined by specific management area (<= 600lbs breaking strength) - Weak links must come from NMFS list of approved gear - Weak links must be attached with a clean line free of knots - Buoy lines must be marked with three 12-inch colored marks: one at the top of the buoy line, one midway along the buoy line, and one at the bottom of the buoy line. - Color requirements for buoy line markings are designated for each management area	Northern Inshore State Waters -Year-round: general requirements apply; gear marking = red Massachusetts Restricted Area - February 1 to April 30: Closed to all trap/pot fishing - May 1-January 31: General requirements apply; gear marking = red Stellwagen Bank/Jeffreys Ledge Restricted Area -Year-round: general requirements apply; gear marking = red or red and green if overlapping Jeffery's Ledge Gear Marking area Great South Channel Restricted Area - April 1-June 30: Closed to all trap/pot fishing - July 1-March 31: General requirements apply; gear marking = red or black, depending on location Northern Nearshore Waters - Year-round: General requirements apply; gear marking = red or red and green if overlapping Jeffreys Ledge Gear Marking Area	Exemptions from minimum trap per trawl requirements: - Maine: waters within 1/4mile of the following islands: Monhegan, Matinicus, Ragged, Matinicus Island group, and Isle of Shoals group - New Hampshire: All New Hampshire State Waters - Massachusetts: From NH border to south of Cape Cod, from the shoreline to 3 nautical miles from shore. - Rhode Island: All Rhode Island State waters.

Region	State Waters	Trap/Pot Gear Regulations	Trap/Pot Sub-Region Regulations	Exemptions
		- Surface buoys must be marked to identify the vessel or fishery with either the owner's motorboat registration number, the federal commercial fishing permit number, or whatever positive identification marking is required by the vessel's home-port state.	Southern Nearshore Waters (Northeast) - Year-round: General requirements apply; gear marking = orange. Offshore Waters (Northeast) - General requirements apply; gear marking = black, or black and purple if overlapping Jordan Basin Marking Area. Weak links <= 1500 lbs in offshore, 2000 lbs if red crab trap/pot. Jeffreys Ledge Gear Marking Area - Gear marking = red and green Jordan Basin Gear Marking Area -Gear Marking = red and purple if overlapping LMA1, black and purple if overlapping offshore trap/pot waters	

Region	State Waters	Trap/Pot Gear Regulations	Trap/Pot Sub-Region Regulations	Exemptions
Mid-Atlantic		- No buoy line floating at the surface - Gear must be hauled at least once every 30 days - Fishermen are encouraged to keep knot-free buoy lines - Groundlines must be sinking line - Anything attached to the buoy line must be attached with a weak link with breaking strength as defined by specific management area - Weak links must come from NMFS list of approved gear - Weak links must be attached with a clean line free of knots - Buoy lines must be marked with three 12-inch colored marks: one at the top of the buoy line, one midway along the buoy line, and one at the bottom of the buoy line. - Color requirements for buoy line markings are designated for each management area - Surface buoys must be marked to identify the vessel or fishery with either the owner's motorboat registration number, the federal commercial fishing permit number, or whatever positive identification marking is required by the vessel's home-port state.	Southern Nearshore Trap/Pot Waters - Sept 1-May 31: General requirements apply; gear marking = orange. Offshore Trap/Pot Waters (MId-Atlantic) - Sept 1-May 31: General requirements apply; gear marking = black, weak links <= 1500 lbs breaking strength and <= 2000 breaking strength for red crab trap/pot fishery	Exemptions -COLREGS waters: waters landward of the 72 COLREGS lines from Maine through Florida are exempt from plan requirements with certain exceptions: Gardiners Bay and Long Island Sound (NY) -New York: certain areas - Delaware: Delaware Bay - Maryland/Virginia: Chesapeake Bay

Region	State Waters	Trap/Pot Gear Regulations	Trap/Pot Sub-Region Regulations
Southeast	South Carolina Georgia Florida	- No buoy line floating at the surface - Gear must be hauled at least once every 30 days - Fishermen are encouraged to keep knot-free buoy lines - Groundlines must be sinking line - Anything attached to the buoy line must be attached with a weak link with breaking strength as defined by specific management area (<= 600lbs breaking strength) - Weak links must come from NMFS list of approved gear - Weak links must be attached with a clean line free of knots - Buoy lines must be marked with three 12-inch colored marks: one at the top of the buoy line, one midway along the buoy line, and one at the bottom of the buoy line. - Color requirements for buoy line markings are designated for each management area - Surface buoys must be marked to identify the vessel or fishery with either the owner's motorboat registration number, the federal commercial fishing permit number, or whatever positive identification marking is required by the vessel's home-port state.	Southern Nearshore Trap/Pot Waters - Dec 1-Mar 30: South of the SE restricted area, General requirements apply; gear marking = orange, weak links <= 600 lbs breaking strength. - Sep 1-May 31: North of SE restricted area, General requirements apply; gear marking = orange, weak links <= 600 lbs breaking strength Offshore Trap/Pot Waters (Southeast) -Sep 1-May 31: N of 32 deg N; general requirements apply, gear marking = black, weak links <= 1500 lbs and <= 2000 lbs for red crab fishery. - Nov 15-Apr 15: Between 32 deg N and 29 deg N; general requirements apply, gear marking = black, weak links <= 1500 lbs and <= 2000 lbs for red crab fishery. - Dec 1-Mar 31: Between 29 deg N and 27 deg 51' N; general requirements apply, gear marking = black, weak links <= 1500 lbs and <= 2000 lbs for red crab fishery. SE Restricted Area North - For all areas, Nov 15-Apr 15; general requirements apply, only single traps allowed, whole buoy line must be the same diameter, made of sinking line. - FL State Waters: weak links <= 200 lbs, vertical line strength <= 1500 lbs, gear marking = blue and orange. - SC/GA State Waters: weak links <= 600 lbs, vertical line strength <= 2200 lbs, gear marking = blue and orange. - Federal Waters: weak links <= 600 lbs, vertical line strength <= 2200 lbs, gear marking = green and orange, gear must be brought to shore at the conclusion of each trip.

Appendix B: Gillnet gear requirements and management areas under the Atlantic Large Whale Take Reduction Plan

Region	State Waters	Gillnet Gear Regulations	Gillnet Sub-Region Regulations	Exemptions
Northeast	Maine New Hampshire Massachusetts Rhode Island Connecticut Federal Waters	- No buoy line floating at surface - Gear must be hauled at least once every 30 days - Fishermen are encouraged to keep knot-free buoy lines - Groundlines must be sinking line - Surface buoys must be marked to identify the vessel or fishery with either the owner's motorboat registration number, the federal commercial fishing permit number, or whatever positive identification marking is required by the vessel's home-port state. - Buoy lines must be marked with three 12-inch colored marks: one at the top of the buoy line, one midway along the buoy line, and one at the bottom of the buoy line. - Anything attached to the buoy line must be attached with a weak link with breaking strength as defined by specific management area (<= 600lbs breaking strength) - Individual weak links are not required in locations where rope of appropriate breaking strength is used - Weak links are not required if no up and down line is present	Cape Cod Bay Restricted Area - Jan 1- May 15: Closed to all gillnet fishing - May 16-Dec 31: General requirements apply; weak links breaking strength of no greater than 1,1000 lb, gear marking = green Stellwagen Bank/Jeffreys Ledge Restricted Area - Year-round: General requirements apply; weak links breaking strength of no greater than 1,100 lb, gear marking = green. Great South Channel Restricted Area - April 1-June 30: Closed to all gillnet fishing (excluding sliver area). - July 1-March 31: General requirements apply; weak links breaking strength of no greater than 1,100 lb, gear marking = green Great South Channel Sliver Restricted Area - Year-round: General requirements apply; weak links breaking strength of no greater than 1,100 lb, gear marking = green	- Fisheries exempt from sinking groundline requirement if at depth >= 280 fathoms - Anchored gillnet fisheries exempt from weak link requirements and to anchor each end of the net string if the floatt line depth is >=280 fathoms Waters exempted areas include: -water landward of the 72 COLREGS lines from Main through Florida, with the exceptions of Casco Bay, Portsmouth Harbor, and Massachusetts state waters - waters in MA landward of the first bridge over any embayment, harbor, or inlet -certain areas in NH - Certain waters in RI - Certain waters in ME

Region	State Waters	Gillnet Gear Regulations	Gillnet Sub-Region Regulations	Exemptions
		- All gillnets, regardless of number of panels, will be required to be anchored with the holding power of at least a 22-lb Danforth-style anchor at each end of the net string (must be a burying anchor; no dead weights) - Fishing with drift gillnet gear at night is prohibited unless the gear is tended (attached to vessel) - All driftnet gear must be removed from the water and stowed on board before a vessel returns to port	Other Northeast Gillnet Waters (North) -Year-round: general requirements apply; weak link breaking strength of no greater than 1,100 lb, gear marking = green. Jeffreys Ledge Marking Area - Gear marking = green and black Jordan Basin Marking Area -Gear marking = green and yellow	

Region	State Waters	Gillnet Gear Regulations	Gillnet Sub-Region Regulations	Exemptions
Mid-Atlantic		- No buoy line floating at surface - Gear must be hauled at least once every 30 days - Fishermen are encouraged to keep knot-free buoy lines - Groundlines must be sinking line - Surface buoys must be marked to identify the vessel or fishery with either the owner's motorboat registration number, the federal commercial fishing permit number, or whatever positive identification marking is required by the vessel's home-port state. - Buoy lines must be marked with three 12-inch colored marks: one at the top of the buoy line, one midway along the buoy line, and one at the bottom of the buoy line. - Anything attached to the buoy line must be attached with a weak link with breaking strength as defined by specific management area - For nets that do not return to port with the vessel: weak links must be incorporated into net panels following suggested configurations and have breaking strengths as defined by management area - For nets that return to port each day with the vessel: net panels are required to have a weak link at the center of each floatline or at least every 25 fathoms along the floatline of a panel longer than 50 fathoms.	Other Northeast Gillnet Waters - Sept 1-May 31: General requirements apply; gear marking = green. Mid/South Atlantic Gillnet Waters - Sept 1-May 31: General requirements apply; gear marking = blue (anchored), green (drift). Breaking strength of no greater than 1100 lb. Gillnets set within 300 yards of the shoreline in NC not returning to port with the vessel have optional gillnet configuration	Exemptions -COLREGS waters: waters landward of the 72 COLREGS lines from Maine through Florida are exempt from plan requirements with certain exceptions: Gardiners Bay and Long Island Sound (NY) -New York: certain areas - Delaware: Delaware Bay - Maryland/Virginia: Chesapeake Bay

Region	State Waters	Gillnet Gear Regulations	Gillnet Sub-Region Regulations	Exemptions
		- Individual weak links are not required in locations where rope of appropriate breaking strength is used - Weak links are not required if no up and down line is present - All gillnets, regardless of number of panels, will be required to be anchored with the holding power of at least a 22-lb Danforth-style anchor at each end of the net string (must be a burying anchor; no dead weights) - Fishing with drift gillnet gear at night is prohibited unless the gear is tended (attached to vessel) - All driftnet gear must be removed from the water and stowed on board before a vessel returns to port		

Region	State Waters	Gillnet Gear Regulations	Gillnet Sub-Region Regulations	Exemptions
Southeast	South Carolina Georgia Florida	- No buoy line floating at surface - Gear must be hauled at least once every 30 days - Fishermen are encouraged to keep knot-free buoy lines - Groundlines must be sinking line - Surface buoys must be marked to identify the vessel or fishery with either the owner's motorboat registration number, the federal commercial fishing permit number, or whatever positive identification marking is required by the vessel's home-port state. - Buoy lines must be marked with three 12-inch colored marks: one at the top of the buoy line, one midway along the buoy line, and one at the bottom of the buoy line. - Anything attached to the buoy line must be attached with a weak link with breaking strength as defined by specific management area - For nets that do not return to port with the vessel: weak links must be incorporated into net panels following suggested configurations and have breaking strengths as defined by management area - For nets that return to port each day with the vessel: net panels are required to have a weak link at the center of each floatline or at least every 25 fathoms along the	Southeast US Restricted Area North - Nov 15-Apr 15: Fishing with or possessing gillnets prohibited. Certain exceptions for transiting through with gillnets Southeast US Restricted Area South - Dec 1-Mar 31: Area closed to fishing with or possessing gillnets Outher Southeast Gillnet Waters - See guide for specific dates, regulations, gear marking, etc. Southeast US Monitoring Area - Dec 1-Mar 31: for shark gillnet with webbing that is 5" or greater stretched mesh. Gear marking = green and blue, fishing vessel must carry an observer if selected by NMFS, fishing vessel must be compliant with VMS requirements found in 50 CFR 635.69.	Southeast US Restricted Area -Fishing for sharks exempt from closure Dec 1- March 31 IF (see guide for full list of exemptions), gear marking = green and blue - Fishing for Spanish mackerel is exempt from closure Dec 1-Dec 31 and Mar 1-Mar 31 IF (see guide for full list of exemptions), gear marking = yellow.

Region	State Waters	Gillnet Gear Regulations	Gillnet Sub-Region Regulations	Exemptions
		floatline of a panel longer than 50 fathoms. - Individual weak links are not required in locations where rope of appropriate breaking strength is used - Weak links are not required if no up and down line is present - All gillnets, regardless of number of panels, will be required to be anchored with the holding power of at least a 22-lb Danforth-style anchor at each end of the net string (must be a burying anchor; no dead weights) - Fishing with drift gillnet gear at night is prohibited unless the gear is tended (attached to vessel) - All driftnet gear must be removed from the water and stowed on board before a vessel returns to port		

Appendix C: Pairwise Scoring Matrices

Table *i*: Pairwise scoring for alternatives (N=15) for decision criterion *Cost*. Scores were used in AHP R code for analysis (Glur, 2018)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
A	1	1	1	4	4	4	1	4	4	4	4	7	4	4	7
B	1	1	1	4	4	4	1	4	4	4	4	7	4	4	7
C	1	1	1	4	4	4	1	4	4	4	4	7	4	4	7
D	1/4	1/4	1/4	1	1	1	1/4	1	1	1	1	3	1	1	3
E	1/4	1/4	1/4	1	1	1	1/4	1	1	1	1	3	1	1	3
F	1/4	1/4	1/4	1	1	1	1/4	1	1	1	1	3	1	1	3
G	1	1	1	4	4	4	1	4	4	4	4	7	4	4	7
H	1/4	1/4	1/4	1	1	1	1/4	1	1	1	1	3	1	1	3
I	1/4	1/4	1/4	1	1	1	1/4	1	1	1	1	3	1	1	3
J	1/4	1/4	1/4	1	1	1	1/4	1	1	1	1	3	1	1	3
K	1/4	1/4	1/4	1	1	1	1/4	1	1	1	1	3	1	1	3
L	1/7	1/7	1/7	1/3	1/3	1/3	1/7	1/3	1/3	1/3	1/3	1	1/3	1/3	1
M	1/4	1/4	1/4	1	1	1	1/4	1	1	1	1	3	1	1	3
N	1/4	1/4	1/4	1	1	1	1/4	1	1	1	1	3	1	1	3
O	1/7	1/7	1/7	1/3	1/3	1/3	1/7	1/3	1/3	1/3	1/3	1	1/3	1/3	1

Table *ii*: Pairwise scoring for alternatives (N=15) for decision criterion *Effectiveness*.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
A	1	4	4	1	4	4	4	1	1	1	4	1	4	4	7
B	1/4	1	1	1/4	1	1	1	1/4	1/4	1/4	1	1/4	1	1	1/3
C	1/4	1	1	1/4	1	1	1	1/4	1/4	1/4	1	1/4	1	1	1/3
D	1	4	4	1	4	4	4	1	1	1	4	1	4	4	7
E	1/4	1	1	1/4	1	1	1	1/4	1/4	1/4	1	1/4	1	1	3
F	1/4	1	1	1/4	1	1	1	1/4	1/4	1/4	1	1/4	1	1	3
G	1/4	1	1	1/4	1	1	1	1/4	1/4	1/4	1	1/4	1	1	3
H	1	4	4	1	4	4	4	1	1	1	4	1	4	4	7
I	1	4	4	1	4	4	4	1	1	1	4	1	4	4	7
J	1	4	4	1	4	4	4	1	1	1	4	1	4	4	7
K	1/4	1	1	1/4	1	1	1	1/4	1/4	1/4	1	1/4	1	1	3
L	1	4	4	1	4	4	4	1	1	1	4	1	4	4	7
M	1/4	1	1	1/4	1	1	1	1/4	1/4	1/4	1	1/4	1	1	3
N	1/4	1	1	1/4	1	1	1	1/4	1/4	1/4	1	1/4	1	1	3
O	1/7	3	3	1/7	1/3	1/3	1/3	1/7	1/7	1/7	1/3	1/7	1/3	1/3	1

Table *iii*: Pairwise scoring for alternatives (N=15) for decision criterion *Response*.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
A	1	1	1	1	1	1	4	4	7	7	4	7	7	7	7
B	1	1	1	1	1	1	4	4	7	7	4	7	7	7	7
C	1	1	1	1	1	1	4	4	7	7	1	7	7	7	7
D	1	1	1	1	1	1	4	4	7	7	4	7	7	7	7
E	1	1	1	1	1	1	4	4	7	7	4	7	7	7	7
F	1	1	1	1	1	1	4	4	7	7	4	7	7	7	7
G	1/4	1/4	1/4	1/4	1/4	1/4	1	1	3	3	1	3	3	3	3
H	1/4	1/4	1/4	1/4	1/4	1/4	1	1	3	3	1	3	3	3	3
I	1/7	1/7	1/7	1/7	1/7	1/7	1/3	1/3	1	1	1/3	1	1	1	1
J	1/7	1/7	1/7	1/7	1/7	1/7	1/3	1/3	1	1	1/3	1	1	1	1
K	1/4	1/4	1	1/4	1/4	1/4	1	1	3	3	1	3	3	3	3
L	1/7	1/7	1/7	1/7	1/7	1/7	1/3	1/3	1	1	1/3	1	1	1	1
M	1/7	1/7	1/7	1/7	1/7	1/7	1/3	1/3	1	1	1/3	1	1	1	1
N	1/7	1/7	1/7	1/7	1/7	1/7	1/3	1/3	1	1	1/3	1	1	1	1
O	1/7	1/7	1/7	1/7	1/7	1/7	1/3	1/3	1	1	1/3	1	1	1	1

Appendix D: Regulatory Pathways for Implementing Alternatives

Once a preferred alternative has been selected by managers, it will need to be implemented. Following a regulatory pathway is one way of employing alternatives in the commercial Dungeness crab fishery; to facilitate managers' evaluation of the political and practical feasibility of implementing any of the changes discussed here, I have compiled a list of key existing regulations for the Dungeness crab fishery (Appendix E).

For example, if managers wanted to require fishermen to use multiple pots per line in Washington State to reduce the number of vertical lines in the water column, then the Washington Department of Fish and Wildlife would need to go through a rulemaking process to change WAC 220-340-435 (Appendix E). In the same way, managers seeking to change the season length or openings in California would look to amend the legislature in FGC § 8276 (Appendix E).

Decision makers could also opt to add regulations, like requiring additional markings on trap buoys and float lines. Although this decision would not directly lessen the likelihood of whale entanglement, specific gear marking for a particular management area like what is enforced on the Atlantic Coast (Appendix A, B) can help to pinpoint potential entanglement problem areas along the West Coast. This can foster targeted and efficient management strategies in the future. The general agency in charge of the commercial crab fishery for each of the West Coast States is their respective Department of Fish and Wildlife. Any changes to fishery regulations would then be enforced by the Department.

Appendix E: List of key regulations and related legislative authority for commercial Dungeness crab fisheries in California, Oregon, and Washington that can be used to instigate regulatory change in State fisheries.

	California	Oregon	Washington
Agency	California Department of Fish and Wildlife (CDFW)	Oregon Department of Fish and Wildlife (ODFW)	Washington Department of Fish and Wildlife (WDFW)
Legislative Authority	FGC § 8276. Crab Season FGC § 8276.4 OPC Task Force FGC § 8280.6 Permit Fee FGC §8275-8284	ORS 506.036 Jurisdiction of Commission ORS 509.415 Crab Gear ORS 508.270 License Fees ORS 508.943 Pot Removal	RCW 77.70.500 Pot Removal RCW 77.70.110 Puget Sound Fishery Licenses RCW 77.70.360 Coastal Fishery Licenses RCW 77.70.400 Crab Resource Plan RCW 77.04.012 Commission Mandate
Existing Regulations	14 CCR § 132.1 Trap/Buoy Tags 14 CCR § 132.2 Pot Retrieval 14 CCR § 132.3 Biennial Trap Permit	OAR 635-005-0405 Crab Permit OAR 635-005-046 Harvest Areas OAR 635-005-0410 Permit Fee OAR 635-005-0480 Buoy/Gear Marking Requirements OAR 635-005-0475 Gear Specifications OAR 635-005-0490 Derelict Gear	WAC 220-340-435 Pot/Gear Specifications WAC 220-340-450 Coastal Fishery Season/Areas WAC 220-340-455 Puget Sound Fishery Season/Areas WAC 220-340-490 Coastal Gear Recovery WAC 220-340-410 Commercial Licenses WAC 220-340-430 Tag and Buoy Requirements

Appendix F: Non-regulatory Pathways for Implementing Alternatives

While regulatory changes will be an important component of delivering necessary changes to reduce whale entanglements, it might also prove necessary to prompt transformation via non-regulatory pathways. Incentivizing voluntary actions to reduce whale entanglements, like shortening float line lengths or removing derelict gear, can be a way to alleviate tension between managers and fishermen. Managers can incentivize greater involvement in derelict gear retrieval programs, for example, by granting fishermen the ability to retrieve more pots in exchange for implementing one of the alternatives discussed in this study. Fishermen, perhaps, might be more interested in voluntarily incorporating GTRs if they were granted extra pots at the end of the season depending on their State's derelict gear program. Providing exemptions from some regulations that fishermen deem particularly taxing may be another method. If regulations shorten a season in order to reduce entanglements, perhaps fishermen would be encouraged to use gear like GTRs and/or line cutting devices if they were allowed to fish past the close of the normal season.

While working groups can be created via regulatory processes in states like California, they can serve a non-regulatory purpose of spurring action in the fishing community. When working groups include valuable stakeholders like commercial fishermen, it allows them to foster a sense of involvement and buy-in in a decision-making process that may be missing from regulatory pathways. California's Dungeness Crab Working Group, composed of stakeholders like commercial and recreational fishermen, has been working on several adaptations to reduce interactions between whales and fishing gear (California Ocean Protection Council, 2017). Their Risk Assessment and Mitigation Program (RAMP) aims to identify circumstances that can reduce risks of entanglement and address situations (California Dungeness Crab Fishing Gear

Working Group, 2017b). The California Working Group has also generated a voluntary best-practices guide for fishing gear to help reduce entanglements, and (California Dungeness Crab Fishing Gear Working Group, 2017a).