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Exposure of whales to entanglement risk in Dungeness crab fishing gear in Oregon, USA, reveals distinctive spatio-temporal and climatic patterns

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A B S T R A C T

Entanglement in fishing gear presents a major threat to marine mammals worldwide and a pressing concern for distinct populations of whales off the US West Coast. The lack of understanding of their fine-scale distribution in relation to fishing activity limits management efforts, specifically in Oregon. Based on year-round predictions of rorqual whale densities and fishing effort compiled from logbooks, we assess co-occurrence between commercial Dungeness crab fishing gear and whales over a decade (2011–2020) as an indicator of exposure to entanglement risk. Generalized Additive Models including temporal, climatic, and ocean upwelling predictors were used to investigate variations in exposure. Exposure peaked in April, at the onset of the upwelling season when whales were predicted to occur in greater numbers and closer to shore. Exposure remained constant until the end of the crab season in nearshore waters <40 fathoms (73 m) and decreased past these depths. Across years, exposure was lower during the marine heatwave (2014–2016) when fishing was more active nearshore and whales were predicted to be less abundant. Exposure was higher before (2011–2013) and after (2017–2020) the heatwave, which correspond to negative phases of the Pacific Decadal Oscillation associated with stronger upwelling, indicating more productive conditions favorable to whales. A recent increase in exposure was also due to a slight shift in fishing effort towards deeper waters. These findings illustrate the use of fine-scale species distribution models to assess space-use conflicts in dynamic marine ecosystems and can be used to guide fisheries management to reduce entanglement risk in Oregon.

1. Introduction

Space use conflicts between fishing activities and megafauna is a long-standing marine conservation issue, with entanglement in fishing gear a main concern for large whale population recovery (Clapham, 2016). Entanglement can cause immediate or delayed mortality as it affects whale health, feeding success, and fecundity (van der Hoop et al., 2017; Carretta and Henry, 2022). These anthropogenic impacts can accumulate and interact with the effects of changing ocean conditions and prey availability resulting from climate change. Recent research indicates that extreme climatic events, such as marine heatwaves and regime shifts, may result in distribution changes that increase the overlap of large whales with fishing activities (Santora et al., 2020; Meyer-Gutbrod et al., 2021; Samhouri et al., 2021). Hence, improved knowledge of the shifting spatio-temporal distribution of large whales with respect to fishing activities is necessary to anticipate entanglement risk and design appropriate conservation measures in a changing ocean.

Elevated counts of large whale entanglements have occurred in the past decade along the US West Coast (California, Oregon, and Washington), with particularly concerning levels recorded since 2014 (NOAA Fisheries, 2022). In cases where fishing gear involved in entanglements could be identified since 2014, commercial Dungeness crab (*Metacarcinus magister*) pot gear was one of the most frequently identified gear types (Saez et al., 2021). This pot fishery operates in relatively shallow and nearshore waters of the continental shelf, with most landings occurring within the first few months of the crab season from December onwards (Feist et al., 2021). Dungeness crab is the most economically important species harvested along the US West Coast (Rasmuson, 2013) and the fishery is culturally significant to coastal communities in the region (ODFW, 2022). This fishery is managed by states independently

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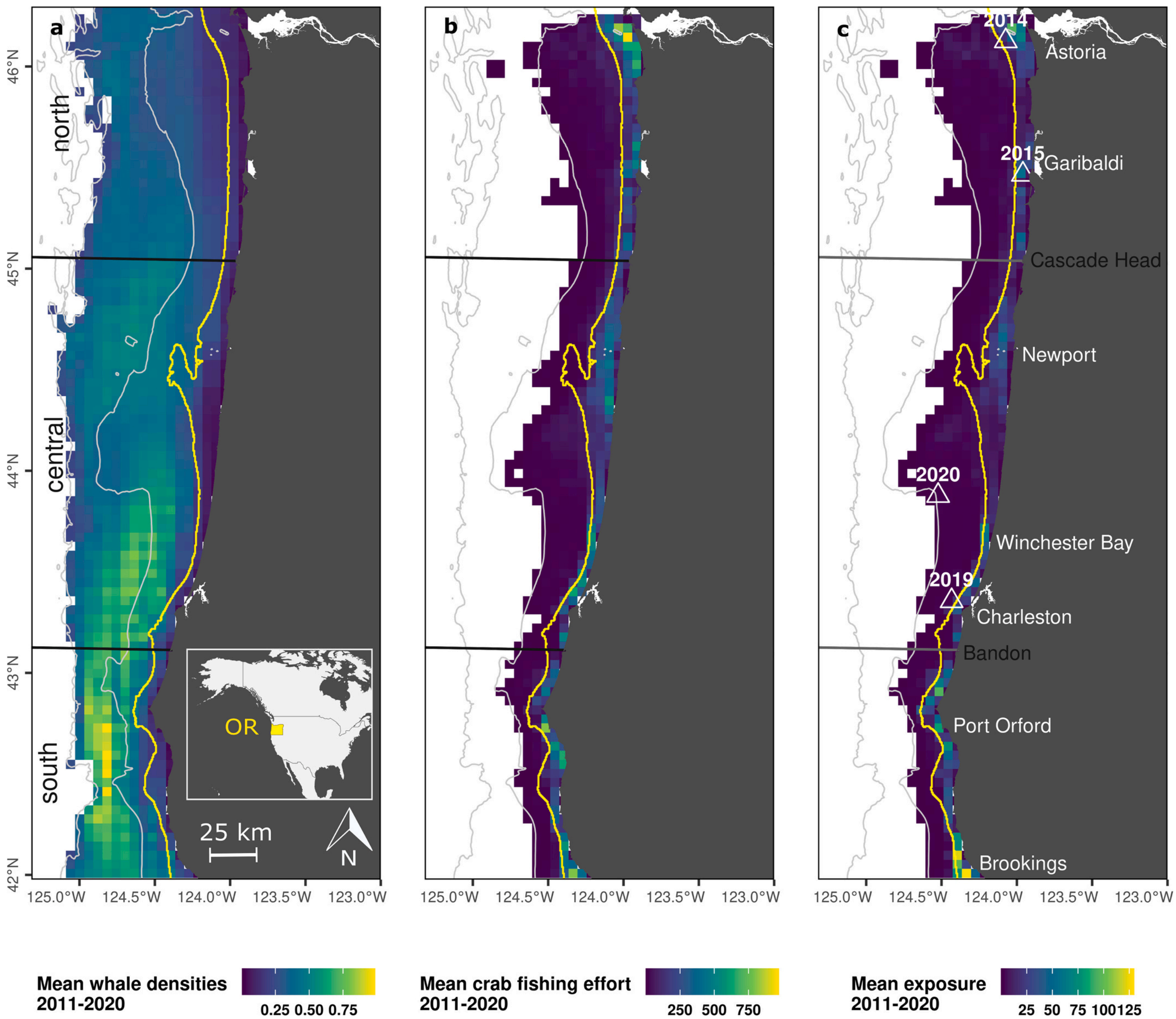

Fig. 1. Average whale densities in number of whales predicted by 5 × 5 km grid cell (a), commercial Dungeness crab fishing effort (b), and exposure to entanglement risk (c) calculated over the study period (2011–2020, n = 83 monthly layers). Isobaths (200 m and 1500 m deep) are shown with grey lines. The 40 fathom (73 m) isobath used in fishing regulations is shown in yellow. In panel c, white triangles indicate the estimated gear set location and year where humpback whales were confirmed to be entangled in commercial Oregon (OR) Dungeness crab fishing gear. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(CDFW, 2021; ODFW, 2021; WDFW, 2022) and is subject to local closures or delayed openings as a result of variable crab meat yield and domoic acid contamination, which are influenced by environmental fluctuations (Santora et al., 2020; Feist et al., 2021; Samhouri et al., 2021). The fishery may also be locally closed or reduced due to whale entanglement, creating an inherent management tension between providing fishing opportunities and managing for whale conservation under variable climatic conditions. For example, since 2019 higher rates of whale entanglements that involved commercial Dungeness crab gear caused significant restrictions in the California crab fishery (CDFW, 2019). Consequently, understanding the environmental and social drivers of whale exposure to fishing activities is urgently needed to both protect whale populations and the vibrant, otherwise sustainable, Dungeness crab fishery across the West Coast.

Humpback whales (*Megaptera novaeangliae*) are most impacted by entanglements in commercial Dungeness crab gear, with the total human-caused serious injury and mortality of the California/Oregon/Washington stock (48.3 whales/year; Carretta et al., 2021) exceeding biologically sustainable levels under the U.S. Marine Mammal Protection Act (Potential Biological Removal level of 29.4 whales/year; Carretta et al., 2021). To a lesser extent, other rorquals (baleen whales of the family Balaenopteridae) such as the endangered blue whales (*Balaenoptera musculus musculus*) and fin whales (*Balaenoptera physalus*) are also at risk of entanglement while they migrate and forage off the US West Coast. These marine predators are known to shift their distribution in response to seasonal and interannual fluctuations of environmental conditions that drive prey availability (Becker et al., 2017, 2018; Derville, 2022). Indeed, rorqual whale distribution in the California Current System (CCS), which extends from California to British Columbia, Canada, is tightly connected to wind-driven upwelling that provides nutrient rich and cool waters that boost primary productivity in surface waters during spring and summer (Hazen et al., 2017; Becker et al., 2018; Abrahms et al., 2019; Derville, 2022). Yet, upwelling intensity, timing and duration vary across years (Benoit-Bird et al., 2019), notably due to basin-wide forcing reflected by climatic indices such as the Pacific Decadal Oscillation or the El Niño Southern Oscillation Index (PDO, SOI, e.g., Bograd et al., 2009; Peterson et al., 2017). Such variability was suggested to be a main driver of increased entanglement rates observed in recent years in the southern CCS (Santora et al., 2020). Relatively less is known about the interplay between whale and fishing activities that cause entanglements in the northern CCS (Riekkola et al., 2023). While less entanglements have involved gear confirmed as originating from Oregon and Washington states compared to California (Saez et al., 2021), the issue is of high concern for local coastal communities and state natural resource managers tasked with protecting single stocks of humpback, fin and blue whales that extend along the entire US West Coast. Specificities in fishing practices (ODFW, 2022), and whale ecological relationships (Derville, 2022) warrant dedicated research efforts to understand patterns of exposure to entanglement risk in the northern CCS.

We leverage recent research outputs that predict rorqual whale distribution over the continental shelf off Oregon during the last 10 years (Derville, 2022) to retrospectively analyze co-occurrence between commercial Dungeness crab fishing activity and rorqual whales indicating exposure to entanglement risk. We hypothesize that 1) whale exposure to entanglement risk varies in space and time, 2) spatio-temporal variations of exposure are related to shifting whale habitat and fishing effort distribution within and across years, and 3) variations of exposure are driven by upwelling conditions reflected by basin- and local-scale environmental indicators. Enhanced knowledge about the physical, biological and social drivers of the spatio-temporal variability of whale entanglement risk in Oregon will help design management strategies to address this threat.

2. Material & methods

2.1. Study area

Our study area includes the entire Oregon coast and was divided into six different zones of varying depth and latitude reflecting different fishing contexts (Fig. 1). Three latitudinal zones were delineated: south, from Bandon to the southern Oregon border; central, between Bandon and Cascade Head; and north, from Cascade Head to the northern Oregon border. Two depth ranges delineated nearshore and offshore zones using the 40 fathom isobath (73.2 m) as this depth limit was recently adopted in fishery regulations effective May 2021 to restrict commercial Dungeness crab fishing annually to waters within 40 fathoms from May to August (Oregon Secretary of State, 2020) where rorqual whales generally occur less at this time of the year (Derville, 2022). All spatial data were projected in a Universal Transverse Mercator coordinate system (UTM zone 10N) prior to analysis.

2.2. Fishing data

Commercial Dungeness crab fishing effort layers were constructed from fishery logbook data from the 2010–2011 (opened February 2011) through 2019–2020 crab seasons (hereafter referred to as "fishing years"). Commercial crab fishing season in Oregon may span from December to August. Fishing effort is reported in logbooks as the number of pot pulls, whereby a pot is lifted out of the water to harvest crab, after which it is usually redeployed. Therefore, pots are typically in the water nearly constantly from the time a vessel enters the fishery until it exits the fishery (ODFW, 2022). By regulation, commercial Dungeness crab pots may not be connected to each other via a groundline, therefore each pot requires a single vertical line connecting it to one or more surface buoys. Logbook data values likely to be outside the range of common fishing practices were excluded using a series of filters. Then, we allocated each vessel's pot limit (the maximum number that may legally be set at one time) proportional to pot pulls across fishing locations that vessel recorded in logbooks, at a monthly time scale. Our approach accounted for sub-sampling of logbooks for data entry in some years, non-compliance (landings with no logbook submitted), and logbook records missing critical data fields (see Supplementary methods). We then generated estimates of the number of pots in the water in layers of 5 km resolution, matching whale model outputs, for each month and year the fishery was open.

2.3. Whale data

Using the year-round rorqual whale models from Derville (2022), we hindcasted rorqual densities by month for each year over layers of 5 km resolution. Three different Generalized Additive Models (GAM) were used to predict whale densities in the winter (December–March), spring (April–July), and summer (August–September), in relation to 10 topographic and dynamic ocean circulation variables averaged at a weekly scale (see Derville, 2022). Predictions were spatially limited to waters displaying environmental conditions analogous to those in which the models were trained. Predictions in non-analogous conditions, a practice known as environmental extrapolation, can lead to extreme and unrealistic predictions (Bouchet et al., 2019). We used the Extrapolation Detection (ExDet) tool developed by Mesgaran et al. (2014) to evaluate this environmental extrapolation over the weekly layers of environmental variables on which the whale predictions were based (see Supplementary methods). ExDet was computed with the *dsmextra* R package (version 1.1.5; Bouchet et al., 2020). ExDet was either considered at the scale of grid cells or averaged by study zone, and removed from further analyses appropriately (see below).

2.4. Fishing and whale center of mass

To detect spatial shifts of crab fishing effort and whale distribution, we calculated the depth and latitude of the center of mass for these layers by month for each year. Mean depths of fishing and whale distribution were calculated separately in the north, central, and south zones (combining together the nearshore and offshore parts of the same latitudinal zone). Mean latitude of fishing and whale distribution were calculated separately in the offshore and nearshore zones (combining together the northern, central, and southern parts of the same depth range). For the purpose of this analysis, we removed all grid cells showing environmental extrapolation with respect to the whale models (i.e., where ExDet < 0 or >1). GAMs were fitted to the mean depth (models "$M_{crab.cmass.depth}$", "$M_{whale.cmass.depth}$") or the mean latitude (models "$M_{crab.cmass.lat}$", "$M_{crab.cmass.lat}$") by zone by month, using a gaussian distribution with identity link and a restricted maximum likelihood method in the *mgcv* R package (Wood, 2011). Explanatory variables included separate penalized thin-plate regression splines of month and year. Smooth basis size was limited to 3 to prevent overfitting. The effect of the explanatory variables on the overall model fit was assessed by examining the percent of deviance explained in comparison to a null model.

2.5. Patterns of overlap

First, the Williamson spatial overlap index (Williamson et al., 1989) was calculated per month to assess whether whale densities were uniformly distributed relative to fishing activity. Williamson index values > 1 and <1 respectively represent overlap greater or less than expected from a uniform distribution:

$$Williamson\ index = \frac{\sum_{z=1}^{m} N_z \bullet n_z \bullet m}{\sum_{z=1}^{m} N_z \bullet \sum_{z=1}^{m} n_z}$$

where z is the spatial unit (grid cells), m is the number of spatial units available (number of grid cells where ExDet $\in]0, 1[$), N is the predicted whale density, and n is the crab fishing effort.

Second, exposure evaluated co-occurrence between whales and

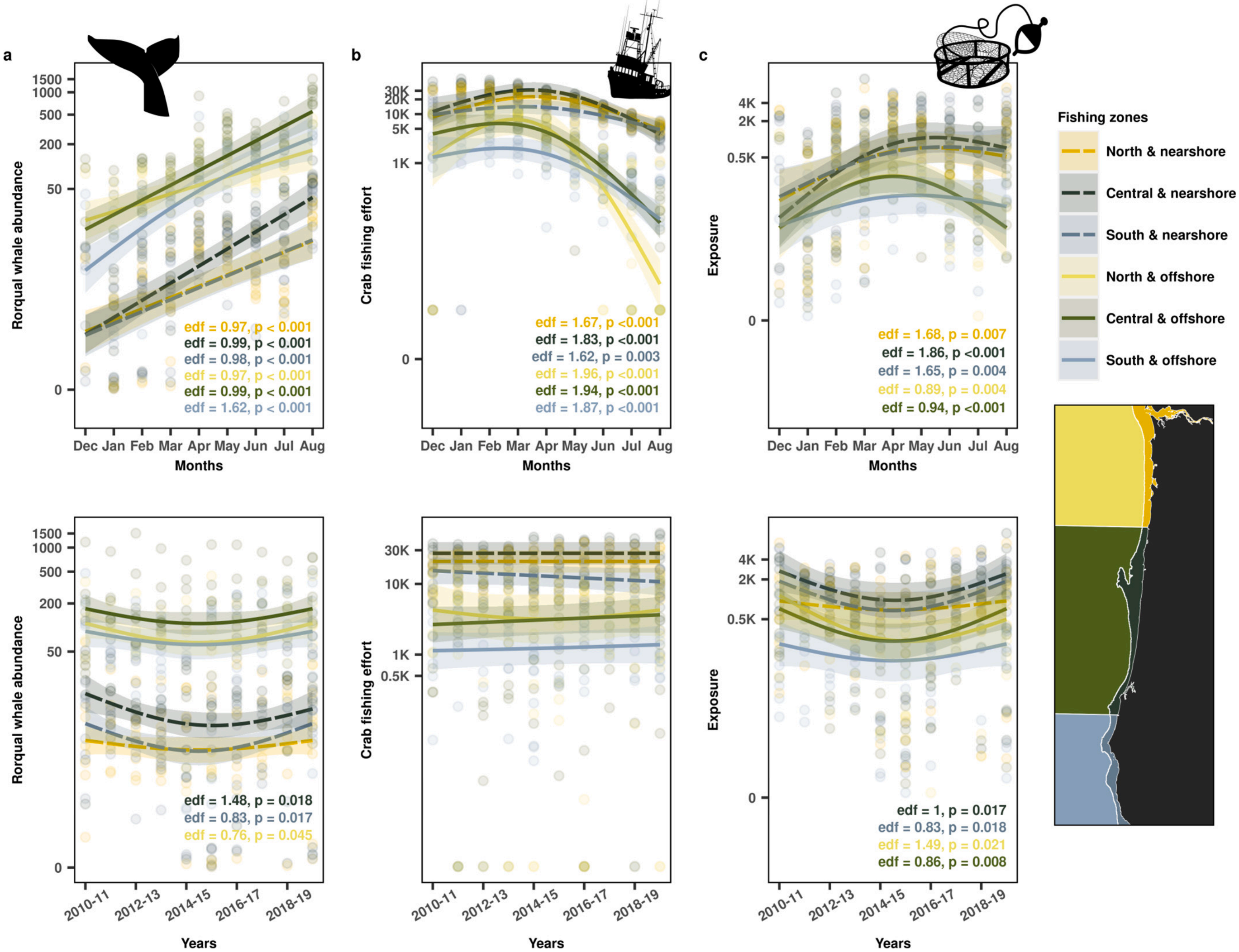

Fig. 2. Fitted relationships between predicted local rorqual whale abundance (a; M_{whale}), crab fishing effort (b; M_{crab}) and exposure to entanglement risk (c; $M_{exposure}$) with month (top) and fishing year (bottom) predictors. GAMs were fitted to each response type in each of the six study zones represented on the map. Solid and dashed lines represent the marginal effect of month and fishing year by zone, and shaded areas represent approximate 95 % confidence intervals. The estimated degrees of freedom (edf) and the approximate smooth significance of predictors is indicated in each panel when the p-values were below a 0.05 threshold. Data points are represented in light shades. Y-axes are presented on a log scale.

fishing activity at a monthly scale, over layers of 5 km resolution calculated as the product between the fishing (number of pots) layers and the density of rorqual whales layers. Maps of monthly exposure were averaged together to identify spatial areas of elevated entanglement risk throughout the whole study period (2011–2020). For the purpose of this analysis, we removed all grid cells showing environmental extrapolation with respect to the whale models (i.e., where ExDet < 0 or >1). These average maps of exposure were compared to the estimated gear set location of four humpback whale entanglement events with confirmed Oregon Dungeness crab fishing gear (data provided by NMFS WCR, April 2021).

2.6. Variations in exposure

Grid cells of monthly exposure, in each of the six study zones were summed to investigate the spatio-temporal variations of entanglement risk in relation to month, fishing year and proxies of ocean conditions. GAMs were fitted to the log-transformed sum of exposure (models “$M_{exposure}$”) by zone, using a gaussian distribution with an identity link and a restricted maximum likelihood method. Explanatory variables included separate penalized thin-plate regression splines of month, fishing year, and a suite of climate and upwelling indices (see below description). Smooth basis size was limited to 3 to prevent overfitting. Models with alternative sets of predictors were compared with one another using the Akaike Information Criterion (AIC).

In parallel, the same models were produced with the log-transformed summed abundance of whales (models “M_{whale}”) by zone and the log-transformed summed fishing effort (models “M_{crab}”) by zone to understand whether the changes in exposure could be due to changes in local whale abundance or the amount of fishing. Although the rorqual density models of Derville (2022) were not meant to derive abundance trends for these whale populations as a whole, they allow the relative comparison of local estimates of abundance calculated over different time periods. For the purpose of these models, all zone x month combinations in which the mean ExDet was <0 were removed (no zone x month were found with ExDet > 1).

2.7. Climate and upwelling drivers

Climate indices known to influence upwelling conditions and productivity in the northern CCS were extracted at a monthly resolution: the PDO and the SOI (see Supplementary methods for data sources).

Table 1
Performance metrics of models of local whale abundance (M_{whale}), crab fishing effort (M_{crab}), and exposure ($M_{exposure}$) by zone, in relation to month, fishing year, PDO, SOI, and CUTI. Performance metrics include AIC (Akaike Information Criterion) and dev.exp (percent deviance explained). The preferred models (lowest AIC with a delta < 2) are highlighted for each zone.

			M_{whale}		M_{crab}		$M_{exposure}$	
Zone		Predictors	AIC	dev.exp	AIC	dev.exp	AIC	dev.exp
north	<40 fathom	month	262	32	262	20	311	12
		month+fishing year	262	33	262	20	311	14
		month+PDO	259	37	262	23	301	25
		month+PDO+SOI	239	36	247	22	279	25
		month+CUTI	234	56	259	23	275	49
		month+CUTI+PDO	235	57	259	27	273	52
	>40 fathom	month	189	26	374	59	260	11
		month+fishing year	187	31	374	59	256	21
		month+PDO	178	45	374	60	244	33
		month+PDO+SOI	165	46	347	59	224	34
		month+CUTI	172	49	374	60	237	45
		month+CUTI+PDO	168	56	373	61	231	51
central	<40 fathom	month	256	55	262	29	304	24
		month+fishing year	252	59	262	29	301	30
		month+PDO	242	64	262	29	288	39
		month+PDO+SOI	225	63	247	27	267	39
		month+CUTI	221	73	257	33	265	58
		month+CUTI+PDO	207	78	257	33	247	67
	>40 fathom	month	233	51	307	55	293	17
		month+fishing year	231	53	307	56	288	24
		month+PDO	222	61	307	55	279	32
		month+PDO+SOI	207	60	288	54	260	30
		month+CUTI	210	67	308	57	265	48
		month+CUTI+PDO	200	73	308	57	254	56
south	<40 fathom	month	270	34	258	12	312	13
		month+fishing year	266	38	258	15	308	19
		month+PDO	266	39	258	12	305	22
		month+PDO+SOI	246	38	243	11	284	23
		month+CUTI	227	66	258	12	274	52
		month+CUTI+PDO	215	71	258	12	259	61
	>40 fathom	month	206	57	325	35	279	7
		month+fishing year	205	59	325	35	278	9
		month+PDO	197	65	325	35	273	20
		month+PDO+SOI	174	69	302	37	248	23
		month+CUTI	192	68	325	37	266	28
		month+CUTI+PDO	181	75	325	38	259	40

Upwelling conditions were estimated with the Coastal Upwelling Transport Index (Jacox et al., 2018a), which provides estimates of model derived vertical transport of seawater (in $m^2 \cdot s^{-1}$) at monthly and daily scales. Monthly CUTI values were incorporated as predictors in the GAMs, while daily values were used to quantify parameters of the upwelling phenology along the Oregon coast (Bograd et al., 2009). Using the algorithms provided by Oestreich et al. (2022), we used the daily values to calculate the cumulative sum of CUTI by day, for each year that the index was available (1988–2021). The climatological mean, 5th percentile, and 95th percentile across years were calculated and smoothed with a 10-day running mean. Then, we calculated the mean spring transition index (STI), the mean peak upwelling (MAX), and the mean end of positive upwelling accumulation (END) based on the climatological mean of CUTI to describe average upwelling phenology by zone (north, central, and south) from 1988 to 2021 (for more details see (Oestreich et al., 2022).

All analyses were performed using R statistical computing (R Core Team, 2021).

3. Results

Overlap between rorqual whales and commercial Dungeness crab fishing was assessed over 10 fishing years (83 months). The mean Williamson index was equal to 0.37 ± SD 0.23, hence indicating that overlap between fishing and whales was low and generally less than expected from a uniform distribution.

3.1. Spatial variations of exposure

The mean pattern of exposure throughout the study period (2011–2020) revealed several areas of higher risk that were mostly driven by the distribution of fishing effort along the coast of Oregon (Fig. 1). Exposure was higher on average in nearshore waters off Astoria, off Garibaldi, north of Newport, north of Charleston, north of Port Orford, and at the southern border of Oregon waters. These areas overlapped with estimated set positions of crab gear involved in three of four confirmed humpback whale entanglements (Data provided by NMFS WCR, April 2021, see Supplementary Table S1) that involved gear estimated to be set in waters off Astoria, Garibaldi, and Charleston

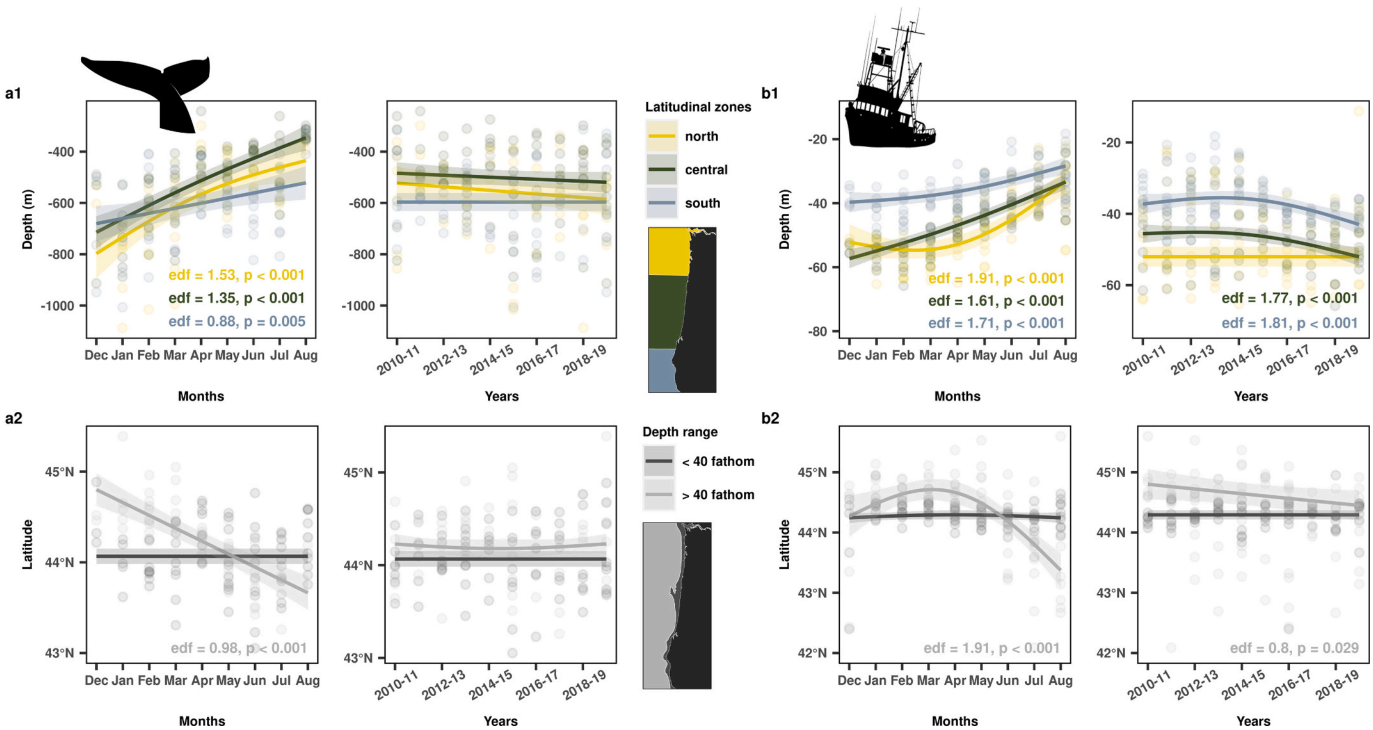

Fig. 3. Fitted relationships between the depth ($a_1 = M_{whale.cmass.depth}$ and $b_1 = M_{crab.cmass.depth}$) and the latitude ($a_2 = M_{whale.cmass.lat}$ and $b_2 = M_{crab.cmass.lat}$) of the center of mass of the predicted local rorqual whale abundance (a_1 and a_2) and the crab fishing effort (b_1 and b_2). GAMs were fitted to each response type in either the three latitudinal zones (panels a_1 and b_1) or the two depth ranges (panels a_2 and b_2) represented on the maps. Solid and dashed lines represent the marginal effect of month and fishing year by zone, and shaded areas represent approximate 95 % confidence intervals. The estimated degrees of freedom (edf) and the approximate smooth significance of predictors is indicated in each panel when the p-values were below a 0.05 threshold. Data points are represented in light shades.

(Fig. 1c).

3.2. Temporal variations of exposure

Local whale abundance increased with month in all zones but was mostly stable across years with a slight decrease in certain zones in the mid study period (M_{whale}, Fig. 2a). The M_{whale} that included month and fishing year explained 46 % of the deviance on average, including a marginal 1 to 5 % deviance explained by fishing year depending on the zone considered (Table 1). In comparison, the crab fishing effort was stable across years and tended to decrease across months of a fishing year, particularly in the offshore zones (M_{crab}, Fig. 2b). The average deviance explained by month and fishing year in M_{crab} was 36 % (Table 1). The resulting temporal variations in exposure showed an increase throughout the first months of the fishing year (December–April), then ended in a plateau (April–August) for the nearshore zones or a decrease in the offshore zones ($M_{exposure}$, Fig. 2c). The average deviance explained by month and fishing year in $M_{exposure}$ was 20 %, including a marginal 2 to 10 % deviance explained by fishing year depending on the zone considered (Table 1). Exposure was significantly lower in most zones during the 2014–2016 marine heat wave (Fig. 2c).

3.3. Whale and fishing distribution shifts

Month and fishing year combined explained 11 %, 38 %, and 52 % of the deviance in the depth of the center of mass for whale distribution ($M_{whale.cmass.depth}$) in the south, north, and central zones respectively. The center of mass did not change across fishing years but it significantly shifted to shallower waters by month throughout the fishing year (min around 400 m; Fig. 3a_1). Within the offshore zones, whale distribution also tended to move southward throughout the fishing year ($M_{whale.cmass.lat}$, deviance explained 51 %, Fig. 3a_2) although it was stable in latitude across years. On average, the center of mass for whale distribution shifted south by 77 km in offshore zones between the months of Dec-Mar and May-Aug (*t*-test: $t = -8.1$, $p < 0.001$***).

Month and fishing year combined explained 46 %, 45 %, and 74 % of the deviance in the depth of the center of mass for crab fishing effort ($M_{crab.cmass.depth}$) in the south, north, and central zones respectively. The center of mass moved to shallower waters throughout the fishing year (min around 20 m; Fig. 3b_1). Fishing effort also tended to move to shallower waters during the marine heatwave (Fig. 3b_1) in the south (Anova: $n = 83$, F-value $= 13.7$, $p < 0.001$***) and central (Anova: $n = 83$, F-value $= 3.7$, $p = 0.029$*) zones while it remained stable in the north (Anova: $n = 83$, F-value $= 0.5$, $p = 0.6$). Indeed, in the central zone the center of mass for crab fishing effort was on average 5.9 m deeper (Tukey post-hoc test: $p = 0.043$*) after the marine heat wave (2017–2020) than it was before (2010–2013). In the south zone, the center of mass for fishing effort was significantly deeper before (mean difference 4.1 m; Tukey post-hoc test: $p = 0.047$*) and after (mean difference 8.2 m; Tukey post-hoc test: $p < 0.001$***) compared to during the marine heatwave. Due to the relatively flat slope of the continental shelf off the coast of Oregon, a 5 m drop in depth is equivalent to a westward shift of up to 10 km. This shift in fishing behavior in the south of Oregon is corroborated by a significant southward shift of the offshore center of mass throughout the study period ($M_{crab.cmass.lat}$, deviance explained 42 %, Fig. 3b_2). On average, the center of mass for crab fishing effort shifted south by 44 km in offshore zones between before and after the marine heatwave (*t*-test: $t = -2.0$, $p = 0.046$*).

3.4. Climatic drivers of exposure

Across the study period, the ecosystem alternated between two negative phases of PDO (2011–2014 and 2017–2021) and a positive phase (2014–2016) corresponding to the marine heat wave (Fig. 4a). Within the fishing year, the upwelling conditions off the coast of Oregon varied with latitude (Fig. 4b). The upwelling season (from STI to END) is

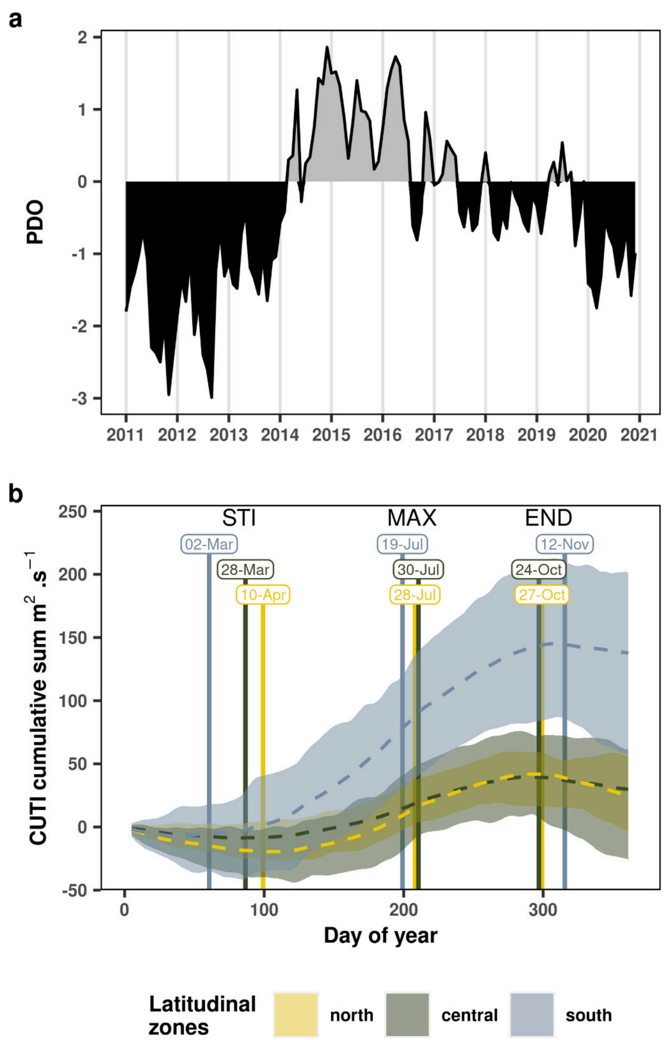

Fig. 4. Temporal evolution of the climatic and upwelling indices affecting ocean conditions in Oregon. a) Pacific Decadal Oscillation (PDO) monthly values from 2011 to 2021. Positive phases are shown in grey and negative phases in black. b) Long-term climatological mean of the cumulative sum of the Coastal Upwelling Transport Index (CUTI) with 5th and 95th percentile intervals. Daily values were averaged from 1988 to 2021, at latitude 43°N (south), 44°N and 45°N (central) and 46°N (north zone). Average timing by zone of the Spring Transition (STI), the peak upwelling (MAX) and the end of the upwelling season (END) are indicated at the top of the plot.

on average longer in the south zone and shorter in the north zone (Fig. 4b). Upwelling strength is also stronger in the south, as reflected in higher cumulative sum of CUTI at the peak and at the end of the upwelling season.

The exposure models including month, CUTI and PDO as predictors were systematically selected as the best models across almost all study zones (Table 1), with deviance explained ranging from 40 % to 67 %. Deviance explained by these predictors was also relatively high in the whale models (56 to 78 %). Overall, CUTI and PDO significantly affected local whale abundance (Fig. 5a) and exposure (Fig. 5c) in almost all study zones but had almost no effect on crab fishing (Fig. 5b). Negative PDO phases and strong upwelling (indicated by higher CUTI) were associated with higher local whale abundance and higher exposure overall, particularly in the south. Although the models of crab fishing effort, local whale abundance, and exposure with month, PDO and SOI were sometimes selected as the most parsimonious (Table 1), the effect of SOI was generally very minor (marginal deviance explained in crab fishing - 0.7 %, local whale abundance + 0.2 %, and exposure + 0.5 % on average across zones).

4. Discussion

We combined long-term fishing effort data and hindcasts of whale densities to identify locations and times with increased entanglement risk, thus providing critical information to managers to reduce space use conflicts between fishers and whales. Variations in exposure rates across months are driven by the timing of whale migration as well as spatial and seasonal patterns of fishing effort. Across years, higher exposure is predicted in the beginning and the end of our study period, due to greater local whale abundance predicted during negative PDO phases and stronger upwelling conditions, and to a lesser extent to a shift of the fishing effort towards deeper waters in recent years.

Co-occurrence indices indicate generally little overlap between the fishing effort and rorqual whale distribution. Yet, even at these low levels of co-occurrence, interactions between whales and fishing gear are occurring. Entanglements have been shown to contribute to biologically unsustainable rates of total human caused mortality for some humpback and blue whale stocks coast-wide (Carretta et al., 2021). However, entanglements are often unobserved or under-reported (Tackaberry, 2022). For example, fresh entanglement scars recorded on humpback whales off the US West Coast revealed that as much as 90 % of entanglements may have gone unnoticed between 2009 and 2010 (Robbins, 2012). The likelihood for past entanglements involving Oregon crab gear to be unreported or impossible to trace back to a specific fishing zone limits our ability to estimate the trends of entanglement risk at a local scale. Yet, our analysis of co-occurrence with fishing gear provides a useful tool to locate the areas of elevated risk. Our modeling approach indicates high coincidence between areas of high mean exposure and three of four entanglement reports involving Oregon crab gear with estimated gear set locations (Fig. 1c), suggesting confidence in the spatial patterns of risk we identified.

The seasonality of Dungeness crab fishing and rorqual whale migration coincides with a peak of exposure around the month of April (Fig. 2c). This temporal pattern is driven by the migratory timing of humpback whales (Derville, 2022), the main species informing our rorqual distribution models. Blue and fin whales occur more rarely off the coast of Oregon, and while they were also assessed in this study, their respective phenology and habitat use patterns are likely to limit their interactions with the Dungeness crab fishery; blue whales tend to occur later than humpback whales (encounter rate peaks in September) and fin whales tend to occur further offshore in the winter (over and off the continental slope; Derville, 2022). To date, there have been no confirmed entanglements of either of these two species in Oregon commercial Dungeness crab gear (Saez et al., 2021). Moreover, during the late crab season (May–August) exposure decreases offshore, but remains stable in nearshore waters (Fig. 2c), a pattern likely driven by hard shell crab distribution as well as social and economic factors (Davis et al., 2017). Larger fishing vessels typically stop fishing Dungeness crab around April, while smaller vessels tend to continue to fish later in the crab season, consolidating gear in more nearshore waters as the season progresses. We therefore identify marked seasonality and spatial patterns in entanglement risk off Oregon that result from a combination of ecological and human factors.

Across years, we found that variations in exposure are associated with environmental fluctuations that drive ocean productivity in the CCS. Exposure increases at all depths and along the whole Oregon coast (Fig. 5c) during negative PDO phases and when upwelling is stronger. On the other hand, positive PDO phases tend to weaken upwelling strength and shift less warm water into the CCS, which results in diminished productivity and influence krill (Peterson et al., 2017), forage fish (Santora et al., 2017) and their predators (Henderson et al., 2014). Between 2014 and 2016/2017, a positive PDO phase coinciding with other climatic drivers generated an anomalously warm water event that had widespread biological impacts throughout the Northeast Pacific

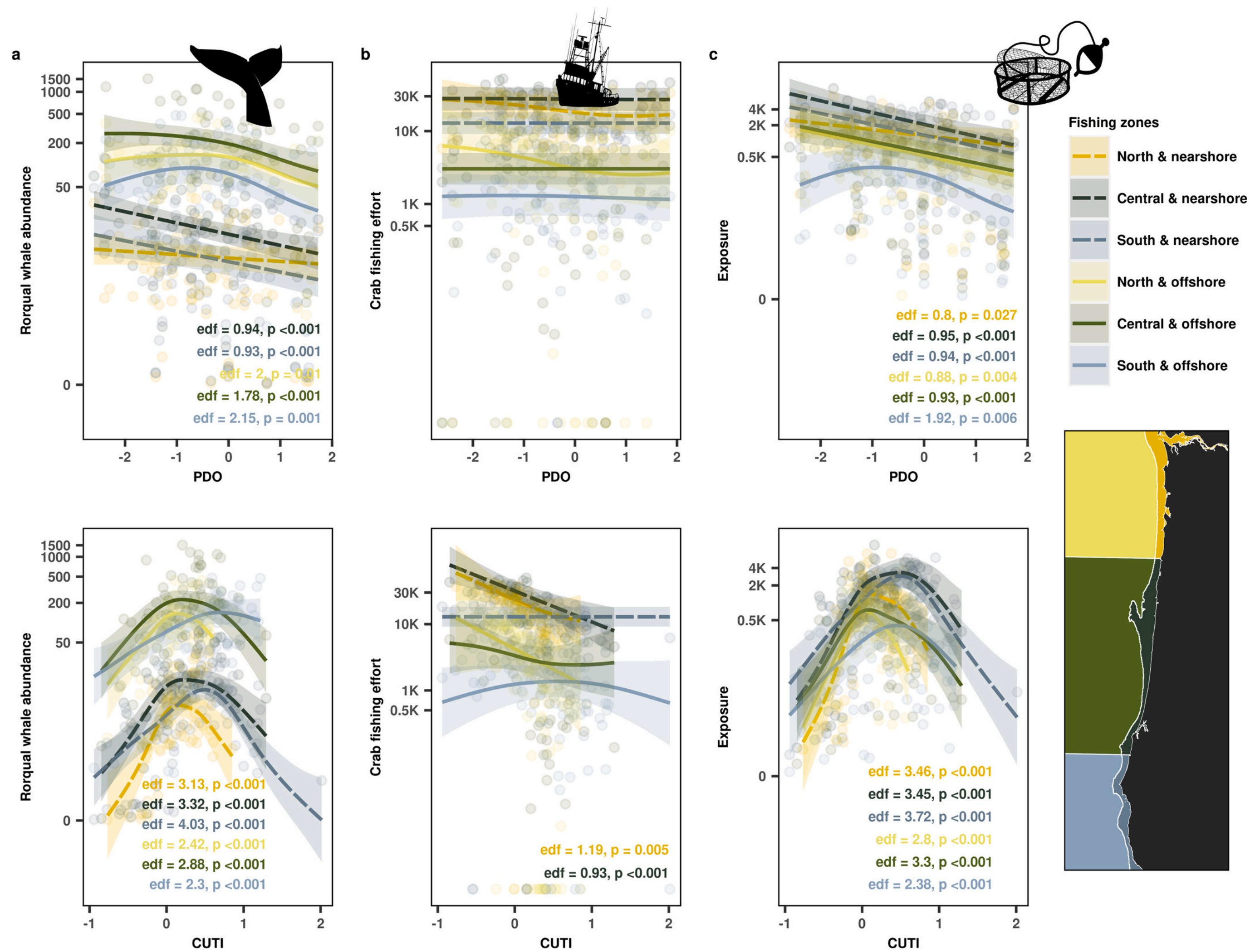

Fig. 5. Fitted relationships between predicted local rorqual whale abundance (a; M_{whale}), crab fishing effort (b; M_{crab}) and exposure to entanglement risk (c; $M_{exposure}$) with the Pacific Decadal Oscillation (PDO; top) and the Coastal Upwelling Transport Index (CUTI; bottom) predictors. GAMs including month, PDO and CUTI as predictors were fitted to each response type in each of the six study zones represented on the map. The fitted relationships to month are not represented here. Solid and dashed lines represent the marginal effect of PDO and CUTI by zone, and shaded areas represent approximate 95 % confidence intervals. The estimated degrees of freedom (edf) and the approximate smooth significance of predictors is indicated in each panel when the p-values were below a 0.05 threshold. Data points are represented in light shades. Y-axes are presented on a log scale.

(Jacox et al., 2018b). Observations of entangled humpback whales off the coast of California increased markedly during that period (Saez et al., 2021), interpreted as the result of habitat compression that increased the overlap of whales with fishing gear (Santora et al., 2020; Feist et al., 2021). In contrast, our model predicted a decrease in exposure of rorqual whales to commercial Dungeness crab fishing during this marine heatwave in Oregon waters. This pattern was likely caused by decreased productivity and foraging conditions (Peterson et al., 2017) that resulted in lower whale densities in Oregon waters. Given the known distinctiveness of oceanographic conditions and seabed topography of the northern CCS (Hickey and Banas, 2008; Castelao and Luo, 2018), we suggest that physical and biological drivers of whale distribution and therefore entanglement risk vary along the US West Coast. More specifically, the wide continental shelf off the coast of Oregon offers larger extents of suitable habitats for whales and fishing grounds, and our applied models indicate a strong link between local whale abundance and upwelling strength in Oregon (CUTI, restricted to a 43° to 46° latitude range, Fig. 5a). While coast-wide management of whale populations that cross state boundaries is necessary, we emphasize the additional need to investigate drivers of whale entanglements at the state level that enable management decisions tailored to local conditions and risks.

Compared to other studies of wildlife-fisheries interaction that used Vessel Monitoring Systems (VMS) data to estimate fishing effort by inferring where fishing events occurred based on vessel location, speed, and bearing reported at pre-determined time intervals (Torres et al., 2013; Breen et al., 2017; Feist et al., 2021), logbook data include the self-reported position where fishing occurred but may be subject to human error. Also, VMS coverage in Oregon is biased as it is not currently required for all vessels participating in the Dungeness crab fishery, whereas logbook data is required for all participating vessels. While logbook data is an improvement, the data processing requires assumptions, particularly to correct for the 30 % sub-sampling for data entry in some years. We assumed that vessels fished their entire pot limit each month if they made a crab landing that month, potentially overestimating the total amount of gear set. Yet, this bias is likely to be randomly distributed and does not prevent the assessment of the relative distribution of entanglement risk across space and time (see Supplementary methods). Also, whale density predictions were generated with seasonal models with variable predictive performance. The winter model that covered the peak of the crab season (December–March) had a lower predictive capacity than the spring and summer models (Derville, 2022). Finally, the whale models predicted density based on habitat quality and did not account for intrinsic population trends of blue, fin, and humpback whales. Indeed, the across-year trend of exposure that we modelled should be interpreted in parallel with the population increase identified in the CCS (Carretta et al., 2021), and encounter rates off the coast of Oregon (Derville, 2022). If these population trends persist and fishing efforts remains the same, exposure to entanglement risk is likely to be exacerbated in future PDO negative phases.

5. Conclusions

There was no major change in the overall amount of commercial crab gear set off Oregon from 2011 to 2020 (Fig. 2b), which is consistent with the time series of fishing distribution acquired through VMS estimates up to 2016 (Feist et al., 2021). Fishing effort slightly shifted to shallower waters during the marine heatwave and then to deeper waters in recent years (Fig. 3b_1), potentially following environmentally-driven changes in Dungeness crab distribution. Although this shift in fishing effort contributed to an increase in exposure to entanglement risk in recent years (2017–2020), the main driver of exposure appears to be whale habitat suitability related to climatic fluctuations. These results can inform fishery management measures to reduce the risk of entanglements of rorqual whales. Temporary area closures and shortening of the crab season are identified as management options with a likely success to reduce whale entanglement, but could burden fishers (Lebon and Kelly, 2019), specifically smaller vessels that continue to fish later into the crab season when more whales use the region. In addition, the effectiveness of any management strategy to balance whale conservation and fishing revenue depends on climatic conditions (Samhouri et al., 2021). To minimize impacts to the industry, one possible approach could be to dynamically fit temporal closures around predicted areas of high whale densities, or only shorten crab fishing seasons during years when upwelling is predicted to be strong (based on negative PDO phase, elevated CUTI and early transition). Nonetheless, managers must consider multiple biological and human factors, such as delayed crab season start due to high levels of domoic acid in crab which can increase co-occurrence of fishing with whales (e.g., California 2016, Santora et al., 2020; Feist et al., 2021). Our models and findings provide scientific grounds for designing management strategies to reduce whale entanglement risk in Oregon. These strategies will require assessment of impacts to the commercial crab industry, management costs and complexity of implementation, and effectiveness to mitigate entanglement.

CRediT authorship contribution statement

Craig Hayslip, Leigh G Torres, Solène Derville, Troy V Buell, Kelly C Corbett: Data acquisition and curation; Solène Derville: Formal analysis; Leigh G Torres, Troy V Buell, Kelly C Corbett,: Funding acquisition; Solène Derville, Troy V Buell: Methodology; Troy V Buell, Kelly C Corbett, Leigh G Torres: Project administration; Solène Derville: Visualization; Solène Derville, Leigh G Torres, Troy V Buell, Kelly C Corbett: Writing.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any conflict of interest.

Data availability

Datasets are made available via the Figshare Digital Repository: https://figshare.com/projects/OPAL_Overlap_Predictions_About_Large_whales/161137

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Appendix A. Supplementary information

Supplementary methods, figures, and tables to this article can be found online at https://doi.org/10.1016/j.biocon.2023.109989.

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