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Footprints of fixed-gear fisheries in relation to rising whale entanglements on the U.S. West Coast

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Abstract

On the U.S. West Coast, reports of whales entangled in fishing gear increased dramatically in 2014. In this study, a time series of fishing activity maps was developed from 2009 to 2016 for the four fixed-gear fisheries most commonly implicated in entanglements. Maps were generated using vessel monitoring system (VMS) data linked to port-level landings databases, which were related to entangled whale reports over the same time period and with modelled distributions of humpback whales *Megaptera novaeangliae* Borowski. Over the full study period, neither marked increases in fishing activity nor changes in fisheries footprints within regions with high whale densities were detected. By contrast, a delayed fishery opening in California due to a harmful algal bloom in spring of 2016 led to ~5–7 times average levels of Dungeness crab *Metacarcinus magister* (Dana) fishing activity, which was consistent with a high rate of entanglement in that year. These results are consistent with current hypotheses that habitat compression caused by a marine heatwave increased the overlap of whales with fishing activity, despite minimal changes in the fisheries themselves. This study adds to literature on bycatch of protected species in otherwise sustainable fisheries, highlighting the value of using VMS data for reducing human–wildlife conflict in the ocean.

KEYWORDS
California current ecosystem, fisheries bycatch, resource conflict, spatial analysis, vessel monitoring system, whale entanglement

1 | INTRODUCTION

Commercial fisheries operations can have many types of indirect impacts on marine ecosystems, such as changes in trophic structure, habitat alteration, and interactions of marine species with actively fished and derelict fishing gears (Watling and Norse, 1998; Worm and Tittensor, 2011; Arthur *et al.*, 2014; Gilman, 2015). Bycatch—incidental catch of non-targeted species—is of particular concern. Bycatch of lower trophic-level species, such as forage fish, has the potential to affect demographic rates of dependent predators, whereas bycatch of higher trophic-level species can influence the dynamics of prey species and their roles in an ecosystem/food web (Bonfil, 1994; Myers and Worm, 2003; Pikitch *et al.*, 2012). High-profile examples of fisheries bycatch leading to species declines or preventing recovery include the endangered North Atlantic right whale (*Eubalaena glaciali*), baiji (*Lipotes vexillifer*), vaquita (*Phocoena sinus*) and New Zealand sea lion (*Phocarctos hookeri*, (Breen *et al.*, 2003; Johnson *et al.*, 2005; Turvey *et al.*, 2007; Jaramillo-Legorreta *et al.*, 2017)). Larger marine mammals are especially vulnerable to bycatch, owing to their

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size, long lifespan, low fecundity and late age at maturity (Lewison *et al*., 2004). The risk posed by bycatch is increasing globally and is considered "the single greatest threat to cetaceans from human activities" (Smith *et al*., 2014; IWC, 2018).

On the west coast of the United States, whale entanglement with commercial fishing gear—especially fixed-gear types—has been a low-level chronic problem (Hanson *et al*., 2019). However, reports of entangled whales increased substantially beginning in 2014, especially for humpback whales, *Megaptera novaeangliae* Borowski (Lebon and Kelly, 2019; Saez *et al*., 2020). The timing of this uptick in reports of entangled whales coincided with a marine heatwave of unprecedented scale, which lasted from 2014 to 2016 (Di Lorenzo and Mantua, 2016). Several non-mutually exclusive factors could explain this increase in reports of entangled whales, including increased size of whale populations, changes in the behaviour and spatial distribution of whales, increased effort devoted to observing entanglements, and increases in the overall amount and/or spatial distribution of fishing activity (O'Connor *et al*., 2009; Calambokidis *et al*., 2017; Santora *et al*., 2020). While other studies have addressed some of these factors, there is surprisingly little quantitative information available regarding fine-scale, spatio-temporal dynamics of the fixed-gear fishing fleets most often implicated in whale entanglements on the U.S. West Coast (Santora *et al*., 2020). Such information could reveal the extent to which shifts in overall fishing activity and the spatial footprints of fisheries could affect risk of whale entanglement.

Humpback whales typically aggregate in feeding grounds off the U.S. West Coast during summer/late autumn months and then migrate to breeding grounds for the winter before returning the following spring (Calambokidis *et al*., 2000; Barlow and Forney, 2007; Calambokidis *et al*., 2015). This behaviour likely kept humpback whales and Dungeness crab fishing activity separated in space and time, but the marine heatwave that began in 2014 caused humpback whales to linger off the west coast much later than usual. In addition, new biophysical evidence suggests that the marine heatwave, which lasted from 2014 to 2016, compressed the prey field of humpback whales closer to the coast and may have contributed to the recent rise in observed entanglements of humpback whales in the California Dungeness crab *Metacarcinus magister* (Dana) fishery (Santora *et al*., 2020), which tends to operate primarily in shallower depths (<150 m; Feist et al. *unpublished*). While shifts in the distribution of humpback whales and dynamics of the marine heatwave have been previously studied, the spatio-temporal dynamics of the actual footprint of fisheries in whale habitat has been poorly resolved. In this paper, this knowledge gap is addressed by quantifying the spatial and temporal variability of fishing activity across the full U.S. West Coast from 2009 to 2016. Specifically, a time series of fishing activity maps were developed in California, Oregon and Washington for four major pot- and trap-based fisheries, using landings informed vessel monitoring system (VMS) data from 2009 to 2016. Fishing activity was then related to modelled whale species distributions and observed entanglements across the same domain, which offers new insight into the potential causes of increased entanglements.

2 | MATERIALS AND METHODS

2.1 | Overview

Reports of entangled whales collected off the west coast of the United States from 2009 through 2016 were analysed to identify general spatio-temporal patterns in entangled whale sightings, and to determine whether there was a significant change in reporting that occurred starting in 2014. The data were also examined for correlations with gear type and whale species. Next, spatio-temporal patterns of pot- and trap-based fishing activity were characterised across the same study area and time period by linking port-level vessel landings data to VMS data to generate time-series maps of fishing activity. In addition, patterns of overlap between humpback whales and fishing fleets were characterised using modelled whale distributions. Comparisons were made before and after 2014, as these time periods comport with a major shift in ocean conditions as a result of an unprecedented marine heatwave (Bond *et al*., 2015; Whitney, 2015; Di Lorenzo and Mantua, 2016) and reports of entangled whales had been relatively low prior to 2014 (see below). Refer to Supplement (1.1–1.3) for further details regarding the spatial analyses referenced in subsequent sections.

2.2 | Data sources and analyses

2.2.1 | Entangled whale reports

A comprehensive, spatially explicit database of reports of entangled whales (Saez *et al*., 2020) was analysed to evaluate trends in the number of reported entanglements by species, location and gear type, from 2009 to 2016. Gear types were grouped into four categories: (1) Dungeness pots/traps; (2) other pots/traps; (3) gillnet, net and other; and (4) unknown. Given humpback and grey (*Eschrichtius robustus* Lilljeborg) whales accounted for the majority of entangled whale reports, all other species, which included blue (*Balaenoptera musculus* (L.)), fin (*Balaenoptera musculusphysalus* (L.)), minke (*Balaenoptera acutorostrata Lacépède*), killer (*Orcinus orca* (L.)), sperm (*Physeter microcephalus* L.) and unidentified whales, were grouped into a single "other" species category. It is important to note that the entangled individuals reported were not observed becoming entangled; the observation was merely one of a cetacean already entangled in fishing gear and the entanglement time and location was unknown in most cases. Further, cetaceans may travel hundreds or thousands of kilometres with gear attached to them, so the time and location of the actual entanglement may have occurred months previously at a location distant from the observation of the entangled whale (Moore and van der Hoop, 2012; Bradford and Lyman, 2015).

Two types of analyses were done with the entangled whale report data. First, descriptive statistics and general spatial patterns were characterised. Specifically, data were mapped pre- and post-2014 for each species category (humpback, grey and other) and gear type (Dungeness pots/traps; other pots/traps; gillnet, net and other; and unknown) described above. The second analysis quantified associations between the number of entangled whale reports and gear type, time period (pre- and post-2014) and species (humpback, grey, and other). A generalised linear model was applied assuming a Poisson distribution using a log-link function (library lme4 [v1.1-23] in R [v3.6.3, R Core Team (2019)]). Stepwise AIC (stepAIC function in library MASS [v7.3- 51.6] in R) was used to compare the full model (all interactions included) to reduce models, and the model with the lowest AIC was chosen as the best one. In this case, the full model and all reduced models were ecologically meaningful, as the interaction terms allowed evaluation of whether the number of entanglement reports in the earlier or later time periods differed for some species or gear types, but not others.

2.2.2 | Mapping fishing activity

Since pot and trap gear is most often associated with humpback whale entanglement (Saez *et al*., 2020), analyses were limited to four commercially important species that were caught using this class of gear: Dungeness crab, spot prawn *Pandalus platyceros* Brandt, California spiny lobster *Panulirus interruptus* (Randall) and sablefish *Anoplopoma fimbria* (Pallas).

VMS data (NOAA, 2016) from January 2009 through June 2016 were used to track fishing vessel locations over time. VMS is used by enforcement agencies to track the locations of a subset of fishing vessels to determine whether they are fishing in closed areas. Vessels are monitored continuously, regardless of whether or not they are actively fishing, and their position, vessel identification number, velocity and time are transmitted every 30 to 60 min to remote monitoring stations on land. VMS data do not include information about which species are being targeted by fishing vessels, nor do they specify when fishing is occurring. To determine target fish species for each fishing trip, port-level vessel landings data, compiled by the Pacific Fisheries Information Network (PacFIN, 2017), were linked to the VMS data using a vessel ID number common between the two databases. The landings data provide detailed information about every fishing trip that offloaded catch at a given port, including vessel ID, date, time, species landed and corresponding biomass (see Supplement: 1.2). By linking these two datasets, it was possible to identify where fishing vessels were operating in the days preceding offloading a given catch. To identify spatio-temporal patterns of fishing activity for each of the four target species across the study area, the landings informed VMS points were then overlaid on a 5-km resolution grid and heatmaps were generated in 4-month intervals from November 2010 through June 2016 (see Supplement: 1.3).

Given a subset of fishing vessels are equipped with VMS transponders, an analysis of VMS representativeness in each fishery and by vessel size class was conducted. Representativeness was characterised by calculating the proportion of vessels and the proportion of landed biomass by VMS equipped vessels, relative to all vessels and landed tonnes in each corresponding fishery. The proportion of fishing activity that occurred aboard VMS equipped vessels was summarised by state and by vessel size class for each of the four target species. Twelve metres was used as the break point between large (≥12 m) and small (<12 m) vessel size classes. The 12 m length cut-off is commonly used to differentiate between small and large fishing vessels (Kasperski and Holland, 2013; Jardine *et al*., 2020). Small vessels were tracked separately in these analyses, as they have less storage space and potentially place less gear in the water. Therefore, small vessels may present lower risk of entanglement to whales.

Because Dungeness crab are the dominant pot- and trap-based fishery on the U.S. West Coast, and since gear from this fishery is the most easily and often identified in reports of whale entanglements, trends in the size of the areas most fished for Dungeness crab were assessed for each state. Specifically, statistically significant hot spots were identified within the footprint of the Dungeness crab fishery for each 4-month interval using the Getis-Ord Gi* criterion (Getis and Ord (1992); see Supplement: 1.3.2 for details) and the Hotspot Analysis tool in ArcGIS. Total area of these hot spots for each 4-month interval for each state were calculated, and the size of these areas was compared pre- and post-2014. A 2-tailed *t*-test with unequal variance was used to test for significance between the two time periods.

2.2.3 | Humpback whale distribution map

A habitat-based spatial model of humpback whales developed by Becker *et al*. (2016) was used to determine overlap of the four fixed-gear fisheries with prime whale habitat. The model predicts average whale density on a 0.05 degrees grid throughout the U.S. West Coast Exclusive Economic Zone (EEZ). Predictions are based on a variety of environmental covariates as well as line-transect whale survey data collected from June through November at two- to five-year intervals from 1991 to 2009. Although the timing of these surveys does not overlap with the entirety of the fishing season for all four fixed-gear fleets considered here, the high-density areas correspond to known, persistent feeding areas classified as Biologically Important Areas (Calambokidis *et al*., 2015), which are considered to represent areas where humpback whales are likely to occur. Grid cells from this model were classified into two density categories: high, defined as greater than two standard deviations above the mean, *sensu* Redfern *et al*. (2017), and low-to-medium (hereafter "low"), defined as less than two standard deviations above the mean.

2.2.4 | Spatio-temporal overlap of fishing with humpback whales

The degree of spatial overlap between fishing activity and humpback whales was estimated to evaluate the hypothesis that spatio-temporal changes in commercial fishing activity contributed to the increase in reporting of entangled whales that began in 2014. If changes in fishing activity were the predominant cause of the dramatic increase in whale entanglements that began around 2014, one would expect to see an increase in the overall magnitude and/or spatio-temporal distribution of commercial fishing activity within whale habitat. The landings informed VMS points for each of the four fisheries target groups were overlaid with the humpback whale distribution map and summarised in monthly time steps for both of the whale density categories (high and low). Years began in November instead of the conventional January of the standard Gregorian calendar to better synchronise with the 13 November start of the Dungeness crab fishing season on the U.S. West Coast. A two-way ANOVA was used (effects included fishery type, time period, pre- or post-2014 and state) to test for statistical significance of the difference in fishing activity overlap in the high-density humpback whale regions.

3 | RESULTS

3.1 | Entangled whale reports

3.1.1 | Descriptive statistics and general spatial patterns

Between 2009 and 2016, there were 187 confirmed reports of entangled whales off the U.S. West Coast: 109 humpback, 52 grey and 26 for all other species combined (unidentified = 11; blue = 4; fin = 5; killer = 2; minke = 2; sperm = 2, hereafter collectively "other"). The vast majority of the reports occurred in California (~85%), with Oregon and Washington each accounting for about 7.5% of all entangled whale reports (Figure 1 maps). Across all species and years, the type of gear involved in the entanglement was unknown in the majority of reports (~55%). For those reports where the gear type could be identified (~45% of all entangled whale reports), pot- and trap-based gear together (Dungeness, and other trap/pot) accounted for the majority (~71%) of the gear observed on entangled whales (Figure 1a-c). For humpback and the other whale species categories, Dungeness crab gear types were identified on entangled whales in 50 to 65% of the cases (Figure 1a,c).

3.1.2 | Annual entanglement by gear type, pre- and post-2014 and species

The analysis of whether annual entanglement reports differed among gear types, time periods or species (*glm*; Table S4) showed that the differences between time periods in annual entanglement reports were primarily due to an increase for humpback whales in 2014–2016 and that there were significant differences among gear types in the number of entangled whales reported across the full study period (Table S4). Comparing 2009–2013 with 2014–2016, mean annual reports of entangled humpback whales increased nearly 10-fold, from 3.4 to 30.7 (interaction term

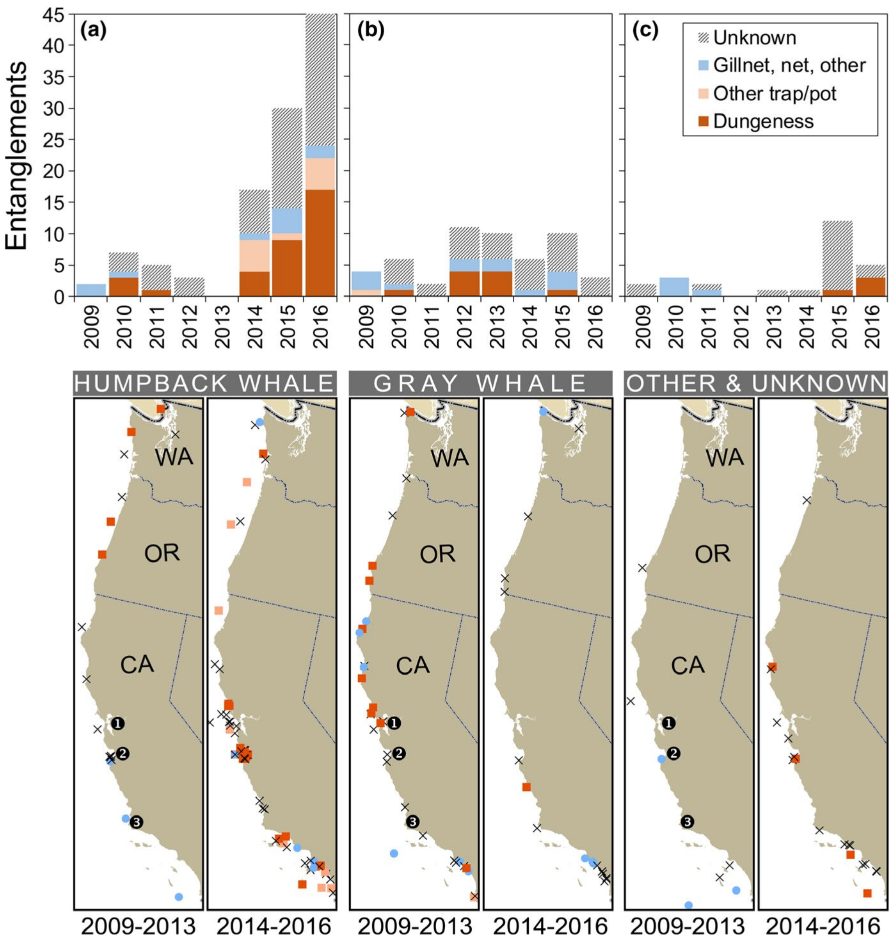

FIGURE 1 Cumulative annual number of confirmed entangled (a) humpback, (b) grey, and (c) all other whale species (including unidentified) reported on the west coast of the United States from 2009 to 2016 by gear type: Dungeness crab gear (dark orange); all other trap/pot gear (light orange) [sablefish, California spiny lobster and spot prawn]; gillnet, net or other gear (blue); and unknown or unidentified gear (hatched grey). For reference, maps below each figure indicate approximate locations along the U.S. West Coast where the entangled whales were observed, by gear and year range (2009-13 and 2014-16). Note, colours of site markers on maps correspond to plots, with Xs denoting unknown gear type. Circled numbers indicate geographic reference locations referred to in the results section, which include (1) San Francisco Bay; (2) Monterey Bay; and (3) Point Conception

between humpback and time period; Table S4). However, this change in annual entanglement reports between time periods was not evident for grey whales (mean 6.6 and 6.3) or the other whale species (mean 2.0 and 6.0) category considered. Across the full study period, annual entanglement reports were significantly higher for unknown gear than for pot- and trap-based gear, significantly higher for pot- and trap-based gear than for gillnet gear, and significantly higher for gillnet gear than for the other pot- and trap-based gear category (Table S4).

3.2 | Mapping fishing activity

3.2.1 | Representativeness of VMS data

From 2009 to 2016 for the fixed-gear fleets that targeted the four species analysed, there were 892,509 port-level landings records from 6,321 vessels. A total of 264,081 (29.59%) of those records came from 1221 (19.32%) boats equipped with VMS transponders. Across the four fisheries, the representativeness of fishing activity from vessels equipped with VMS varied considerably in terms of biomass landed and number of boats (Figure S1). The vast majority (>90%) of sablefish were landed from VMS equipped boats. For spot prawn, spiny lobster and Dungeness crab the representativeness ranged from 10 to 35% (Figure S1). With regard to vessel length, larger vessels were more likely to be equipped with VMS, so smaller vessels were usually under-represented (Figures S2–S4). Across seasons and fishing fleets, the proportion of vessels equipped with VMS transponders remained relatively constant from 2009 to 2016 (right side plots in Figures S2–S4). The exception was Washington spot prawn boats, where VMS coverage dropped essentially to zero starting in the 2012–13 season (Figures S3E,F), possibly because those few boats that had been fishing for spot prawn and were

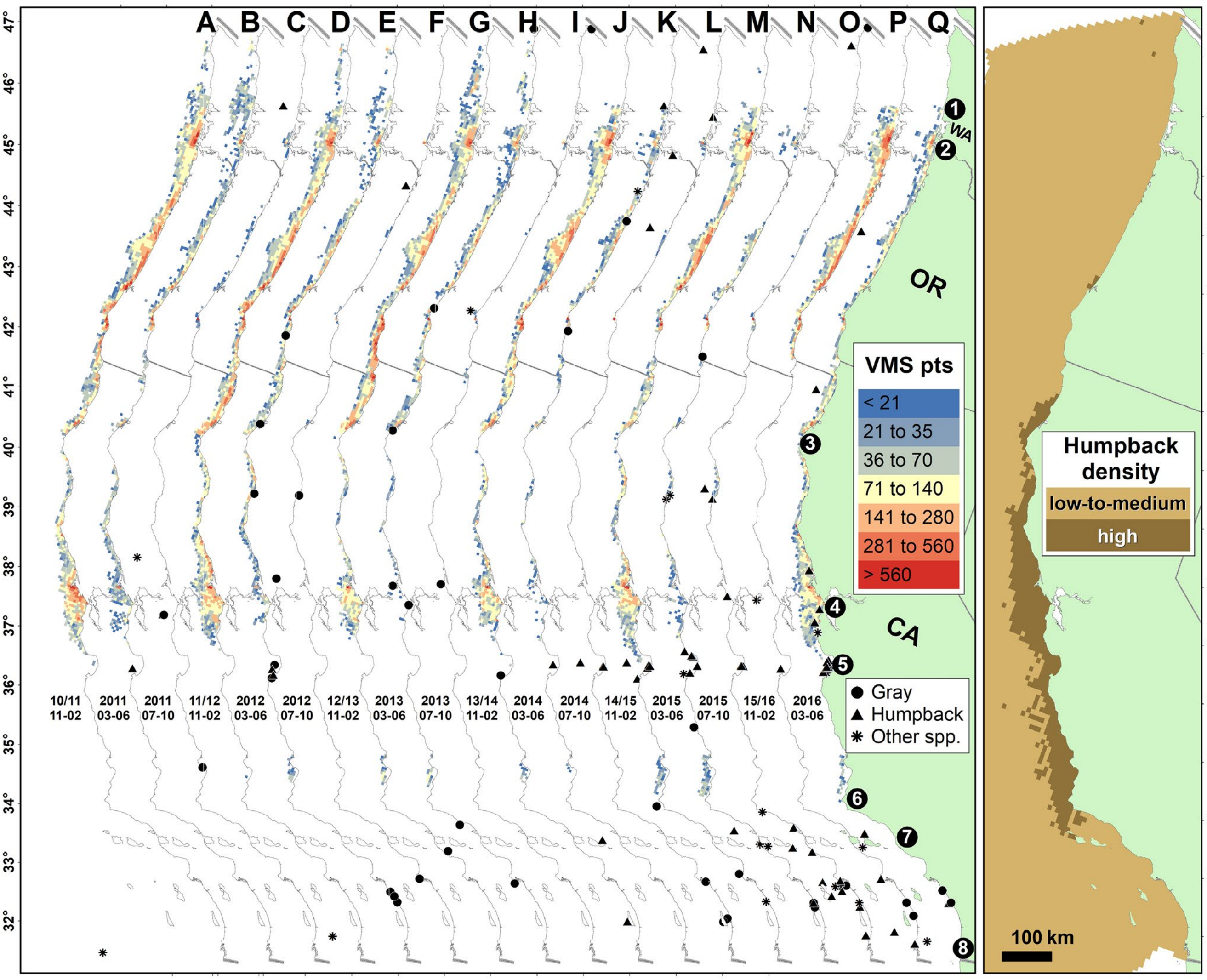

FIGURE 2 Spatial distribution of landings informed VMS data for vessels targeting Dungeness crab from November 2010 through June 2016, summarised in four-month intervals (maps A – Q). Map on far right illustrates the high and low-to-medium modelled humpback whale density regions used in the overlap analyses (from Becker *et al.*,2016). For reference, points are locations of confirmed reports of entangled whales within the corresponding four-month interval across all gear types. Circled numbers indicate geographic reference locations referred to in the results section, which include (1) Grays Harbor, (2) Columbia River, (3) Cape Mendocino, (4) San Francisco Bay, (5) Monterey Bay, (6) Point Conception, (7) Channel Islands and (8) San Diego

equipped with VMS transponders stopped fishing for spot prawn in Washington after the 2011–12 season, or they did not have their VMS transponders activated while fishing for spot prawn.

3.2.2 | Spatio-temporal patterns of fishing activity

The Dungeness crab fleet was the dominant fixed-gear fishery amongst the fleets that were analysed, in terms of biomass landed, number of vessels involved and total activity (Figure 2). From the beginning of the season in mid-November in any given year to February of the following year, activity was intense and nearly continuous across much of the west coast from Point Conception, California, to just north of Grays Harbor in Washington (Figure 2, maps A, D, G, etc.). Activity generally diminished from March through June each year, ceased completely by July off California, but continued at low levels in late spring and summer off the coasts of Oregon and Washington (Figure 2). Due to a domoic acid closure that delayed the 2015–16 crab season by up to 5 months in California, there was essentially no crab fishing from November 2015 through February 2016, a time period when the majority of crab fishing typically occurs (Figure 2, map P). Once the fishery eventually opened in California, there was anomalously high fishing activity from March through June 2016 (Figure 2, map Q).

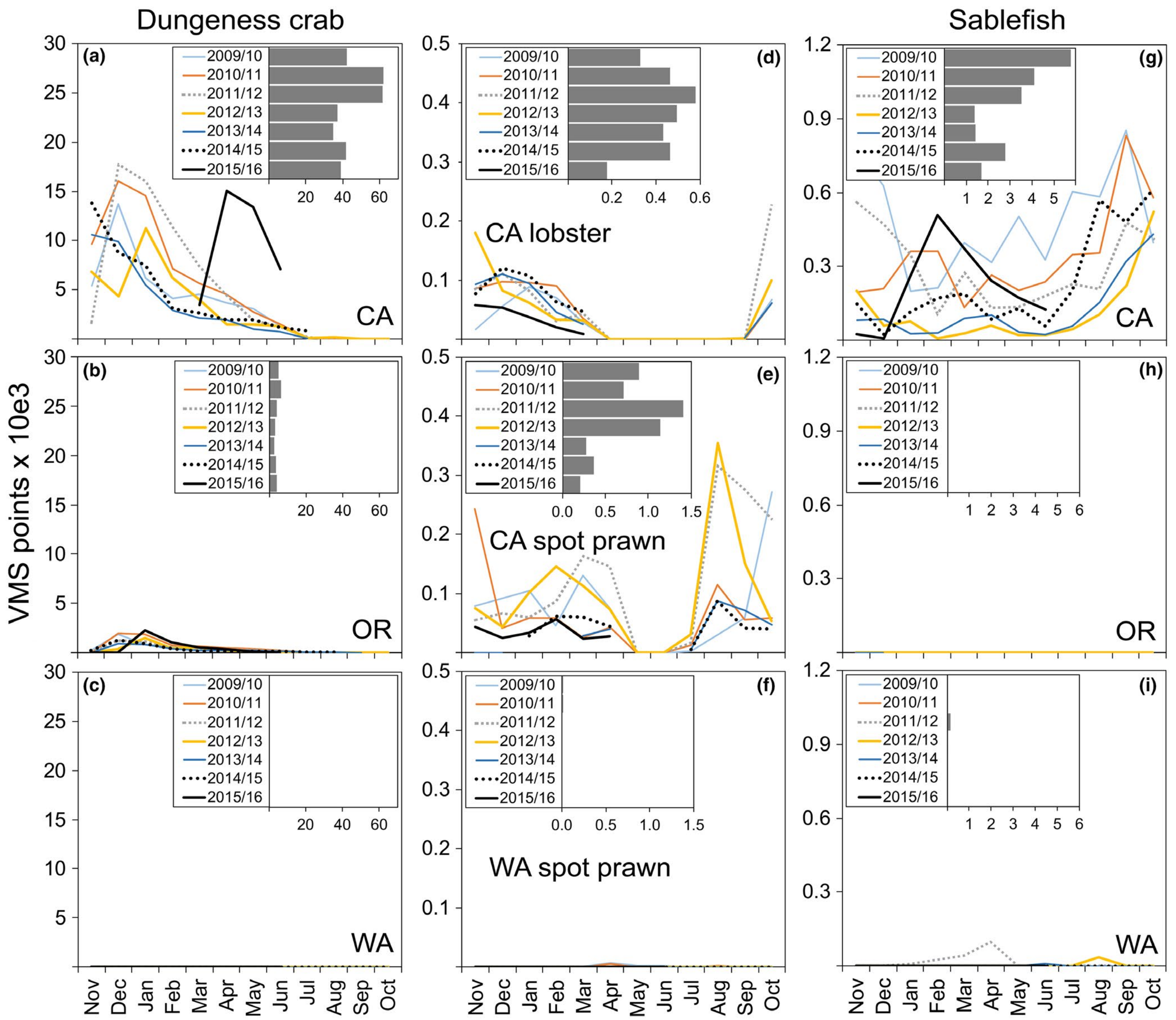

FIGURE 3 Cumulative monthly and annual (individual inset bar charts) landings informed VMS points that fell within high whale density regions (overlaid on humpback whale density map from Becker *et al.*,2016) for pot- and trap-based fisheries in Washington, Oregon and California from November 2009 to June 2016. (a) California Dungeness crab; (b) Oregon Dungeness crab; (c) Washington Dungeness crab*; (d) California spiny lobster; (e) California spot prawn; (f) Washington spot prawn*; (g) California sablefish; (h) Oregon sablefish*; and (I) Washington sablefish. *zero or negligible number of VMS points overlap in high humpback whale density regions for this fishery in this state

Based on the Dungeness crab hot spot mapping, the total area of the most intense fishing activity for pre-2014 (Nov 2009–Oct 2013) compared with post-2014 (Nov 2013–Jun 2016) decreased in California and Washington, and increased in Oregon. However, none of these changes in the total area of these hot spot patches were statistically significant (Table S5).

Spiny lobster fishing activity only occurred off the coast of southern California, concentrated primarily around the Channel Islands and San Diego (Figure S5). The fishery was most active from October of any given season through to the following February (Figure S5, maps A, D, G,). The fixed-gear based sablefish fishery was generally limited to a small region just south of Cape Mendocino, California, and in the vicinity of the Columbia River mouth at the border of Oregon and Washington (Figure S6). Unlike the Dungeness and spiny lobster fisheries, the sablefish fishery did not have as punctuated a season, so the patterns were more consistent over time (Figure S6). The spatial extent of the spot prawn fishery was extremely limited and the patchiest of all the fisheries examined, with most activity in the vicinity of the Channel Islands (results not shown due to data confidentiality restrictions).

3.2.3 | Spatio-temporal overlap of fishing with humpback whales

From 2009 to 2016, across all four fisheries operating within areas of both high and low humpback whale densities, there was considerable monthly variation of fishing activity within years (Figures 3 and 4 line

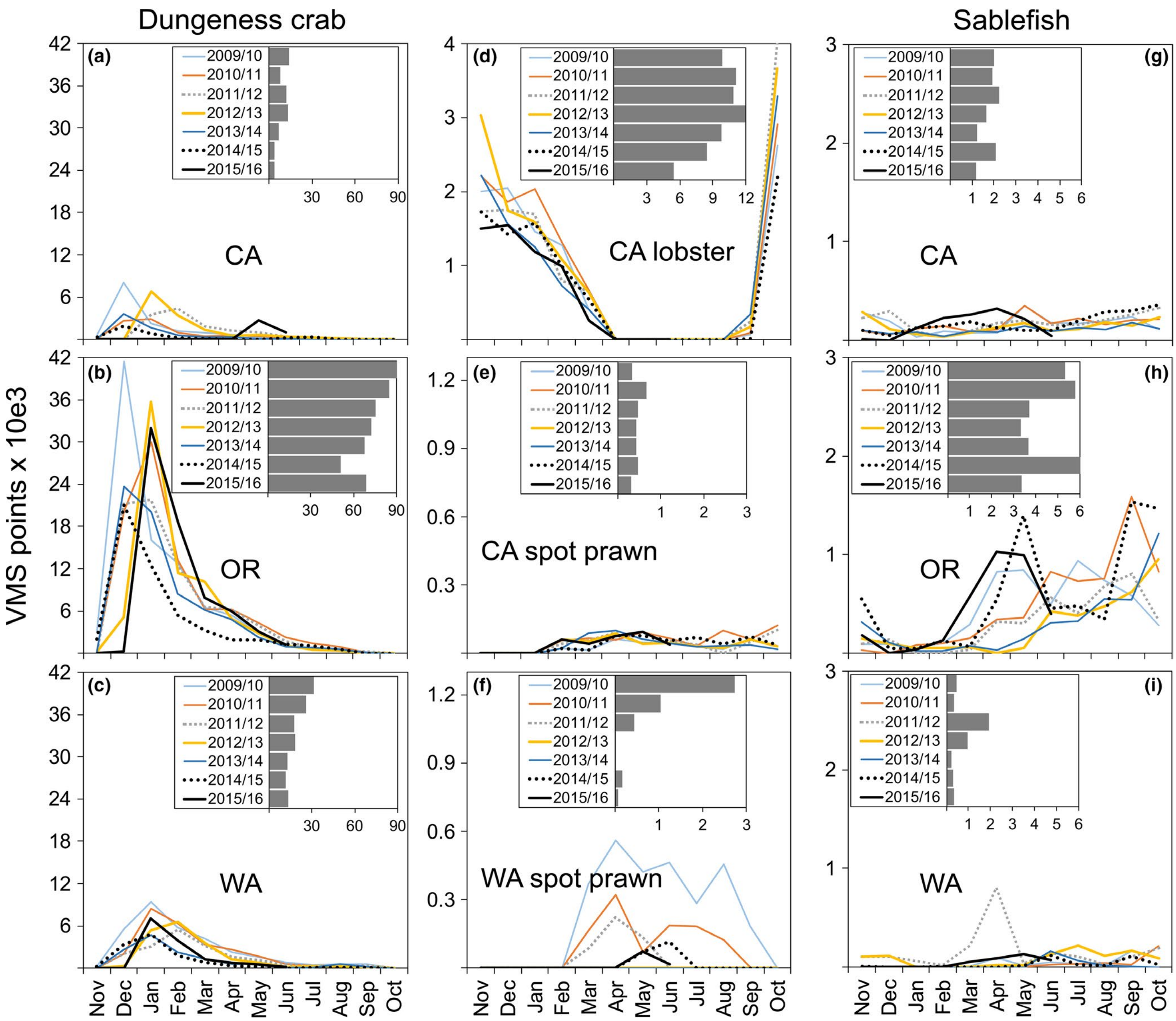

FIGURE 4 Cumulative monthly and annual (individual inset bar charts) landings informed VMS points that fell within low-to-medium whale density regions (overlaid on humpback whale density map from Becker *et al.*,2016) for pot- and trap-based fisheries in Washington, Oregon and California from November 2009 to June 2016. (a) California Dungeness crab; (b) Oregon Dungeness crab; (c) Washington Dungeness crab; (d) California spiny lobster; (e) California spot prawn; (f) Washington spot prawn; (g) California sablefish; (h) Oregon sablefish; and (i) Washington sablefish

plots). However, there was not an overall annual increase in activity that would be expected given the rise in humpback whale entanglements that began in 2014 (Figures 3 and 4 insets).

In the highest humpback density regions off the west coast, the Dungeness crab fishery was the most active of the four pot- and trap-based fisheries that were evaluated. Note scale of *y*-axis in Figures 3 and 4 compared with *y*-axis of other fixed-gear fisheries, and the scale of the *x*-axis in the horizontal bar chart insets. Nearly all of the Dungeness fishing activity that overlapped with the highest humpback density regions occurred off the coast of California (Figure 3a), with no overlap in Washington (Figure 3c) and minimal overlap in Oregon (Figure 3b). Overlap in low-density humpback whale regions in California was far less (Figure 4a).

There was a marked peak of fishing activity off California in both the high whale density (Figure 3a black monthly line, see also Figure 2 map Q) and low whale density regions (Figure 4a black monthly line). Owing to the 5-month domoic acid closure that occurred in the 2015–2016 Dungeness crab season, activity was ~5–7 times greater than mean levels for the months of April, May and June in high whale density regions. In the low whale density regions, May was the only month with above normal fishing activity (Figure 4a black monthly line). The vast majority of Dungeness crab fishing activity off the coasts of Washington and Oregon occurred in the low humpback density regions (Figure 4c,b, respectively). The Dungeness crab fishery off the coasts of Oregon and Washington did not have the same late season peak observed in California in either of the whale density regions (Oregon: Figures 3b and 4b black lines; Washington: Figures 3c and 4c black lines).

The vast majority of California spiny lobster fishing activity occurred in regions with low densities of humpback whales (Figures 3d and 4d). The spot prawn fishery had a relatively small footprint compared with Dungeness crab, where the majority of activity occurred in regions with high humpback whale density off the coast of California (Figure 3e), but fishing declined in this region over time (Figure 3e inset). There was no overlap with spot prawn within high-density humpback whale habitat in Washington (Figure 3f insets) and in low regions activity declined (Figure 4f inset). For the pot- and trap-based sablefish fishery most of the overlap in high humpback whale density regions occurred off California (Figure 3g), although activity diminished starting in 2012-13 (Figure 3g inset). There was no overlap and minimal overlap in Oregon (Figures 3h and 4h) and Washington (Figures 3i and 4i), respectively.

Pre- and post-2014 comparisons in high-density humpback whale habitats

While there was an anomalous uptick of Dungeness crab fishing activity that corresponded to the 5-month delay in the opening of the California crab season, there was no statistically significant increase in fishing activity before and after 2014 in high-density whale regions (Table S6). Based on the 2-way ANOVA of pre- and post-2014 fishing activity in high-density whale regions for each state, there was a decrease in overall fishing activity (Table S6). However, this decrease was only statistically significant for the spot prawn and sablefish fisheries in California (Table S6).

4 | DISCUSSION

Fisheries interactions with protected species are a chronic problem globally and a central issue related to conservation, particularly for marine mammals (Read, 2008; Reeves *et al*., 2013; Smith *et al*., 2014). Whale entanglements in fishing gear, in particular, generate a large amount of public interest and concern, along with raising issues in the United States surrounding management of the problem under the Endangered Species Act (ESA, 1972) and Marine Mammal Protection Act (MMPA, 1972). The substantial rise in entanglements on the U.S. West Coast in recent years may involve a number of factors, including changes in oceanographic conditions that compressed the humpback whale prey field closer to shore, concentrating the whales in closer proximity to pot- and trap-based fleets (Santora *et al*., 2020). Prior to this study, however, the spatial dynamics of changes in fishing activities that may have increased the likelihood of entanglements had not been quantified. Here, these analyses add to an understanding of this environmental problem by characterising the spatio-temporal dynamics of pot- and trap-based fishing fleets operating off the U.S. West Coast on how those patterns have contributed to the whale entanglement phenomenon.

Based on the analyses of four commercial pot- and trap-based fisheries from 2009 through 2016, there were no increases in fishing activity in areas with historically high mean annual whale densities, or increased fishing in general, that could explain the dramatic increase in entangled whale reporting that occurred starting around 2014. However, there was anomalously high Dungeness crab fishing activity in spring of the 2015–2016 season. This was caused by a delay in the opening of the fishery as a result of persistent elevated domoic acid concentrations in crab viscera, a consequence of a massive harmful algal bloom (Moore *et al*., 2019). This anomalously high Dungeness crab fishing activity in California in the spring of 2016 likely placed crab fishing gear in the same place at the same time with foraging humpback whales that had returned from their winter breeding areas off Mexico and Central America. In all other years, the majority of Dungeness crab fishing was typically completed well before the arrival of humpback whales in the system, which generally occurs in spring (Calambokidis *et al*., 2000).

In 2014–2015, there were no dramatic increases in fishery activity for pot- and trap-based gear, which suggests that large whales moved into closer proximity to long-standing fisheries footprints. Evidence to date suggests that a marine heat wave that persisted from 2014 through mid-2016 compressed humpback whale habitat (Di Lorenzo and Mantua, 2016; Hobday *et al*., 2018). A key consequence of this anomalous warming was that total biomass of the prey field available to humpback whales was reduced and what remained was limited to nearshore regions (Santora *et al*., 2020). These insights about changing whale distributions provide a more complete picture of the impacts of fishing on whale entanglement. They also highlight a drawback of the static models of humpback whale distributions that were analysed here, which represent average long-term foraging areas. Future analyses that incorporate dynamic whale distribution models will more accurately reflect spatio-temporal patterns of whale distributions, and could perhaps even use near real-time environmental data such as remotely sensed sea surface temperature and chlorophyll to better understand overlap with fishing activity (Maxwell *et al.*, 2015).

There were at least two limitations to this study that warrant discussion. First, the coarse temporal grain (locations every 30 to 60 min) of the VMS data presents challenges to identifying accurately where pot- and trap-based gear was deployed. The use of depth filters helps to refine estimates, but vessel speed filters may not be as effective as they are for vessels deploying more speed sensitive fishing gear such as bottom- and mid-water trawl nets (Jennings and Lee, 2012; Charles *et al.*, 2014). Pot- and trap-based fishing fleets generally deploy their gear at rapid speeds, and slow to retrieve gear. However, they do not reduce their speed for hours at a time, as trawl-based vessels do, so detecting active fishing locations is not as accurate. Despite the approach used for filtering out VMS points that did not represent active fishing, these methods are in line with previous studies, so they likely afford a reasonable estimate of fishing activity (Mullowney and Dawe, 2009; Charles *et al.*, 2014).

Second, given VMS transponders are not present on all fishing vessels (with the exception of the sablefish boats), these analyses and conclusions therein regarding where and when fishing is occurring are based on a sub-sample of vessels that fish for the respective fish species. Further, there is likely a bias in this sub-sample, given VMS transponders are more prevalent on larger vessels. Thus, these analyses based on the landings informed VMS data likely adequately represent the patterns of larger vessels, while under-represent the behaviour and influence of smaller vessels.

While the present analyses were mainly focused on contemporaneous overlap between fishing activity and entanglement sightings, there may also be lagged impacts of fisheries on whales due to derelict gear. Derelict fishing gear poses a chronic threat to marine organisms, including cetaceans, that persists even after active fishing has ceased and may be increasing in magnitude over time (Arthur *et al.* (2014); Stelfox *et al.* (2016); Richardson *et al.* (2019), but see Asmutis-Silvia *et al.* (2017) and Stelfox (2017)). On the west coast of the United States, there are approximately 400,000 Dungeness crab traps fished each year and the annual loss rate is estimated to be up to 10% (Pacific Fishery Management Council, 2013). Indeed, within the whale entanglement data analysed in this paper, there was at least one entangled whale report where derelict gear was the known source and the buoy tags from the gear were two to three years old (Saez *et al.*, 2020). To worsen the problem, fishing gear can become entangled with other gear, which increases the probability that the gear becomes lost and irretrievable (see Gilman, 2015). While it does not appear that the majority of entanglements with whales involve derelict gear, mapping out fishing activity, as has been done in these analyses, is also useful for developing risk management plans with regard to entanglement with derelict gear (Brown and Niedzwecki, 2020).

4.1 | The future for reducing the risk of whale entanglement

Identifying where and when threats and stressors to a given species occur is a critical first step in assessing the overall risk a given perturbation poses (Halpern *et al.*, 2008). Whale entanglement with commercial fishing gear is a global problem that poses a significant risk to populations (Read *et al.*, 2006; Smith *et al.*, 2014; Kraus *et al.*, 2016). Minimising the risk of entanglements to ensure compliance with conservation laws and also sustaining thriving fisheries is a complex balancing act that requires the involvement of stakeholders, close integration between managers and researchers, a robust framework for incorporating new information and adaptive management (Borggaard *et al.*, 2017). Future research can build upon the results from these analyses by explicitly incorporating the overlap or exposure between the threat and the target species and assessing the consequences of the stressor to the target organism. Output from these analyses could be used for spatial planning directed at strategic areas where cetaceans are most likely to experience entanglement with fishing gear, which would provide insight at finer spatial and temporal scales into how management measures will influence not only risk of entanglement for whales, but also economic impacts on fishing fleets. Finally, efforts to incorporate emerging technologies (Bradley *et al.*, 2019), as well as dynamic, near real-time forecasts of large whale distributions, fishery target species (sensu Kaplan *et al.* (2016)) and harmful algal blooms (Smith *et al.*, 2018; Trainer *et al.*, 2019) would greatly enhance the utility of risk assessments by arming managers with multiple management options before environmental conditions have precipitated a fishing closure.

The patterns that were observed in this study add to a growing body of evidence related to bycatch of protected species in otherwise sustainable fisheries (e.g. North Atlantic right whales and lobster fisheries off the U.S. East Coast, (Borggaard *et al.*, 2017; Ingeman *et al.*, 2019)) and demonstrate the importance of developing novel methods to model spatio-temporal fishing activity using existing data sources and analyses in order to reduce human–wildlife conflict in the ocean (Guerra, 2019). And the techniques for generating time-series maps of fishing activity using existing remote sensed and landings data are critical for managing fisheries that pose risk to other marine organisms. Developing a risk assessment of whale entanglement with commercial fishing gear on the west coast that also incorporates human social or economic components could give resource managers a richer tool set for managing this phenomenon. Therefore, analyses that consider approaches to simultaneously minimise risk to whales and economic vulnerability of commercial fishermen may help to find a more forward-looking, long-term solution to continue the recoveries of protected cetaceans and sustain fisheries. Beyond the

U.S. West Coast, integrative studies that seek to understand the causes and consequences of climate-driven distributional changes in bycatch species and fisheries, and evaluate trade-offs associated with alternative management measures intended to mitigate negative consequences for fisheries species, protected species and dependent human communities, will help to create fisheries that are more climate-ready in the face of continued change (Wilson *et al*., 2018; Holsman *et al*., 2019).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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