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Retrospective analysis of measures to reduce large whale entanglements in a lucrative commercial fishery

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ABSTRACT

Recovering marine animal populations and climate-driven shifts in their distributions are colliding with growing ocean use by humans. One such example is the bycatch of whales in commercial fishing, which poses a significant threat to the conservation and continued recovery of these protected animals and is a major barrier to sustainable fisheries. Long-lasting solutions to this problem need to be robust to variability in ecological dynamics while also addressing socio-cultural and economic concerns. We assessed the efficacy of gear reductions as an entanglement mitigation strategy during 2019 and 2020 in the highly valuable Dungeness crab fishery (Washington State, USA) in terms of changes in the entanglement risk to protected blue and humpback whales, and in terms of economic consequences for the fishery. Using a combination of fishery logbooks, landings data, and whale habitat models, we found that in the two seasons with mandatory crab pot reductions, entanglement risk was reduced by up to 20 % for blue whales, and 78 % for humpback whales, compared to seasons with no regulations. Spatio-temporal variability in the distribution of each whale species was a key factor in determining risk. Importantly, the conservation measure did not have a substantial negative effect on fleet-level fishery performance metrics, despite a reduction in fishing effort. Results indicated that a simple, fixed management strategy achieved the desired conservation goals in an economically sustainable way. Our findings underscore the value of carefully considering the dynamic nature of species' spatial distributions and key social and economic impacts that together determine conservation efficacy.

1. Introduction

Human-wildlife conflicts are increasingly prevalent across the globe (Nyhus, 2016; Guerra, 2019). Climate change and recovering animal populations are likely exacerbating these interactions that result in adverse outcomes for both people and wildlife (Marshall et al., 2016; Ingeman et al., 2019; Abrahms, 2021). Conflicts between marine animals and human uses of the ocean are especially notable because they can simultaneously threaten charismatic megafauna and high-value industries. High-profile examples include shipping traffic effects on the endangered North Atlantic right whales, and the increasing abundance of large sharks in popular tourist areas (Kraus et al., 2005; Pirotta et al., 2019; Chapman and McPhee, 2016; Adigun, 2015). Bycatch, defined here as "the unintended capture of non-target species during fishing operations," is another growing human-wildlife conflict that currently threatens many populations of marine animals, and remains a major global barrier to sustainable fisheries (Lewison et al., 2014; Sims and Queiroz, 2016; Molina and Cooke, 2012). Bycatch of marine mammals, such as large whales, is one of the most significant anthropogenic threats to the conservation and recovery of these long-lived and low fecundity

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animals (Avila et al., 2018; Oldach et al., 2022). Despite the clear need, ecologically effective and socially tenable management solutions to this issue are lacking.

Bycatch is a particularly difficult conservation issue because managers are often placed in the unenviable position of pitting human livelihoods against regulatory requirements to conserve species. Common solutions to mitigating marine mammal bycatch include changes in fishing gear and methodology, acoustic and visual deterrents, as well as spatio-temporal management strategies such as fishery time-area closures (Senko et al., 2014; Hamilton and Baker, 2019). However, the dynamic and complex interactions between ecological, social and economic drivers of bycatch risk can make it difficult for managers to navigate the associated trade-offs. For example, changing global climate is driving shifts in species distributions, in many places exacerbating human-wildlife conflicts (Poloczanska et al., 2013; Santora et al., 2020). Under this new climate reality, bycatch mitigation strategies that work in some places and times may be inadequate or even deleterious in other contexts. Therefore, the best way to determine whether fisheries bycatch management strategies are ecologically sustainable and cost effective, is to rigorously evaluate their efficacy over time and under changing environmental conditions (Bisack and Magnusson, 2016; McIntosh et al., 2018).

The Dungeness crab (*Metacarcinus magister*) fishery, one of the most valuable fisheries on the U.S. West Coast (Rasmuson, 2013), is currently ensnared in conflict with the conservation of protected whale species. Since 2014, there has been an approximately five-fold increase in confirmed large whale entanglements coastwide relative to historical averages (Saez et al., 2021; Fig. 1a). Two species of high conservation concern include the humpback whale (*Megaptera novaeangliae*) - one of the most frequently reported entangled species - and the endangered blue whale (*Balaenoptera musculus*), which had never been observed entangled until 2015 (Saez et al., 2021). Both species have been increasing in abundance on the West Coast (Calambokidis and Barlow, 2020) and the Dungeness crab fishery has been implicated in most entanglement cases where the gear was identifiable (Saez et al., 2021). Since the number of licensed vessels in each of the California, Oregon and Washington limited entry Dungeness crab fisheries is capped, increased fishing effort does not explain this rise in entanglements. Whale entanglement risk off the U.S. West Coast is driven by the spatio-temporal overlap between whale foraging habitat and the Dungeness fishery (Samhouri et al., 2021). Peak whale abundance partially overlaps in time with Dungeness crab fishing (November–July in California, December–September in Washington; Calambokidis et al., 2015) and corresponds to the timing of the majority of reported entanglements (Saez et al., 2021; Oldach et al., 2022). Entanglements in fixed gear fisheries represented 49 % of human-related injury and mortality cases for large whales on the U.S. West Coast between 2015 and 2019 (excluding ‘unidentified fishery interactions’; Carretta et al., 2021), with research indicating that entangled whales have a significantly lower resighting rate and are known to be alive for fewer years post-entanglement (Tackaberry et al., 2022).

In response to increases in entanglements associated with the commercial Dungeness crab fishery, the Washington Department of Fish and Wildlife (WDFW) recently introduced a simple, fixed management strategy to mitigate risk of large whale entanglements: a 33 % reduction in the maximum number of crab pots allowed per vessel between May 1st and September 15th (Washington Administrative Code 220-340-480). The choice of 33 % was driven by the need to maintain viable opportunities for vessels with a smaller maximum pot allocation (WDFW, pers. comm.). This new regulation is designed to be in place during peak whale abundance off the Washington coast, when entanglement risk is presumed to be at its highest. The recent implementation of this management measure provides an opportunity to assess its ecological, social, and economic impacts early on in the management response process, allowing for modification of the policy if necessary. In this study, we used WDFW Dungeness crab logbook data, port level landing records, and whale habitat models to assess the efficacy of the new summer gear reductions as a bycatch mitigation strategy by i) estimating the relative change in entanglement risk to protected blue and humpback whales in Washington waters between years with and without regulations, and ii) assessing the economic consequences of the regulations for the fishery (on an aggregate, fleet-level). We highlight the importance of considering annual variability in the distribution of both fishing effort and the bycatch species, and accounting for fishery interactions with multiple bycatch species with differing behaviors and distribution patterns.

2. Methods

We used the following information to assess the effectiveness and

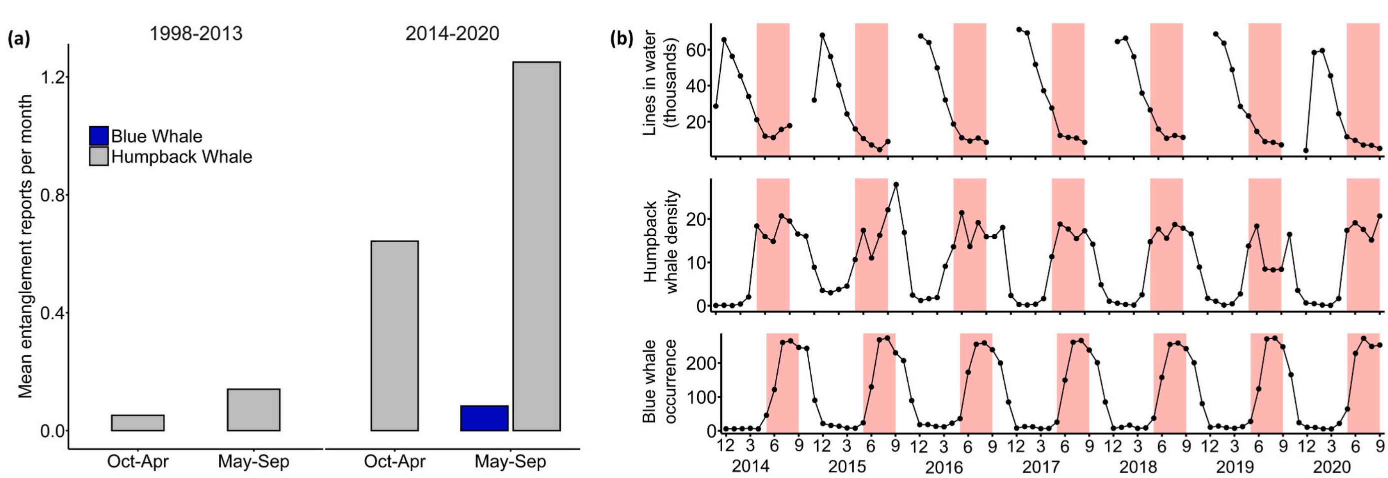

Fig. 1. a) Mean monthly confirmed entanglement reports for blue and humpback whales along the U.S. West Coast between October–April and May–September months across two time periods: 1998–2013 and 2014–2020. Entanglement rate is calculated as the cumulative total confirmed entanglements reported across each month and time period combination divided by the total number of months in the time period. Only confirmed entanglements in Dungeness crab gear, other trap/pot gear or unidentified gear are included (data from Saez et al., 2021). b) Top Panel: maximum number of lines (connecting pots to surface buoys) in the water by month (calculated as the sum of the maximum allowed pots by all unique vessels that were active, i.e., submitted a logbook in Washington in each month), Center Panel: sum of the predicted humpback whale densities, and Bottom Panel: sum of the predicted blue whale probability of occurrence values across all grid cells in the study area (see Fig. 2) by month. Colored background in the time series denotes the months of May–September when whale presence is highest. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sustainability of Washington's new entanglement regulations:

i) spatial estimates of changes in the density of vertical lines in the water, which is represented by estimates of Dungeness crab pot density (pots per km^2);

ii) spatial estimates of changes in whale presence and distribution over time, and;

iii) estimates of fishery impacts (spatial and non-spatial).

We focused our analyses on seven fishing seasons, which included five seasons before the new regulations (2014–2018), and two seasons with regulations (2019 and 2020). The Washington crabbing season typically opens on December 1st (with potential delays to protect the resource and/or human health), and closes on September 15th the following year (i.e., the 2014 crab season runs from December 2013 through September 2014). All analyses were performed in R (R Core Team, 2021).

2.1. Spatial estimates of fishing effort

Dungeness crab is fished using cylindrical or rectangular shellfish pots (or traps) with each pot connected to its own surface buoy with a weighted rope (Washington Administrative Code 220-340-435, 220-340-430). Crab pots are generally deployed at even intervals, forming 'string' lines of pots (Fig. 2), which can be made up of anywhere from just a few pots to more than a hundred. Pots can be set from near the surf zone up to depths of around 200 m, however the length of the rope connecting a pot and a surface buoy cannot be longer than what is necessary to compensate for tides, currents and weather (Washington Administrative Code 220-340-430). The most comprehensive source of information for spatial estimates of fishing effort (pot density) off the Washington coast are commercial fishery logbook records, which are required to be filled out and submitted by all permitted Dungeness crab fishing vessels (Washington Administrative Code 220-340-460). Raw logbook data provided by WDFW included the start and end locations of each 'string' of crab pots, the number of pots fished on each of these strings, and the date the pots were retrieved. We converted the start and end geocoordinates for each string into spatial line features. We used the reported pot count for each string to simulate individual pots, spaced evenly along each string line. Simulated pots that were reported in the Washington logbooks, but occurred in Oregon waters, south of the 46°15′N parallel, were excluded as fishing effort in Oregon waters is subject to Oregon licensing, pot limits and regulations, rather than those of Washington State. However, pots fished in Washington waters, but landed in Oregon ports were included, as they were subject to the Washington regulations.

We overlaid the simulated pots on a 5 km resolution grid used in previous whale entanglement studies (Feist et al., 2021; Samhouri et al., 2021) in order to estimate pot densities. We calculated pot density in each grid cell on a monthly time-step using each vessel's pot limit based

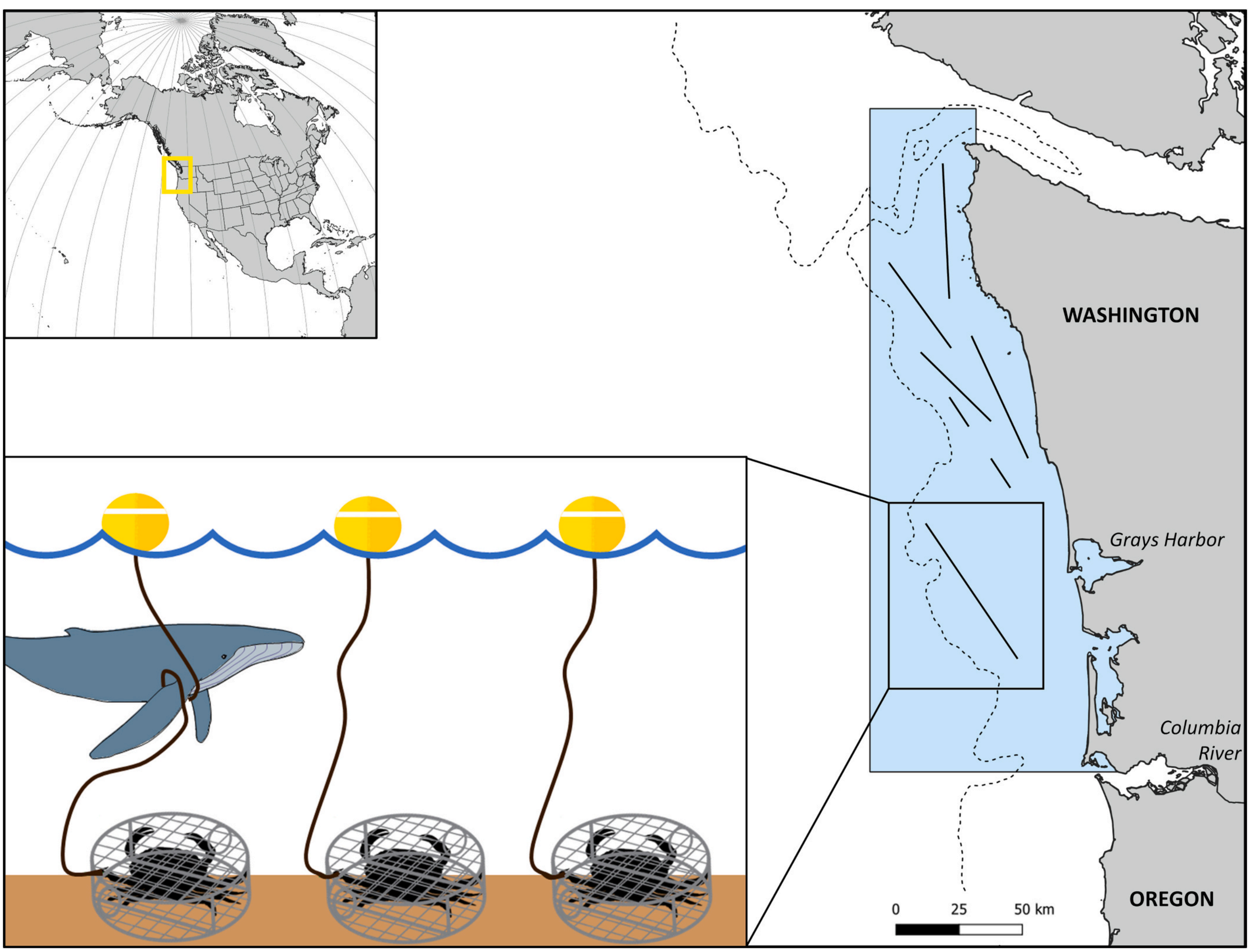

Fig. 2. Map of the U.S. West Coast indicating the location of the study area (in blue) off Washington. Dotted line denotes 200 m depth contour. Solid black lines on the map denote fictional Dungeness crab string lines (lines of crab pots), with insert (not to scale) showing a line of pots and the ropes connecting them to surface buoys. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

on their Washington state fishing license. There are two license categories in the coastal Washington Dungeness crab fishery that allow the holder to fish either a maximum of 300 or 500 pots (Washington Administrative Code 220-340-430). We assumed that each vessel submitting logbook records used the maximum number of pots allowed by their license throughout each monthly interval (cf. Oregon Department of Fish and Wildlife, 2021; Free et al., in prep.), and therefore weighted the simulated pots accordingly. For example, if a vessel in the 500-pot license category reported a total of 1000 pots in a month in their logbook, we knew that at any given time there could only have been 500 pots out in the water. To avoid overestimating the number of pots in the water, we down-weighted the pots as 500/1000 = 0.5 (i.e., each reported pot was worth half a pot). This assumption likely overestimates fishing effort in instances when vessel operators do not have their full allotted number of pots in the water. However, anecdotal information suggests that vessel operators aim to fish the maximum number of pots possible throughout the season (WDFW, pers. comm.). In months when the 33 % gear reduction was in place, the maximum allowed 200 and 330 pots were assumed fished by 300 and 500 license category vessels, respectively. Pot density was then calculated as the total number of pots per unit area in each grid cell.

To examine the temporal patterns in fishing effort, we estimated the maximum number of lines in the water in each month as the sum of the maximum pot limits (adjusted for summer regulations in 2019 and 2020) of all unique vessels that submitted logbooks in that month. Additionally, we used the Harrell-Davis quantile estimator of the 'WRS2' package (Mair and Wilcox, 2020) to investigate changes in pot densities between pre- and post-regulation seasons. Since the gear reduction rule in 2019 was implemented only on July 1st by emergency rule (due to delays in implementing the permanent rule), all comparisons between pre-regulation seasons and 2019 were done across July–September, while all comparisons between pre-regulation seasons and 2020 were done across May–September.

A fully detailed description of the above methods for processing logbook data can be found in Supplementary Materials 1.

2.2. Spatial estimates of whale presence and distribution

Predicted spatial estimates of whale presence and distribution were derived from habitat models that estimate the density of humpback whales (Forney et al., 2020; Forney et al., in prep.) and the probability of occurrence of blue whales (Abrahms et al., 2019). Both whale models have previously been validated against independent datasets, including localized aerial surveys, shipboard marine mammal surveys and standardized whale-watching data (Abrahms et al., 2019; Forney et al., 2020; Forney et al., in prep.). Following methods in Samhouri et al., 2021, we overlaid the predictions from the blue and humpback whale habitat models onto the 5 km grid used to estimate pot densities from logbook data. Further details about the whale models can be found in Supplementary Materials 2 and 3.

Since both whale model outputs extend beyond the likely Washington Dungeness crab fishing grounds, we focused our analyses of the whale models to a smaller study area (Fig. 2). This study area is limited in the east by the coastline, in the south by the Washington and Oregon border, and in the north and the west by the maximum extent where Dungeness crab fishery has occurred based on the logbook data. To showcase the seasonally variable presence of blue and humpback whales in Washington waters, we summed the modeled whale values across all grid cells within the study area on a monthly time step. We used the Harrell-Davis quantile estimator to examine changes in the modeled whale densities and occurrence within the study area between pre- and post-regulation seasons.

2.3. Estimating the impact of new regulations on entanglement risk

To quantify how the summer gear reduction affected the risk of entanglement for protected blue and humpback whales, we constructed a simple overlap risk metric based on the overlap of fishing effort and the whales. Following Samhouri et al. (2021), we estimated risk $R_{S,i,y,m}$ to each whale species S based on their co-occurrence with the Washington Dungeness crab fishery effort in each 5 km grid cell i in each crab fishing season (or year) y and month m as the product of pot density $F_{i,y,m}$ and either the predicted probability of occurrence (blue whales, $W_{b,i,y,m}$) or density (humpback whales, $W_{h,i,y,m}$), such that

$$R_{S,i,y,m} = F_{i,y,m} \text{ x } W_{S,i,y,m} \tag{1}$$

This approach assumes that risk increases linearly as whale density/occurrence and pot densities increase, which is a commonly utilized assumption in various risk assessment studies (e.g., Redfern et al., 2020; Samhouri et al., 2021; Womersley et al., 2022). Here, we have also made this assumption in lieu of any established, empirical relationship between whale density, fishing effort, and entanglement risk. Each of $W_{S,i,y,m}$ and $F_{i,y,m}$ were normalized to the scale of 0–1 by subtracting the minimum value and dividing by the range of values across all months and grid cells within the study area. As the fishery footprint moves in space and changes in shape and size between seasons, to keep the risk estimates comparable between seasons, we summed all risk values ($R_{S,i,y,m}$) across all grid cells within the study area to gain one estimate of risk per month for each whale species. The risk metric is not a measure of absolute risk of entanglement, but rather allows us to measure the relative change in risk between pre- and post-regulation seasons. The percent change in risk was calculated using the mean across all summer months of the pre-regulation seasons, and the mean of the summer months in each of the post-regulation seasons. We used Generalized Linear Models (GLMs), with a Gaussian error distribution and identity link function, to statistically compare pre- and post-regulation seasons. In the GLMs risk was the response variable, and the two predictor variables were whether a season was a pre- or a post-regulation season, and month.

To parse the relative influence of the amount and distribution of (i) fishing effort, and (ii) whale presence on the risk metric, we also tested two hypothetical scenarios (Table 1). In the 'static whale distribution' scenario, we held whale distribution static, as either the 2019 or 2020 distribution, and used that together with variable fishing effort (as estimated from logbooks for each year) to recalculate risk. This hypothetical scenario allowed for an investigation of the marginal effect of fishing effort change (gear reduction) on entanglement risk, while holding whale distribution constant. Conversely, in the 'static fishing effort' scenario, we held fishing effort static, as estimated for 2019 or 2020 with the 33 % gear reduction, and used that together with dynamic whale distributions (as predicted by the whale models for each year) to recalculate risk. We used this hypothetical scenario to investigate the marginal effect of changing whale distributions on entanglement risk, while holding fishing effort constant.

To investigate how inter-annual variability in whale distribution, specifically in 'whale hotspots', affected risk, we constructed a whale habitat risk metric. This complimentary risk metric allowed us to examine the gear reduction strategy from a conservation triage perspective. While entanglements are rare events, we assume that they are slightly less rare in areas with more whales, and the summer gear reduction rule could have inadvertently caused fishing effort to shift into areas with higher densities or likelihood of whale presence. Because of differences in the structure of the two whale models, we defined most likely whale habitat separately for the two species: for blue whales, we chose all grid cells with a predicted probability of occurrence greater than the mean across all summer months; and for humpback whales, we chose all grid cells in the top 25th percentile of predicted density across all summer months (see Supplementary Material 2 and 3). We conducted sensitivity analyses around the cutoff values used to define most likely whale habitats (see Supplementary Material 2 and 3). Risk was calculated essentially in the same manner as above, as a summed product of the whale and pot density data, but we only calculated one risk value per

Table 1
Table showcasing what fishing data and what whale data were used to calculate the risk metric in different scenarios. In the hypothetical scenarios, either fishing effort data or whale data were held constant to gauge the relative impact that the variation in fishing effort or in whale data had on the risk metric. Comparisons between pre-regulation seasons (2014–2018) and 2019 are across July–September, comparisons between pre-regulation seasons and 2020 are across May–September. HW = humpback whales, BW = blue whales. Bolded values indicate cases where the 'pre/post-regulation' variable was a statistically significant predictor of risk.

Scenario	Scenario interpretation	Fishing data used	Whale data used	Results (change in risk from pre-regulations)
Simple overlap risk metric	How did risk change from pre-regulation seasons to 2019 and 2020?	Amount and distribution of fishing effort (pot densities) estimated from logbooks for each year	Distribution and density/ probability of occurrence of whales predicted by whale models for each year	HW: 2019: **−78 %** 2020: **−51 %** BW: 2019: −12 % 2020: −20 %
Static fishing effort	How would risk have changed from pre-regulation seasons to 2019 and 2020, if all the pre-regulation seasons had had the same distribution and density of fishing effort as 2019 and 2020?	Amount and distribution of fishing effort (pot densities) held constant as estimated from logbooks for 2019 and 2020	Distribution and density/ probability of occurrence of whales predicted by whale models for each year	HW: 2019: **−70 %*** 2020: −10 % BW: 2019: **+11 %** 2020: **+24 %**
Static whale distribution	How would risk have changed from pre-regulation seasons to 2019 and 2020, if all the pre-regulation seasons had had the same distribution and density of whales as 2019 and 2020?	Amount and distribution of fishing effort (pot densities) estimated from logbooks for each year	Distribution and density/ probability of occurrence of whales held constant as predicted by whale models for 2019 and 2020	HW: 2019: −23 % 2020: **−45 %** BW: 2019: −21 % 2020: **−34 %**

season rather than per month. We also measured the amount of overlap between the most likely whale habitats and the fishery in each summer season as the number of overlapping grid cells.

2.4. Consequences of the new regulations for the Washington Dungeness crab fishery

We estimated changes in the spatial distribution of fishing effort in the Washington Dungeness crab fishery by mapping the pooled fishery footprint across winter (December–April) vs. summer (May–September) months across all years (i.e., grid cells that had fishing effort in any of the winter or summer months in any year). In order to make comparisons between pre- and post-regulation seasons, we also measured the size of summer fishery footprints (in km^2) as the summed area of all grid cells that had fishing effort in a given season.

We quantified the economic impact that the summer gear reduction rule had on the Washington Dungeness crab fishery by joining logbook records to the Pacific Fisheries Information Network (PacFin) database of landing receipts (or fish tickets; Washington Administrative Code 220-352-020) based on each individual vessel's unique identification number, and the date of landing. The PacFin landing receipts describe the catch, revenue, and other characteristics associated with vessels landing crab on the U.S. West Coast. We used these logbook-matched fish tickets to calculate total landings (dollars and pounds) and catch per unit effort for all pre- and post-regulation summer seasons, as well as total number of unique vessels and mean monthly revenue per vessel for both the 300 and 500 pot license categories. All dollar values were adjusted to 2014 dollars[1] in order to facilitate comparison. Percent change in the above metrics was calculated from the median of the pre-regulation seasons, and we used GLMs to statistically compare pre- and post-regulation seasons.

3. Results

3.1. General patterns in the Washington Dungeness crab fishery

The Washington Dungeness crab fishery operates as a derby, with most effort (including the highest number of lines in the water) occurring in the first few months of the season, and the least occurring between May and September (Fig. 1b). Based on logbook data, the fishery effort contracted towards the coast each year during the summer period, occupying a smaller area in shallower waters compared to the winter period (Supplementary Fig. S4.1). In some seasons, this contraction resulted in a concentration of effort, and therefore an increase in pot densities at the end of the season (Supplementary Fig. S4.2). The size of the summer fishery footprint (km^2) varied from year-to-year (from <1000 km^2 to >4000 km^2), but was similar between seasons with and without summer pot regulations (Supplementary Fig. S4.1). Pot densities were highest near the coast (within ~10 km off the coast) especially between Grays Harbor and Columbia River, with lower pot densities occurring in the fringes of the fishery footprint both in the winter and summer portions of the fishing season (maps of data not shown due to confidentiality restrictions).

3.2. Simple overlap risk metric: pre-regulation vs. post-regulation seasons

There was a 78 % and a 51 % reduction in the mean risk to humpback whales from pre-regulation seasons to 2019 and to 2020, respectively (Table 1, Fig. 3a). The 'pre/post-regulation' variable was a statistically significant predictor of risk in both comparisons ($p < 0.05$, Supplementary Material 5). For blue whales, there was a 12 % and a 20 % reduction in the mean risk from pre-regulation seasons to 2019 and to 2020, respectively (Table 1, Fig. 3b), however the 'pre/post-regulation' variable was not a statistically significant predictor of risk in either comparison ($p > 0.05$, Supplementary Material 5). (Similar qualitative conclusions (significant reduction in risk to humpback whales, non-significant reduction to blue whales) were also drawn in a complimentary analysis, whereby we only looked at July–September months across all the pre- and post-regulation years; unpublished results).

3.3. Influence of whale distributions on the risk metric

To investigate the influence of whale distributions on the simple overlap risk metric, we examined changes in the modeled blue and humpback whale distributions within the study area between pre- and post-regulation seasons. Modeled humpback whale densities were significantly lower in all quartiles in July–September of 2019 than in the pre-regulation seasons (Fig. 4a; $p = 0$, Supplementary Material 6). For

[1] https://www.minneapolisfed.org/about-us/monetary-policy/inflation-calculator/consumer-price-index-1913-

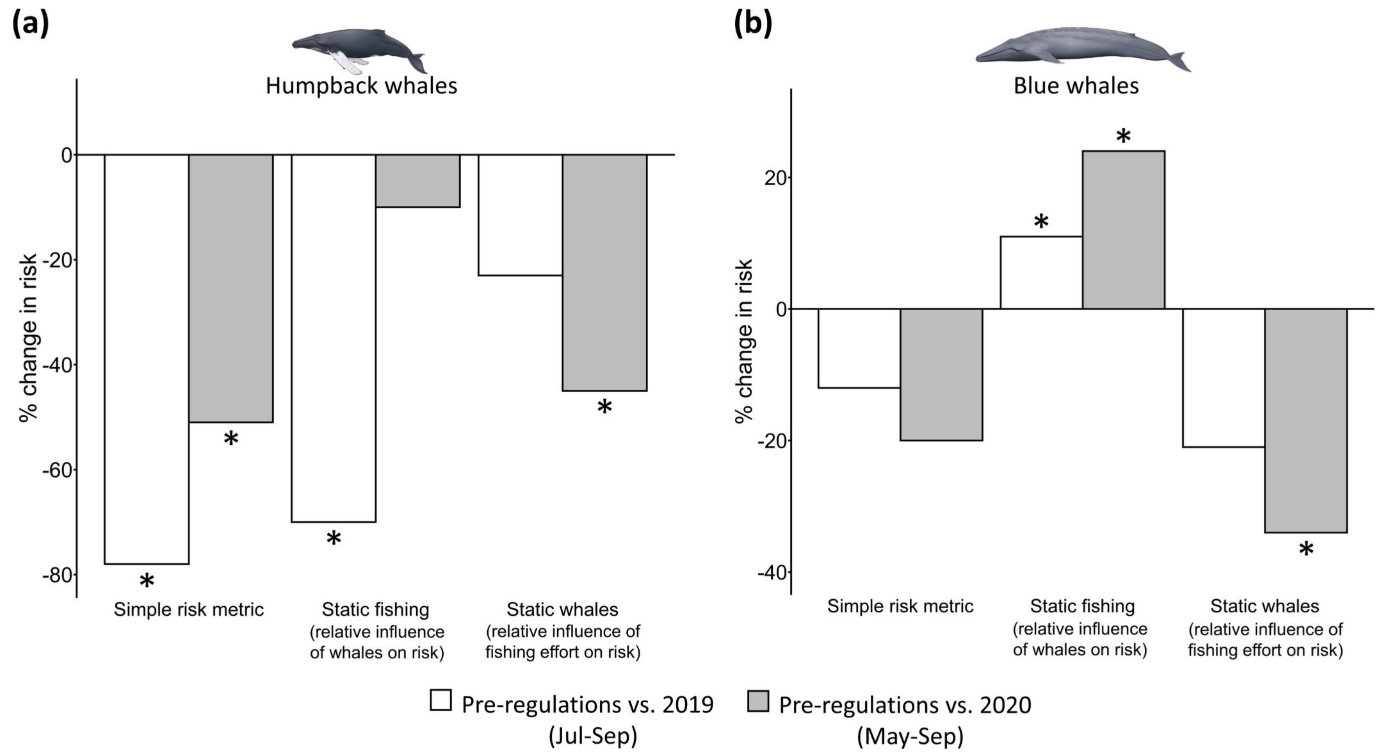

Fig. 3. Percent change in risk to a) humpback whales and b) blue whales between pre-regulation (2014–2018) and post-regulation (2019 and 2020) seasons in different risk estimation scenarios. Comparisons between pre-regulation seasons and 2019 are across July–September, comparisons between pre-regulation seasons and 2020 are across May–September. Stars indicate comparisons where the 'pre/post-regulation' variable was a statistically significant predictor of risk. For descriptions and further results of the different scenarios see Table 1, and Supplementary Materials 5, 7, 9. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

all other comparisons, there were statistically significant increases in modeled humpback whale densities and blue whale probability of occurrence from pre-regulation seasons to post-regulation seasons in the first three quartiles, but not in the fourth quartile (Fig. 4b-d; $p = 0$, Supplementary Material 6).

We further examined the relative influence of inter-annual variability in the whale data on the risk metric through a hypothetical 'static fishing effort' scenario (Table 1, Fig. 3). In this scenario (where fishing effort was held constant, but whale data were varied), there was a 70 % reduction in the mean risk to humpback whales from pre-regulation seasons to 2019 ($p < 0.001$, Supplementary Material 7), and a 10 % reduction from pre-regulation seasons to 2020 ($p = 0.39$, Supplementary Material 7). This scenario also revealed an 11 % increase in the mean risk to blue whales from pre-regulation seasons to 2019 ($p = 0.04$, Supplementary Material 7), and a 24 % increase from pre-regulation seasons to 2020 ($p = 0.01$, Supplementary Material 7).

3.4. *Influence of fishing effort & summer regulations on the risk metric*

To investigate the influence of fishing effort and the gear reduction rule on the simple overlap risk metric, we examined changes in pot densities between pre- and post-regulation seasons. Pot densities were significantly lower in all quartiles in July–September of 2019 than the pre-regulation seasons and in all quartiles in May–September of 2020 than the pre-regulation seasons (Fig. 4e-f, $p < 0.05$, Supplementary Material 8). There was a 48 % and a 47 % reduction in the median pot density from pre-regulation seasons to 2019 and 2020, respectively.

We further examined the relative influence of fishing effort and the gear reduction rule on the risk metric through a hypothetical 'static whale distribution' scenario (Table 1, Fig. 3). In this scenario (where whale data was held constant, but fishing effort was varied), there was a 23 % reduction in the mean risk to humpback whales from pre-regulation seasons to 2019 ($p = 0.37$, Supplementary Material 9), and a 45 % reduction from pre-regulation seasons to 2020 ($p = 0.001$, Supplementary Material 9). There was a 21 % reduction in the mean risk to blue whales from pre-regulation seasons to 2019 ($p = 0.26$, Supplementary Material 9), and a 34 % reduction from pre-regulation seasons to 2020 ($p = 0.01$, Supplementary Material 9).

3.5. *Whale habitat risk metric*

To investigate how inter-annual variability in whale distribution (specifically 'whale hotspots') affected risk, we constructed a whale habitat risk metric. There was a large (99.6 %) reduction in risk in the most likely humpback whale habitat from the pre-regulations average to 2019 (Fig. 5a; Supplementary Table S3.1). This was accompanied by a similarly large reduction (93 %) in the overlap between most likely humpback whale habitat and the Washington Dungeness crab fishery. There was a 67 % reduction in risk from the pre-regulations average to 2020, but only a 33 % reduction in the overlap between most likely humpback whale habitat and the fishery (Fig. 5a; Supplementary Table S3.1). We conducted sensitivity analysis by testing multiple values as the cutoff points for our definition of most likely humpback whale habitat. The sensitivity analysis produced similar results for both comparisons regardless of the cutoff value used (Supplementary Fig. S3.2). The 'pre/post-regulation' variable was a significant predictor of risk, as well as of the amount of overlap between most likely humpback whale habitat and the fishery for both comparisons ($p < 0.05$, Supplementary Table S3.2). The cutoff value used to define the most likely humpback whale habitat was generally not a significant predictor of risk or the amount of overlap, with the only significant difference occurring between the lowest and highest threshold values (i.e., the least and most conservative definitions of most likely humpback whale habitat; Supplementary Table S3.2).

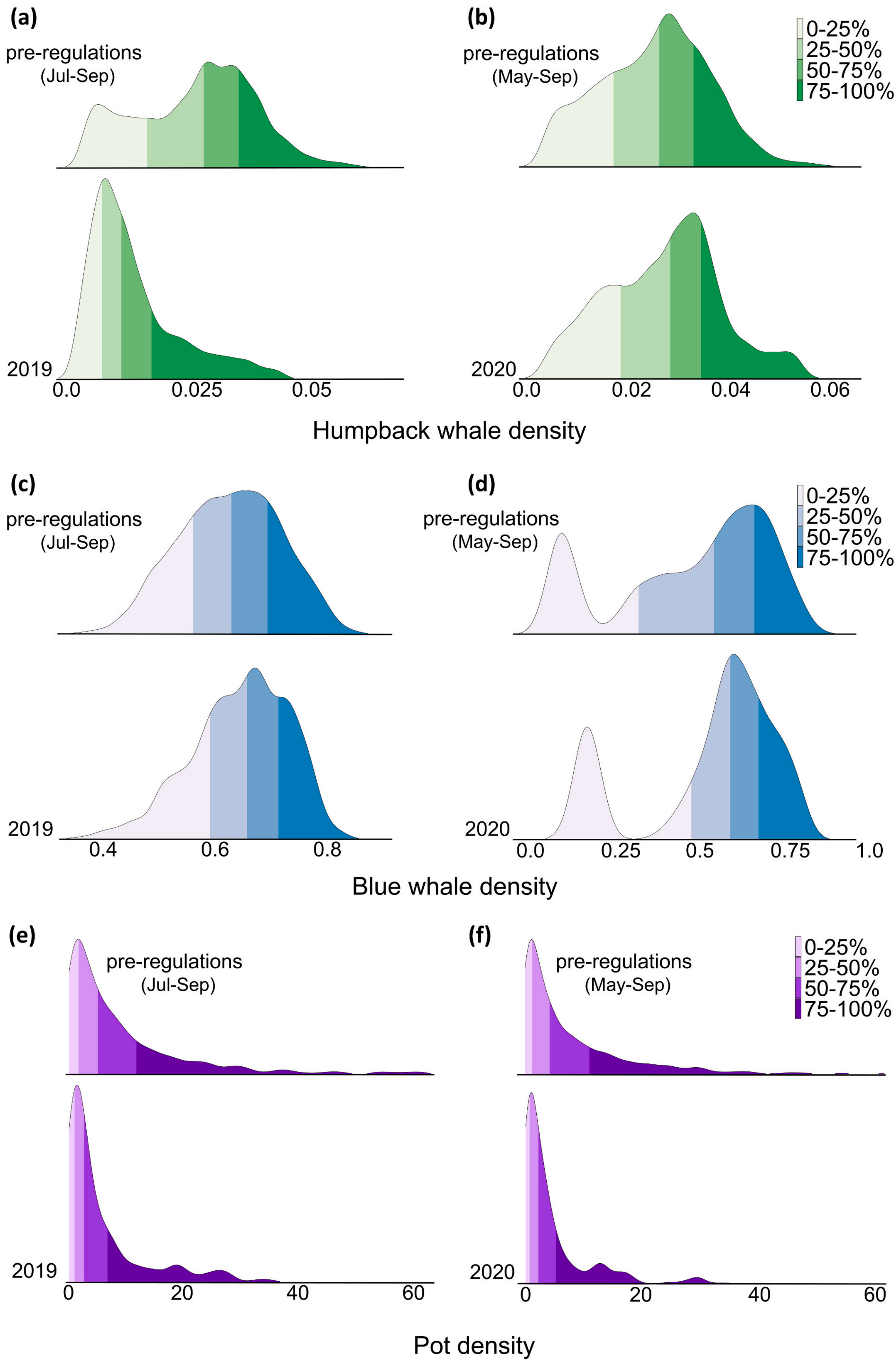

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Fig. 4. Density plots of modeled humpback whale densities in the study area in a) July–September of pre-regulation seasons (2014–2018) vs. 2019, and b) May–September of pre-regulation seasons vs. 2020; density plots of modeled blue whale probability of occurrences in the study area in c) July–September of pre-regulation seasons vs. 2019, and d) May–September of pre-regulation seasons vs. 2020; and density plots of pot densities (pots/km^2) in e) July–September of pre-regulation seasons vs. 2019, and f) May–September of pre-regulation seasons vs. 2020. The position of quartiles calculated from the data are shown with different colors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For blue whales, there was a large increase in the overlap between most likely blue whale habitat and the fishery (72 % and 120 % increase from pre-regulations average to 2019 and 2020, respectively; Fig. 5b; Supplementary Table S2.3). This increase in overlap resulted in a 39 % and a 44 % increase in risk from the pre-regulations average to 2019 and 2020, respectively. The sensitivity analysis produced similar results for both comparisons regardless of the cutoff value used to define most likely blue whale habitat (Supplementary Fig. S2.3). The 'pre/post-regulation' variable was not a significant predictor of risk ($p > 0.05$), and it was a significant predictor of the amount of overlap between most likely blue whale habitat and the fishery only in the 2019 comparison ($p = 0.04$; $p = 0.09$ in the 2020 comparison, Supplementary Table S2.4). The cutoff value used to define the most likely blue whale habitat was a significant predictor of risk and the amount of overlap between most likely blue whale habitat and the fishery in some comparisons (Supplementary Table S2.4).

3.6. Consequences of summer regulations for the Washington Dungeness crab fishery

The total summer season revenue, landings and CPUE metrics were variable across years. There was a 16 % increase in the total summer revenue, and an 18 % increase in the total landings from the pre-regulation seasons' median to 2019 (Fig. 6a-b). There was a 6 % decrease in the total summer revenue, and a 0 % change in the total landings from the pre-regulation seasons' median to 2020 (Fig. 6a-b). However, the 'pre/post-regulation' variable was not a significant predictor of either revenue or landings in any of the comparisons ($p > 0.05$, Supplementary Table S10.1). There was a 22 % decrease in the mean dollars per pot and a 13 % decrease in the mean pounds of crab per pot between the pre-regulation seasons' median and 2019 (Fig. 6c-d). There was an 18 % increase in the mean dollars per pot and a 25 % increase in the mean pounds of crab per pot between the pre-regulation seasons' median and 2020 (Fig. 6c-d). However, the 'pre/post-regulation' variable was not a significant predictor of either CPUE metric in any of the comparisons ($p > 0.05$, Supplementary Table S10.2). The level of participation in the fishery was variable across months and seasons, however it was similar between years with and without summer gear regulations (Fig. 7a). For those vessels that were participating in the fishery (i.e., submitted logbooks), the mean monthly revenue per vessel did not differ significantly between pre- and post-regulation seasons (Fig. 7b, Supplementary Table S10.3).

4. Discussion

The incidental catch of non-target species in fisheries, exemplified by whale entanglements, can threaten bycatch species population viability, as well as the long-term sustainability of the associated fishery. Bycatch problems are likely to increase as climate-driven shifts in the distributions of historically-depleted but now recovering species collide with the changing and increasing opportunities for human ocean users (Ingeman et al., 2019; Carretta et al., 2020). Long-lasting solutions to this problem must be robust to temporal variability in ecological dynamics (Lewison et al., 2015; Pons et al., 2022) while also addressing socio-cultural and economic concerns. Here, based on this assessment of a recently-implemented management strategy, we found that gear reductions in the Washington Dungeness crab fishery during the period of greatest whale presence decreased the risk of entanglements for blue and humpback whales with no detectable economic consequences for the fishery.

Although many fisheries interact with multiple bycatch species, studies often tend to focus on reducing bycatch for one species at a time (Brillant and Trippel, 2010; Ortiz et al., 2016; Virgili et al., 2018; Savoca et al., 2020), even though mitigation strategies may not necessarily have equivalent ecological consequences for all species (Wakefield et al., 2017; Hamilton and Baker, 2019). In our study, we found important heterogeneous impacts of summer gear reduction in the crab fishery on humpback and blue whales. For humpback whales, in the two seasons with entanglement risk reduction measures, there was a large and significant reduction in entanglement risk (Fig. 3a) for two different reasons. In 2020, reduced risk to humpback whales resulted from reduced crab fishing effort (gear reduction; Figs. 3a, 4b), whereas in 2019 reduced entanglement risk was driven by low modeled humpback whale densities (Fig. 4a). The predicted lower densities of humpback whales in 2019 were likely due to the occurrence of a marine heatwave off Washington in that year (Amaya et al., 2020; Weber et al., 2021). Therefore, our findings highlight how environmentally-driven variability in species' distributions can have large impacts on risk assessment, and how overlooking such variability could lead to incorrect attribution of causality in relation to new management actions. It also highlights the potential for application of "dynamic ocean management" strategies, intended to adjust rapidly as environmental, biological, or socioeconomic conditions change (Lewison et al., 2015; Hazen et al., 2018; Pons et al., 2022). In this case, it could be that different fisheries management actions could have been applied with equivalent success in 2019 and 2020 based on evolving ecosystem conditions, rather than using a fixed management schedule decided upon prior to the start of the fishing season.

We found that gear reduction resulted in a smaller (statistically non-significant) reduction in risk to blue whales compared to humpback whales (Fig. 3). This effect was not due to lower modeled probability of blue whale occurrence in 2019 and 2020 compared to pre-regulation seasons. Rather, we observed a reduction in risk for blue whales despite an increasing occurrence and overlap (Figs. 4c-d, 5b), implying that the gear reduction management strategy reduced entanglement risk to blue whales. In this case, protection measures that were highly effective for one species (humpback whales) seemed to serve as an umbrella for another (blue whales), but multispecies management may not always follow this pattern (Simberloff, 1998; Mace et al., 2007; Redfern et al., 2020). It remains unclear whether gear reduction will work equally well for all species reported as entangled in Dungeness crab fishing gear, such as killer whales (*Orcinus orca*) and gray whales (*Eschrichtius robustus*; Saez et al., 2021; NOAA Fisheries, 2022), or in other locations. Additionally, we acknowledge that a better understanding of the exact relationship between increasing bycatch species presence, fishery effort and risk is still needed to identify any potential thresholds (Supplementary Fig. S5.1).

In addition to this complex array of ecological considerations, bycatch mitigation measures can also result in economic losses (Smith et al., 2020; Seary et al., 2022). However, we found that the new gear reduction regulation did not have a statistically significant effect on fishery performance metrics, including the total amount of crab landed, total fishery revenue, or CPUE metrics (Figs. 6, 7; Supplementary Materials 4, 10). Similar total revenue and landings as in pre-regulation seasons were likely a result of high fishery participation levels in 2019 (Fig. 7a, Supplementary Fig. S4.3), despite slightly, but not significantly, lower CPUE metrics (Fig. 6c-d). We cannot eliminate the possibility that high CPUE levels in 2020 (Fig. 6c-d) were due to, for example, high crab

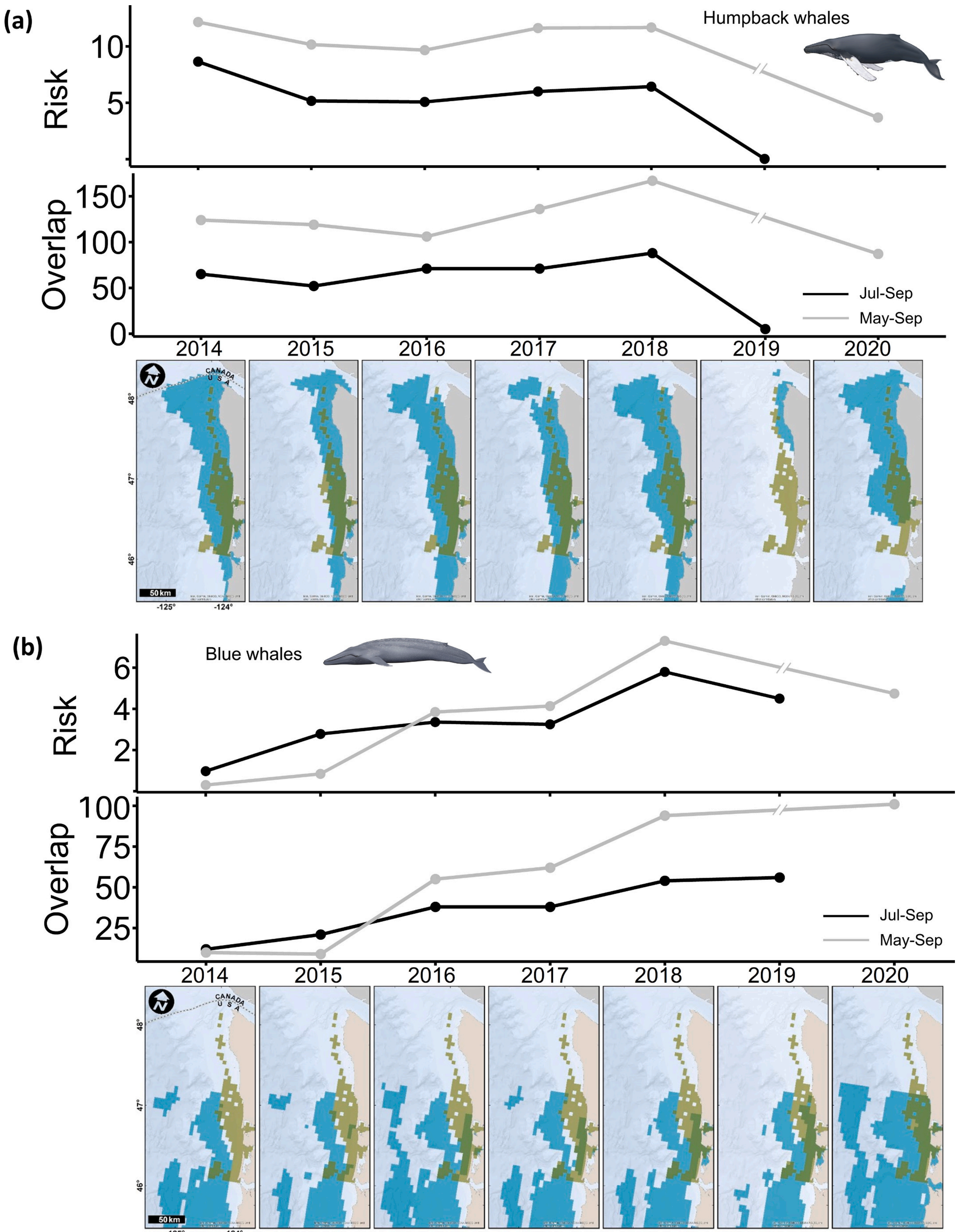

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Fig. 5. a) Risk to humpback whales in the most likely humpback whale habitat (top panel) and the overlap (number of grid cells) between Washington Dungeness crab fishery and the most likely humpback whale habitat (center panel) in each season. Bottom panel: maps of most likely humpback whale habitat in May–September (in blue) when using 75th percentile density value (central value of the sensitivity testing) as the cutoff for defining most likely humpback whale habitat. b) Risk to blue whales in the most likely blue whale habitat (top panel) and the overlap between Washington Dungeness crab fishery and the most likely blue whale habitat (center panel) in each season. Bottom panel: maps of most likely blue whale habitat in May–September (in blue) when using 0.469 probability of occurrence value (central value of the sensitivity testing) as the cutoff value for defining most likely blue whale habitat (note that the northern extent of the blue whale model predictions are limited to the ROMS extent, see Supplementary Materials 2 for details). Details on the definition of most likely whale habitat is provided in Methods (Section 2.3) and in Supplementary Materials 2 and 3. Green area in all maps shows pooled non-confidential fishery footprint in May–September across all 2014–2020 seasons (due to confidentiality restrictions grid cells containing data from two or fewer fishing vessels across the pooled time period are not displayed). Actual fishery footprints of each season were used in the analyses. Only May–September maps are shown, however they are visually similar to the July–September period. In the time series plots, July–September comparisons are for pre-regulation seasons (2014–2018) vs. 2019, May–September comparisons are for pre-regulation seasons vs. 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

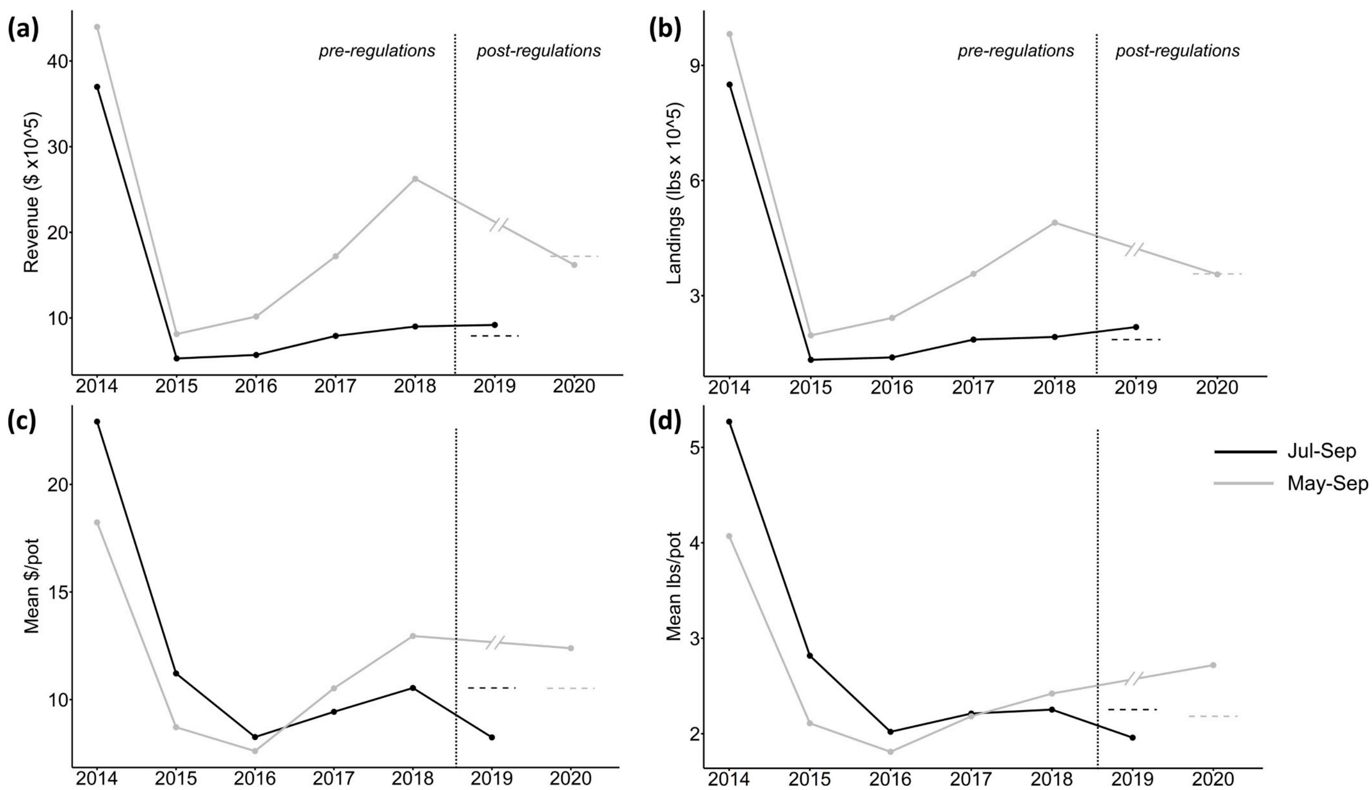

Fig. 6. a) Total revenue (dollars), b) total landings (pounds of crab landed), c) mean dollars per pot, and d) mean pounds of crab per pot based on landing receipts matched to logbook effort within Washington waters. Vertical dotted line separates pre- and post-regulation seasons. Black lines denote July–September months (comparing pre-regulation seasons to 2019), and gray lines denote May–September months (comparing pre-regulation seasons to 2020). Horizontal dashed lines in plots represent pre-regulation median values. The 2014 summer season had exceptionally high revenue and landings prior to the Washington Department of Fish and Wildlife (WDFW) introducing a weekly landing limit (see Supplementary Material 10).

abundance, because there are no data yet available to evaluate this possibility (Richerson et al., 2020). Alternatively, CPUE levels may have been higher because somewhat fewer vessels participated in the fishery in 2020 compared to pre-regulation seasons (Fig. 7a, Supplementary Fig. S4.3), possibly allowing each individual vessel to catch more crab. In addition to fishing fleet and crab population size, the fishery performance metrics will also be influenced by where the crabs are distributed in relation to the fishery effort, and the market price for crab. Overall, our analyses from the first two years following implementation of whale bycatch mitigation measures in the Washington crab fishery indicate movement in the direction of desired ecological and economic outcomes.

Given we observed interannual variability in underlying drivers of whale risk and in crab fishery revenue, and given other species with different distribution patterns and behaviors are also incidentally caught in this fishery, it remains unclear how robust the current fixed management strategy used in Washington will be over long term. Therefore, there is value in comparing dynamic and fixed management solutions via an ecosystem management strategy evaluation (MSE; Punt et al., 2016; Kaplan et al., 2021). An ecosystem MSE would help identify management approaches tailored to obtain the most cost-effective solution for the greatest number of bycatch species. An ecosystem MSE could also assess the relative value of various sources of information (e.g., whale sightings data, entanglement reports, vessel fishing locations, fisher knowledge/individual behavior) that could be used to monitor and evaluate entanglement risk and fishery impacts. Studies on the value of information are increasingly used to provide proactive recommendations on cost-effective strategies for addressing resource management issues under uncertainty (e.g., Essington et al., 2018; Davis et al., 2019; Stier et al., 2022), and are a key element of adaptive management embodied in integrated ecosystem assessment approaches (Levin et al., 2009).

Applications of ecosystem MSEs are relatively uncommon in a conservation context, though they could provide integrative evaluations of ecological and social impacts of the new regulations, such as shifts in fishing effort, reduced catch of target species, and economic impacts to

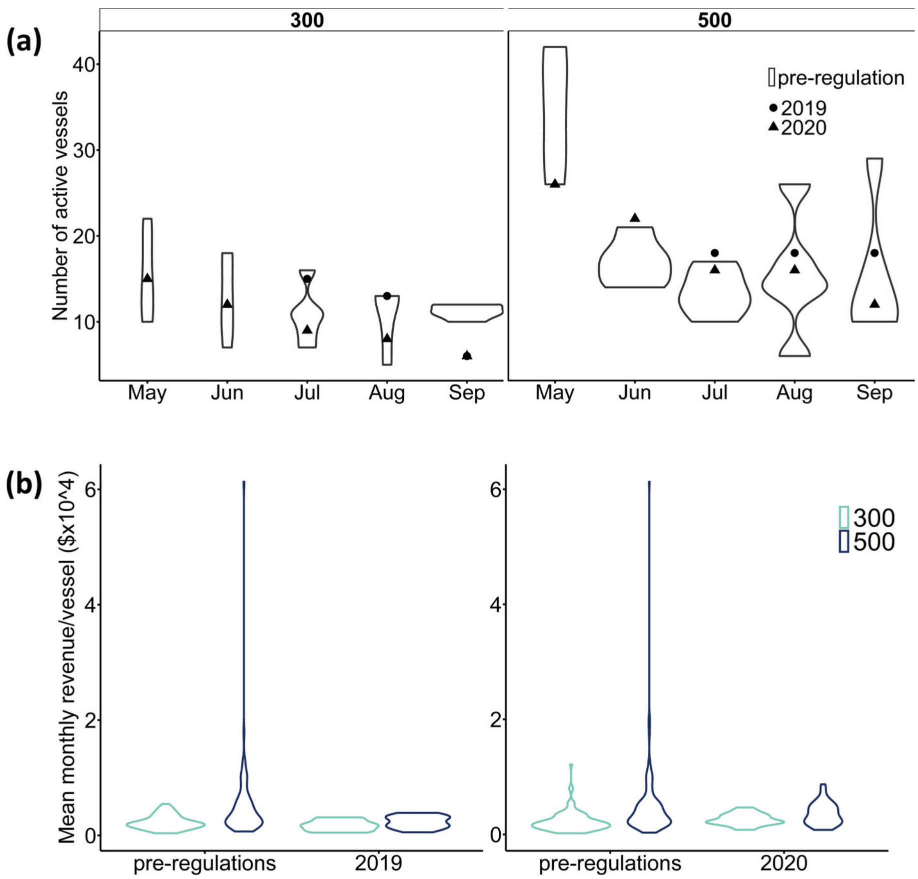

Fig. 7. a) Number of active vessels (unique vessels operating in Washington waters that submitted logbooks) by license category ('300' or '500', indicating the maximum allowed number of pots by a vessel) in pre-regulation seasons (2014–2018) vs. 2019 and 2020. Data for 2019 is not shown for May and June as regulations only came into effect in July of 2019. b) Mean monthly revenue (dollars) by vessel and by license category in pre-regulation seasons vs. 2019 and 2020. Comparisons between pre-regulation seasons and 2019 are across July–September, comparisons between pre-regulation seasons and 2020 are across May–September. The highest mean revenue per vessel values were driven by the 2014 season, with exceptionally high catches and revenue (see Supplementary Material 10).

fishing fleets (O'Keefe et al., 2014; Bisack and Magnusson, 2016). Similar to fisheries responding to climate shocks, there can be unanticipated results of bycatch mitigation strategies (i.e., 'policy shocks'), such as shifts in fishery effort and even spillover to other fisheries (Fisher et al., 2021; Cole et al., 2021; Papaioannou et al., 2021). While we did not explore these possibilities in the current study, it is worth considering the ripple effects of management strategies in one fishery towards other fisheries. For example, imposing certain management actions might lower the entanglement risk by the Dungeness crab fishery, while simultaneously increasing the risk by other fisheries due to spillover of effort. Furthermore, bycatch mitigation strategies may have inequitable impacts on different elements of a fishery, given that, for example, in the California Dungeness crab fishery smaller vessels have generally been found to experience more adverse effects from changes to scheduled fishing regulations (Jardine et al., 2020; Fisher et al., 2021). Therefore, actions such as gear reductions could have larger economic impacts on smaller vessels with lower gear allotments (Free et al., in prep.). While we did not see obvious adverse effects on aggregate measures of subgroups (i.e., license categories) of the fishery (Fig. 6), fully assessing this potential impact was beyond the scope of our work. Additionally, regulations relating to the COVID-19 pandemic may have had compounding effects, given we found that the overall participation in the fishery was slightly lower in 2020 than in pre-regulations seasons (Supplementary Fig. S10.1). Such compounding effects may extend beyond fishery participants to associated fishery-dependent coastal communities (Moore et al., 2019). While feedback from fishers and their communities was not available here (WDFW, pers. comm.), such information might be valuable in guiding the development and refinement of new management measures.

Consideration of individual and compounding effects of new regulations on crab fishery participants and fishing communities may also benefit from evaluation of the potential for new fishing gear innovations designed to reduce marine megafauna entanglements. These include technologies that leverage sensory capabilities such as illuminated fishery gear, which have been successful in reducing bycatch in gillnets, while still maintaining target species catch rates (Mangel et al., 2018; Senko et al., 2022). However, assessments on the effectiveness of gear illumination have so far focused on net-based fisheries, and further research is still needed to assess the responses of different whale species to varying rope colour (Kot et al., 2012; Kraus et al., 2014; How et al., 2015; Hamilton and Baker, 2019). Alternatively, variations of ropeless or pop-up gear (e.g., inflatable bags or bottom-stored ropes that surface only during expected fishing activity, Lebon and Kelly, 2019), would reduce or eliminate the amount of time vertical lines associated with pot gear would spend in the water. However, the challenges associated with widespread adoption of ropeless or pop-up gear include high costs for both managers and the fleet, reliability and/or compatibility of technical components across manufacturers and systems, and the complex combination of policy, management, and enforcement considerations that must be addressed to ensure compliance and achievement of fishery management goals (Myers et al., 2019; Stevens, 2021).

In conclusion, we found that substantial variability in year-to-year fishing effort and especially whale distributions altered the risk landscape, but the conservation intervention was effective across this variability. We encourage comparison of the current approach to more dynamic management strategies that account for interannual changes and interspecific differences in entanglement risk. Dynamic entanglement management strategies may be especially relevant if climate change triggers shifts in crab fishing and/or whale distributions that increase their overlap and therefore the risk of entanglement. While dynamic management can be data-intensive, costly to implement, and difficult to enforce (Lewison et al., 2015; Maxwell et al., 2015), these factors can sometimes be mitigated through appropriate incentive schemes (e.g., Squires et al., 2021), or in cases where robust occurrence models for bycatch species exist (such as the U.S. West Coast). In comparison, fixed but proactive management may have fewer of these drawbacks and be effective when ecological and social uses are more consistent and predictable (Vanderlaan and Taggart, 2007, 2009; Redfern et al., 2020). Fisheries bycatch is a global issue, and while there may not be a universal solution, it is clear that data- and model-informed approaches to evaluating impacts of management interventions in relation to societal values offer a promising path forward towards social and ecological sustainability (Senko et al., 2014; Hamilton and Baker, 2019).

CRediT authorship contribution statement

Leena Riekkola: Conceptualization, Data curation, Methodology, Formal analysis, Software, Visualization, Project administration, Writing – original draft. **Owen R. Liu:** Conceptualization, Methodology, Software, Writing – review & editing. **Blake E. Feist:** Conceptualization, Methodology, Resources, Visualization, Writing – review & editing. **Karin A. Forney:** Data curation, Methodology, Resources, Writing – review & editing. **Briana Abrahms:** Data curation, Methodology, Resources, Writing – review & editing. **Elliott Hazen:** Data curation, Resources, Writing – review & editing. **Jameal F. Samhouri:** Conceptualization, Data curation, Methodology, Resources, Funding acquisition, Supervision, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Aggregate, non-confidential versions of data frames are available at https://zenodo.org/record/7412597. Confidential vessel-level landings, registration and logbook data may be acquired by direct request from the Washington Department of Fish and Wildlife and the U.S. National Marine Fisheries Service Office of Law Enforcement, subject to a non-disclosure agreement. All outputs from the blue whale habitat suitability model are available at https://coastwatch.pfeg.noaa.gov/projects/whalewatch2/whalewatch2_map.html. Outputs from the humpback whale habitat model are in the process of being published by K.A.F.; humpback whale sightings data used to build the model are available on the Cetacean and Sound Mapping website (https://cetsound.noaa.gov/cda) and the ROMS output is publicly available on the U.C. Santa Cruz Ocean Modeling and Data Assimilation website (https://www.cencoos.org/data/models/roms/westcoast). Entanglement report data are available at https://oceanview.pfeg.noaa.gov/whale_indices/map.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2022.109880.

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