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Original Research Article

Evaluating alternatives to reduce whale entanglements in commercial Dungeness Crab fishing gear

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ABSTRACT

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 whale population. Here, we compare management alternatives to reduce entanglements, thereby reducing conflicts between whales and fishermen, scoring these alternatives according to estimated cost to fishermen, likely technical effectiveness, and anticipated reaction of fishermen in response to the change. We analyze these alternatives quantitatively using a Multi-Criterion Decision Analysis, and provide the analytical code as a decision-aid tool for managers and policy makers to use when contemplating changes to the West Coast commercial Dungeness fishery. We find a small number of high-ranking policy options; most prominently among these are Galvanic Timed Releases, which minimize the time that crab-pot lines are in the water and thus reduce the likelihood of entanglement. In addition, we include in an appendix a detailed list of regulations affecting the commercial Dungeness fishery, thereby providing both a substantive and procedural roadmap for reducing fishery-whale conflict.

1. Introduction

Fishing lines, traps, and other equipment generally target particular commercially important marine 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 – the general term for mammal conflict with fishing gear, because the mammals are often literally entangled – 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

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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 intensive whaling activities in the past. For example, ropes wrapped around a whale can cause lacerations, often leading to infection and subsequent death (Moore and 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 and Hoop, 2012). Line from fixed gear may become embedded in a whale's baleen plates, disrupting water flow patterns and general feeding ability (Moore and 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 (van der Hoop et al., 2016, 2017).

Here, we compare management alternatives to reduce entanglements. There is relatively little information on the in-water effectiveness of many of the alternatives we discuss below; accordingly our analysis focuses more heavily on the human elements of policy change – namely, the cost and reception of different alternatives among the fishermen likely to be affected. We weigh these factors alongside the prospective technical effectiveness of each policy alternative in a transparent and broadly applicable framework, providing information and analysis to facilitate what we view as a likely necessary policy change along the West Coast of the United States.

1.1. Whale entanglements along the West Coast of the United States

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 (*Metacarcinus magister*; NMFS, 2015) (see Fig. 1).

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 would likely force changes to fishing-industry practices and which has consequently raised concerns within the industry (Rahaim, 2018; Banse). Entanglements on the West Coast have transitioned from involving mostly Gray whales (*Eschrichtius robustus*) in net fisheries (in the 1980s) to Humpback whales interacting with commercial Dungeness gear (Fig. 2). There were 71 cases of reported entanglements in 2016 (NMFS, 2016). Of those, 48 were confirmed by NOAA and 22 were identified as involving commercial Dungeness gear (NMFS, 2016); most of the remaining entanglements were from unknown gear types (Fig. 2).

1.2. The Dungeness crab fishery

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; in California alone, the catch may be worth up to $88 million to fishermen at first sale (NOAA Fisheries). As a result, Dungeness crab fishing is the

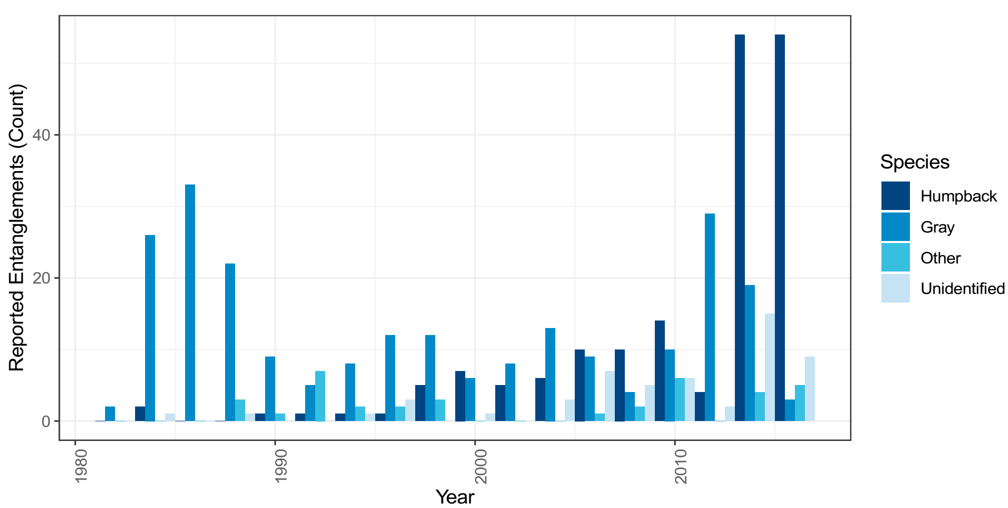

Fig. 1. Reported whale entanglements by species and year. Data: NOAA.

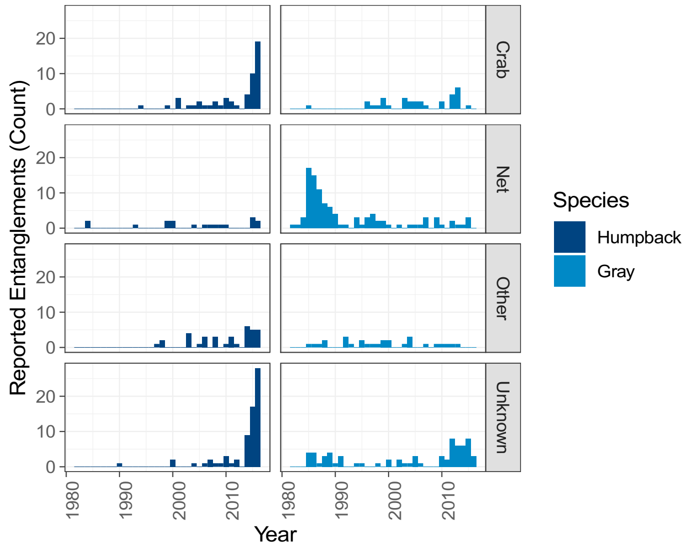

Fig. 2. Reported whale entanglements by species, year, and fishery-gear-type for the two most commonly entangled species along the US West Coast. Data: NOAA.

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 et al., 2004).

Commercial crab fishermen use crab pots, each set with an individual buoy attached to a float line. Commercial crabbers typically place their pots in 18–92 m of water (Hankin and Warner, 2001; 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 any given license holder (14 CCR § 132.1; OAR 635-005–0405; WAC 220-340–430). Although fishing effort varies between areas along the West Coast, recent models there are up to 38.56 commercial Dungeness crab traps per km (Kot et al., 2012), each with its own line that could, in principle, pose an entanglement threat (Macks, 2018). The normal crabbing season ranges from mid-November/early-December through August/September, depending on the management area, with season openings designed to avoid peak molting or mating periods (Hankin and Warner, 2001).

1.3. The regulatory context

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 (U.S. Public Law 115-49, codified at 16 U.S.C. § 1856). However, the federal MMPA and ESA remain as overarching limitations on the harm that commercial fisheries may do to particular species of interest.

The MMPA imposes a blanket moratorium on the take and importation of marine mammals, with some exceptions, including one for incidental take in commercial fisheries (Marine Mammal Protection Act of 1972, 1972). However, if marine mammal species numbers fall below their optimum sustainable yield level, the law requires immediate action to replenish the populations (Marine Mammal Protection Act of 1972, 1972). 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 (Marine Mammal Protection Act of 1972, 1972); 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 (Marine Mammal Protection Act of 1972, 1972). The PBR allocation for the California/Oregon/Washington stock of Humpback whale in U.S. waters is 11 whales per year (Carretta et al., 2017). As such, Humpback entanglements in recent years have threatened to force federal intervention in the Dungeness fishery, which would first be via 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 (U.S. Endangered Species Act, 1973). 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.

Conflicts between North Atlantic right whales (Eubalaena glacialis) 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 (Knowlton et al., 2012). The ALWTRP has focused on furthering research on methods to reduce entanglements, disentanglement efforts, timed area-closures, and gear modifications (62 FR 39157, 1997) (See Appendices A and B for a summary of current ALWTRP rules). NMFS can and does promulgate rules under the MMPA, implementing ideas from the Take Reduction Plans (Marine Mammal Protection Act of 1972, 1972; 62 FR 62587, 2007), but in general these Teams have seen little tangible success, often struggling to meet deadlines for developing draft plans, publishing final plans, and failing to reduce bycatch levels in strategic stocks (Mcdonald et al., 2016; United States Government Accountability Office, 2008).

Although the ALWTRP is the closest precedent for the set of policy challenges currently facing the Dungeness fishery, other fisheries have also experimented with whale deterrents including acoustic noisemakers ("pingers") in California drift gillnets (Appendix A, B) and with other measures such as reducing the length of lines or changing fishing seasons (Moore and Hoop, 2012; Knowlton et al., 2012; Jefferson and Curry, 1996; Kraus, 1999) (Appendix A, B).

Entanglement-reduction strategies, regardless of fishery, can be difficult to examine for effectiveness, and there is a lack of literature detailing supporting studies of entanglement-mitigating modifications. Consequently, any change is likely to be driven by the social acceptability of policy tools, rather than their demonstrated efficacy in reducing entanglement. Below, we weigh a total of 16 different gear modifications, social interventions, and regulatory changes in an effort to comprehensively evaluate the management alternatives to reduce conflict between whales and the West Coast Dungeness fishery. We find a small number of alternatives to be uniformly favorable across many cost-weighting scenarios, pointing the way to likely avenues of policy change to minimize future entanglements while protecting the Dungeness fishery. We view these results as reflecting primarily the social desirability of different interventions.

2. Methods

We first reviewed the available peer-reviewed and federal-agency literature to identify a set of available management alternatives. Gear modifications and other alternatives are ways for the West Coast Dungeness crab fishery to alleviate whale entanglements before federal intervention is required by either the MMPA or the ESA. We summarize available options below. This list includes all of the interventions we encountered that had sufficient information available that we could score them along three axes: cost to fishermen, technological effectiveness, and likely response of fishermen (a proxy for political feasibility). Following the explanation of these management alternatives, we present the methods for a limited survey of fishery-industry participants (used to guide our scoring of alternatives) and the methods for the quantitative Multi-Criterion Decision Analysis of the resulting scores under different cost-weighting scenarios.

2.1. Pingers and other acoustic deterrents

Whale-pingers placed on lines or nets emit noises at frequencies intended to alert or warn whales away from gear (Werner et al., 2006). Such 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). Overall, pingers have had limited success in deterring whales (Pirotta et al., 2016). Humpback whales have, however, shown in some studies limited responses to specific frequencies and durations (Harcourt et al., 2014), and in the California drift gillnet fishery, pingers were so effective that they became mandatory (Carretta et al., 2004).

2.2. 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 minimize line-length and therefore entanglement risk, but this line is more expensive than traditional floating line (Cavatorta et al., 2005). Moreover, *floating* line made with polypropylene generates less friction with baleen plates, and itself can reduce the risk of entanglement (Cavatorta et al., 2005). Weakening the line – decreasing the threshold force required to break it – is another modification that can allow whales to break free after a certain amount of pressure has been applied (Knowlton et al., 2016), although presumably this comes at a cost of false-positive failures and expense to fishermen to replace lost equipment.

2.3. Line color

Initial studies on marine mammal eyesight suggest they are L-cone monochromats, implying color-blindness especially in poor light conditions (Peichl et al., 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 could plausibly aid in reducing entanglements, given the untested assumption that whales would avoid ropes in their environment if they knew they were present, by allowing the whale to see the gear before they collide with it (Kot et al., 2012).

2.4. Weak links

In an effort to reduce North Atlantic Right whale entanglements, East Coast fixed-gear fisheries currently employ weak links in their lines. These have the same effect as reducing line strength; weak links are connectors between vertical lines and buoy systems designed to break free at a set pressure threshold (Knowlton et al., 2012). These weak links are already widely employed, however, their effectiveness is an open question (Levesque, 2009; Vanderlaan et al., 2011). For example, 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 et al., 2003). As with line material or strength (above), presumably there is a necessary calibration to optimize tradeoffs between false-negative and false-positive breakage.

2.5. Galvanic Timed Releases (GTRs)

Fixed-gear fisheries in Australia and New Zealand employ GTRs, devices that keep lines submerged until the pots are ready to be picked up (Salvador et al., 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. GTRs appear to work as designed, for example, by accurately releasing within the manufacturer's given erosion time (Salvador et al., 2006).

2.6. Timed line-cutting device

Timed tension-line cutters (TTLCs) are links between a 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 (Salvador et al., 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.

2.7. Acoustic buoy releases

Acoustic buoy releases are a set of techniques in which all gear remains submerged, with the trap on the ocean floor, until the fishermen employ an acoustic trigger to release the buoy back to the surface for retrieval (Werner et al., 2006). This method eliminates the need for vertical lines in the water column until necessary, drastically reducing the time available for whales to interact with gear. Because the traps are completely submerged, however, there is potential for increased gear conflicts between both mobile and other fixed gear fisheries (NMFS, 2010). Additionally, acoustic buoy releases are currently high in cost, and repacking lines for resetting traps can be time consuming for fishermen (Werner et al., 2017; Davie, 2018). Improvements in gear technology show potential for acoustic gear that reports its position to nearby ships involved in either mobile or fixed gear fisheries, and increased demand for this technology can aid in bringing overall costs down in the near future (Werner et al., 2017; Davie, 2018; Baumgartner, 2018). In 2018, the California Dungeness Crab Fishing Gear Working Group completed field trials of various acoustic buoy release designs (Shester, 2018). The field trials demonstrated that acoustic releases show promise for future implementation in the fishery but highlighted current weaknesses in design types such as release failures and time-consuming trap resetting procedures. The Working Group plans to continue their field testing in 2019.

2.8. 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 et al., 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 and Hoop, 2012). One can imagine certifying Dungeness Crab as “whale-safe” in much the same way tuna 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 could 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. The effectiveness of this method would depend on the participation of consumers as part of a social movement, as well as on stringent certification requirements, and is accordingly difficult to evaluate in the abstract.

2.9. Boycotts

Consumer boycotts can be a powerful tool to force industries to alter their behaviors. For example, environmental groups like the NRDC are pushing for US consumers to avoid imported lobster from foreign fisheries that frequently endanger North Atlantic right whales (Smith et al., 2014), and in the 1980s tuna was subject to a highly effective boycott in favor of dolphins; one study showed nearly 78% of interviewed subjects having taken part in the tuna boycott (Wright, 2000). Consumers could choose 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 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.

2.10. Shorter fishing season

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). Here, the East Coast lobster fisheries in Maine are a useful example: these might have 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 and Coughran, 2012; Myers et al., 2007). West Coast Dungeness crab seasons could similarly 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 by reducing the temporal extent of conflict between whales and crab lines.

2.11. 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 and 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.

2.12. 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.

2.13. Derelict-pot buyback

Reducing derelict fishing gear reduces the number of lines in the water over long stretches of time, and therefore reduces the danger of entanglement. California, Oregon, and Washington each have laws issuing permits for fishermen to retrieve derelict crab pots, earning a bounty for their efforts, and reuniting the original owner with the pots in exchange for a fee (ODFW Post-Season Derelict Gear Recovery Program; California Senate Bill No. 1287, 2016; RCW 77.70.500). To the extent that these programs might be expanded – for example, in collaboration with non-governmental organizations such as The Nature Conservancy, which appears to be collaborating with west-coast Dungeness fishermen – they might be an attractive option for reducing entanglements (California Oceans Program). We note, however, that active gear appears more likely to cause entanglements than derelict gear, and accordingly buyback programs may be less effective than policies that target gear in use (Stelfox, 2017; Asmutis-Silvia et al., 2017; Stelfox et al., 2016).

2.14. 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, 2017). Suggestions include float line lengths of between 18 and 30 ft depending on the depth of water the traps are set in (California Dungeness Crab Fishing Gear Working Group, 2017). This eliminates extra float line in the water forming loops that whales may become trapped in.

2.15. Multiple pots-per-line

It is currently illegal to attach more than one trap by a common line in West Coast Dungeness fisheries (CA FGC Sec 9012; OAR 220-340–430; 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, 2017a). 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, 2017a).

2.16. Cooperation among fishermen

Cooperation among fishermen encompasses noncompulsory efforts that occur between members of the industry without the need for outside intervention. This 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 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 (discussed below), fishermen can discuss steps to reduce the chances of entanglement as well as give input on strategies considered by managing entities (Pacific States Marine Fisheries Commission, 2017a).

2.17. Survey of fishery-industry participants

Pacific States Marine Fisheries Commission (PSMFC) convened a two-day workshop in March 2017. PSMFC is an interstate compact agency established by Congress that assists West Coast states with policies and fisheries management (PSMFC Info, 2018). This entanglement workshop allowed Dungeness crab fishermen, fishing gear specialists, and marine mammal experts from the West Coast to discuss the growing entanglement problem along with potential solutions (Pacific States Marine Fisheries Commission, 2017b). At the end of the workshop, participants were given a short survey. The survey listed entanglement alternatives discussed during the workshop, and asked participants to estimate the costs, feasibility, and effectiveness of each alternative. We used this survey to inform our scores for each policy alternative we evaluated. A summary of survey results can be found at https://bit.ly/2ErkI9m.

2.18. Multi-Criterion Decision Analysis

We employed a form of Multi-Criterion Decision Analysis (MCDA) to rank each of the above policy alternatives using the three criteria listed above: cost, effectiveness, and feasibility within the industry. MCDA combines factors such as these – or in other contexts, stakeholder views and cost/benefit information – to rank proposed alternatives for decisionmakers (Huang et al., 2011; Ishizaka and Lusti, 2006; Linkov and Moberg, 2012). Here we use the Analytic Hierarchy Process to implement MCDA (Saaty, 1990). 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 (Linkov and Moberg, 2012).

2.19. Scoring criteria for policy alternatives

We 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 et al., 1987). For this study, those considerations translated into the following criteria (1) *Cost*, an order-of-magnitude estimate of the financial burden of an alternative for 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. Following a literature review, we selected the 16 alternatives described above, which are already implemented or frequently discussed in fisheries from around the world encountering entanglement issues with marine mammals (Table 1). Alternatives were scored for each of the three decision criteria using a Saaty scale (Saaty, 1980) (Appendix C; Fig. 4). We used information obtained from literature reviews, historical data, management plans, NOAA gear tests, minutes and surveys from an entanglement workshop (noted above), discussions with experts, and other relevant reports and documents as the basis of scoring the alternatives with respect to the three decision criteria.

We carried out the MCDA using the package “ahp” for R 3.4.3, and varied the weights of our three evaluation criteria at random to create 100 different decision scenarios (R Core Team, 2017). We report the rankings of each of the policy

Table 1
Abbreviations used for policy alternatives in the Multi-Criterion Decision Analysis.

Alternative	Abbreviation
Galvanic Timed Releases	GTR
Float/Trailer Line Length	LineLength
Acoustic Buoy Releases	Acoustic
Seafood Certification	Certification
Derelict-Pot Buyback	Buyback
Rope Material/Breaking Strength	RopeStrength
Rope Color	RopeColor
Cooperation Among Fishermen	Cooperation
Temporary Area Closures	AreaClosures
Permanent Area Closures or MPAs	MPAs
Shorter Fishing Season	Season
Weak Links	WeakLinks
Line Cutter Device	LineCutters
Multiple Traps Per Line	MultiTraps
Boycotts	Boycotts
Whale Pingers	Pingers

alternatives under each of the 100 scenarios (R Core Team, 2017; Glur, 2018). All analytical code is included in the Supplemental Information.

3. Results

Independent of the weight given to each of the three scoring criteria — that is, for all 100 different decision scenarios — Galvanic Timed Releases is the highest-ranking alternative, outscoring the other alternatives (Fig. 3). 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, acoustic buoy releases (i.e., acoustic gear retrieval), seafood certification programs, and derelict-pot buybacks also consistently ranked high across all scenarios (Fig. 3). Across the

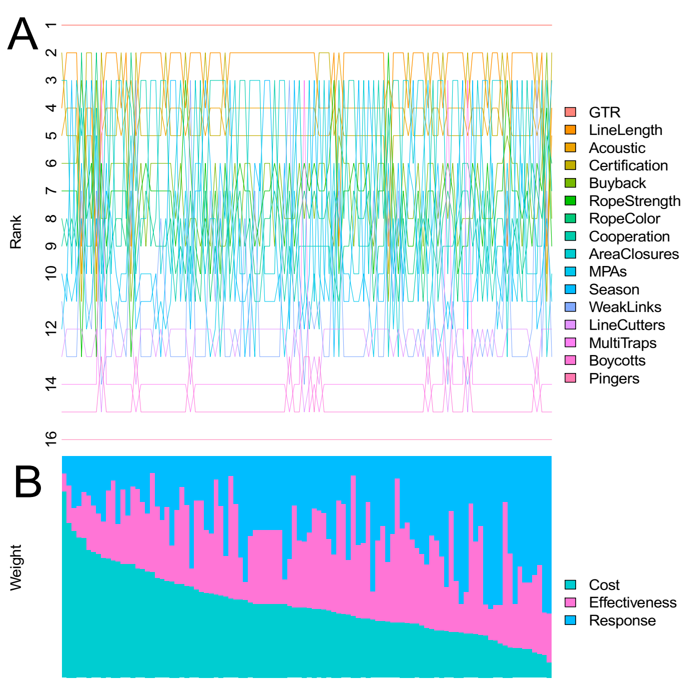

Fig. 3. A) The relative rankings of each of 16 policy alternatives (here labeled with abbreviations; see text for full descriptions) across each of 100 randomly generated weighting scenarios. Each scenario assigned a different weight to the three scoring criteria — cost, effectiveness, and the likely response of the fisheries communities. Rank of 1 was the highest-scoring (i.e., most desirable) option; rank of 16 was the least-desirable option. B) Each of the 100 weighting scenarios, with relative weights for each criterion represented by the length of the respectively colored bar.

spectrum of desirability, the ranking of alternatives tended to be highly robust to different weighting schemes (Fig. 3); no weighting scheme systematically changed the rank order of alternatives, and the same alternatives appeared in the same rank order with high frequency (Fig. 4).

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. Employing multiple traps per line, boycotts, and whale pingers scored the lowest across all decision scenarios (Fig. 3). 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.

4. Discussion

We found surprising agreement across weighting scenarios that a few policy options — namely, GTRs, reducing float trailer line length, and seafood certification programs — consistently ranked highly as feasible ways of reducing whale entanglements in the West Coast Dungeness crab fishery. These alternatives could offer a way to reduce entanglements without generating undue financial constraints on fishermen, potentially avoiding federal intervention under the MMPA and ESA.

Implementing any these or other policy alternatives will require some action via regulatory or non-regulatory pathways (Appendix E). 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 we 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

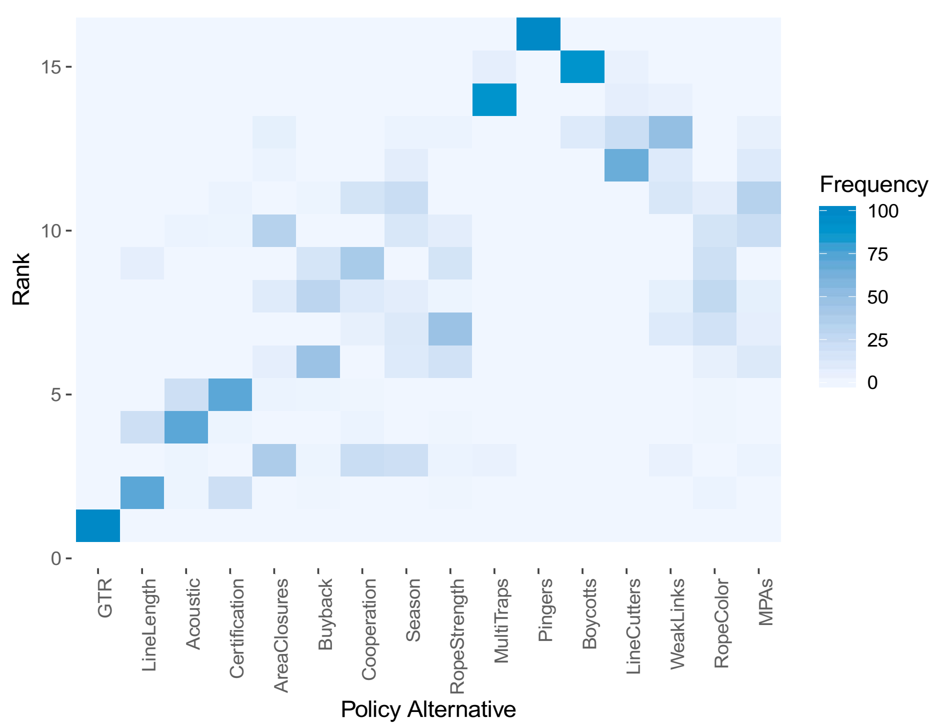

Fig. 4. The frequency, across all 100 weighting scenarios, with which each policy alternative attained a given rank. As in Fig. 3, ranks are given in order of most desirable (1) to least desirable (16). High frequencies indicate that policy alternatives had a given ranking largely independent of weighting scenario.

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. The approach used in this analysis can be applied to fisheries outside of the West Coast commercial Dungeness crab fishery hoping to mitigate negative large whale interactions in their areas.

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). 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, 2017). 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.

In scoring policy alternatives, we were faced with a scarcity of data, particularly surrounding the effectiveness of each alternative in reduce whale entanglements; our estimates are informed guesses, and different scoring values would lead to different preferred alternatives. Some alternatives, however, have obvious drawbacks such as creating 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 (3 kHz Whale Pinger). Pingers also displayed limited to no success in several studies involving whales and the most frequently employed frequencies (Pirotta et al., 2016; Harcourt et al., 2014; Dunlop and Dunlop, 2013). 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, 2017a). 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.

5. 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.

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Appendix A. Supplementary data

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