Supporting Information

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

Supplementary methods

Fishing data

To fully account for effort off Oregon's north coast and eliminate any double counting of multi-state permitted vessels that fish off Oregon and land crab into both Washington and Oregon states, the logbooks from both states were combined and processed together beforehand. California fishermen are not required to submit logbooks, therefore the fishing effort of multi-state permitted vessels fishing off Oregon but exclusively landing their catch only into California ports were not accounted for in this study. From the combined Washington and Oregon logbook dataset, we selected records with fishing locations off Oregon, between 46.25° and 42.0° N latitude.

Logbook data is self-reported by fishing vessel captains, and we used several data quality filters to remove incomplete or inaccurate data. We developed data quality filters by examining raw data distributions and consulting with fishery participants to identify values likely to be outside the range of common fishing practices. Series of individual pots are generally set in a line, frequently along a depth contour, which is termed a "string". Each string constitutes a logbook record, with information including but not limited to the vessel, date, depth, soak time, number of pots pulled, and start and end location. We removed all records with missing or incomplete data on location, pot pulls, date, port, or vessel identification. We also removed records with grossly inaccurate location data (e.g., points on land or beyond depth range of fishery), more than 160 pots pulls, the same start and end location, or a distance greater than 28 km between the start and end locations. We retained records with incomplete or inaccurate depth or soak time as these fields were not ultimately used for estimates. Applying these data quality filters retained 92% of the raw data.

After filtering for data quality, 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, to generate estimates of the number of pots in the water for each 5 km grid cell for vessels that appeared in the logbook data.

To estimate the maximum potential number of pots per grid cell from logbook data that is incomplete due to 30% subsampling for data entry in seasons 2011-12 through 2017-18, non-compliance (landings with no logbook submitted), and logbook records missing critical data fields, we took a series of steps. First, for each year x month, we divided the sum of pot limits across vessels represented in the processed logbook data by the sum of pot limits across vessels that made a landing to derive the percentage of potential pots represented in logbook data. The estimates of pots per grid cell from logbook data were then divided by this percentage for each year x month x 5 km grid cell to scale estimates to the total potential pots deployed:

$$Number\ of\ pots\ deployed = \frac{z}{m/n}$$

Where z is the sum of pots allocated to a grid cell for vessels represented in logbook data, m is sum of pot limits for vessels represented in the logbook data, and n is the sum of pot limits for all vessels that made a landing.

This approach accounts for logbook data that is incomplete from any season for any of the reasons described above. The robustness of this approach is based on a few assumptions, including that any time a vessel has made a landing within a year x month: 1) the vessel's entire pot limit (200, 300, or 500 pots) was deployed in the water for the entire month, 2) the vessel's pot limit is distributed spatially in proportion to pot pulls, and 3) the spatial distribution of pot limits for vessels that are not represented in the logbook is the same as for vessels that are. Crab fishing season openings are variable and can occur at any point within a month from December 1 to February 15. In addition, the start of fishing is sometimes voluntarily delayed beyond the regulatory opening while a starting price is negotiated between harvesters and buyers. Months that were closed to fishing or fishing did not start due to negotiations for price for more than 15 days were removed from the analysis.

Whale data

Using the year-round rorqual whale models from Derville *et al.*, (2022), we hindcasted rorqual densities by month x year over layers of 5 km resolution matching the fishing layers. This resolution was selected by *Derville et al.,* (2022) as the optimal trade-off between high spatial resolution appropriate for management of nearshore fisheries and the coarser resolution at which certain important environmental variables could be acquired as well as the spatial scale at which transects were surveyed. Densities in the most nearshore grid cells were corrected by the proportion of the cell surface covered by land. Moreover, predictions were limited to the continental shelf where crab fishing occurs (coastline out to 1500 m of depth) and to waters displaying environmental conditions analogous to those in which the models were trained. We used the Extrapolation Detection (ExDet) tool developed by (Mesgaran, Cousens, & Webber, 2014) to evaluate this environmental extrapolation over the weekly layers of environmental variables on which the whale predictions were based. ExDet was computed with the *dsmextra* R package (version 1.1.5; Bouchet et al., 2020) to detect type 1 novelty (ExDet < 0 occurring when at least one variable is outside the univariate range of reference data) and type 2 novelty (ExDet > 1 occurring when variables are within the univariate range of reference but display non analogous combinations). ExDet was computed on a subset of the most influential environmental variables contributing to each of the three rorqual whale seasonal models: depth, sea surface temperature, sea surface height standard deviation, wind stress curl and isothermal layer depth for the spring model (Apr-Jul); depth, sea surface temperature, sea surface height standard deviation, bulk buoyancy frequency and isothermal layer depth for the summer model (Aug-Nov) and depth, sea surface height and sea surface height standard deviation for the winter model (Dec-Mar).

Climate and upwelling drivers

Monthly Darwin SOI standardized data was provided by the Climate Analysis Section, NCAR, Boulder, USA, Trenberth (1984, https://climatedataguide.ucar.edu/climate-data/southern-oscillation-indices-signal-noise-and-tahitidarwin-slp-soi, updated regularly, accessed 21-Jan-2022). Monthly PDO data was provided by the NOAA National Centers for Environmental Information (https://www.ncdc.noaa.gov/ teleconnections/pdo/, accessed 21-Jan-2022).

CUTI provides estimates of vertical transport (in m2.s-1), as the total volume of water upwelled and downwelled in a given time period in 1° latitudinal bins extending 75 km offshore. Compared to the Bakun Upwelling index, CUTI incorporates improved estimates of the Ekman transport and accounts for cross-shore geostrophic flow related to the sea surface height alongshore gradient. CUTI was downloaded from https://mjacox.com/upwelling-indices/ (accessed 22-Feb-2022) at daily and monthly scales, at latitude 43°N (south zone), 44°N and 45°N (averaged together in the central zone), and 46°N (north zone).

References

Bouchet, P. J., Miller, D. L., Roberts, J. J., Mannocci, L., Harris, C. M., & Thomas, L. (2020). dsmextra: Extrapolation assessment tools for density surface models. Methods in Ecology and Evolution, 11(11), 1464–1469. doi:10.1111/2041-210X.13469

Derville, S., Barlow, D. R., Hayslip, C. E., & Torres, L. G. (2022). Seasonal, Annual, and Decadal Distribution of Three Rorqual Whale Species Relative to Dynamic Ocean Conditions Off Oregon, USA. Frontiers in Marine Science, 9, 1–19. doi:10.3389/fmars.2022.868566

Mesgaran, M. B., Cousens, R. D., & Webber, B. L. (2014). Here be dragons: A tool for quantifying novelty due to covariate range and correlation change when projecting species distribution models. Diversity and Distributions, 20(10), 1147–1159. doi:10.1111/ddi.12209

Supplementary figures

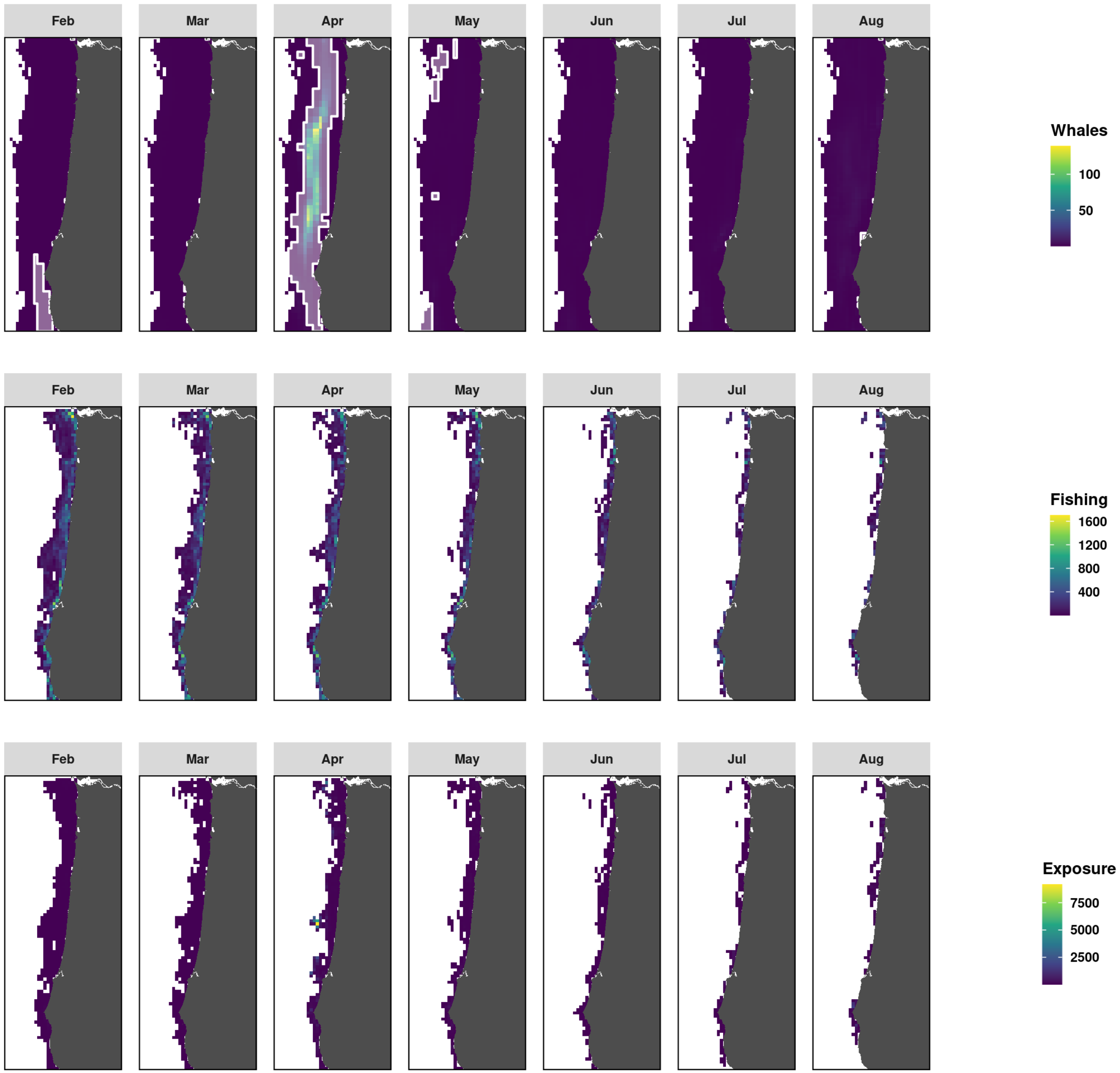

Figure S1: Monthly spatial layers for crab season 2010-2011. A) Whale densities in number of whales predicted by 5 x 5 km grid cell overlayed with white polygons representing the areas of extrapolation. B) Commercial Dungeness crab fishing effort. C) Exposure to entanglement risk.

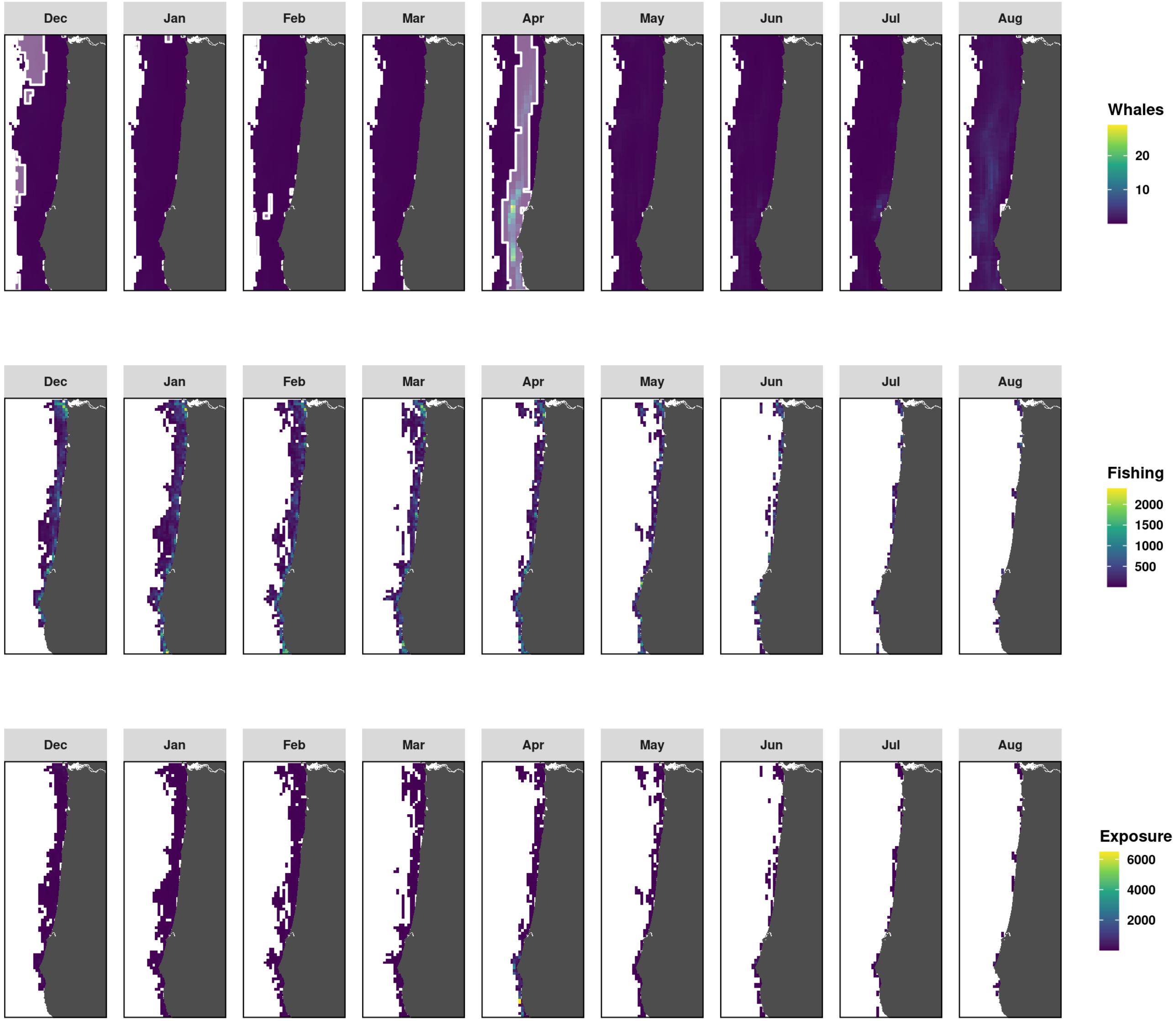

Figure S2: Monthly spatial layers for crab season 2011-2012. A) Whale densities in number of whales predicted by 5 x 5 km grid cell overlayed with white polygons representing the areas of extrapolation. B) Commercial Dungeness crab fishing effort. C) Exposure to entanglement risk.

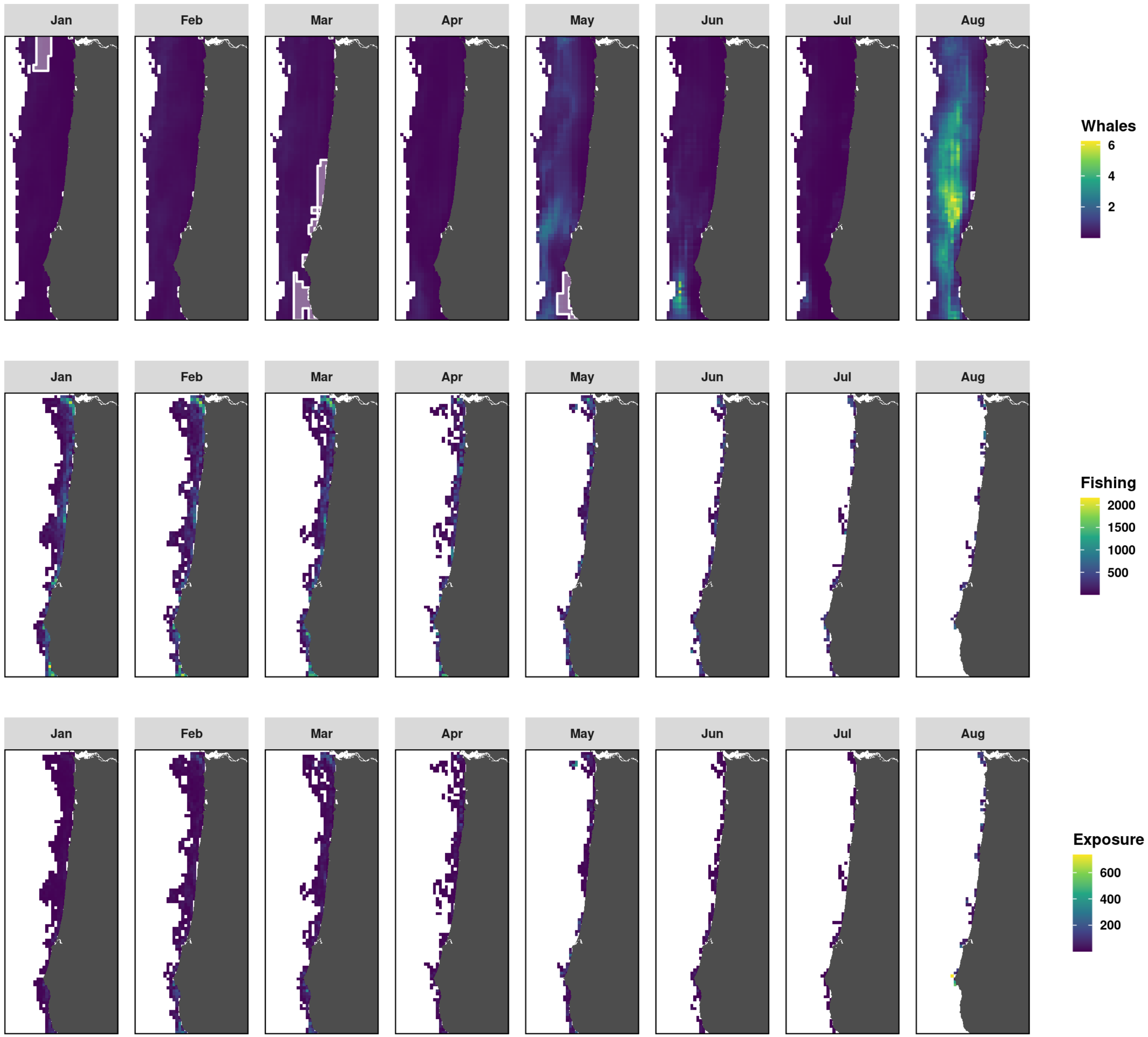

Figure S3: Monthly spatial layers for crab season 2012-2013. A) Whale densities in number of whales predicted by 5 x 5 km grid cell overlayed with white polygons representing the areas of extrapolation. B) Commercial Dungeness crab fishing effort. C) Exposure to entanglement risk.

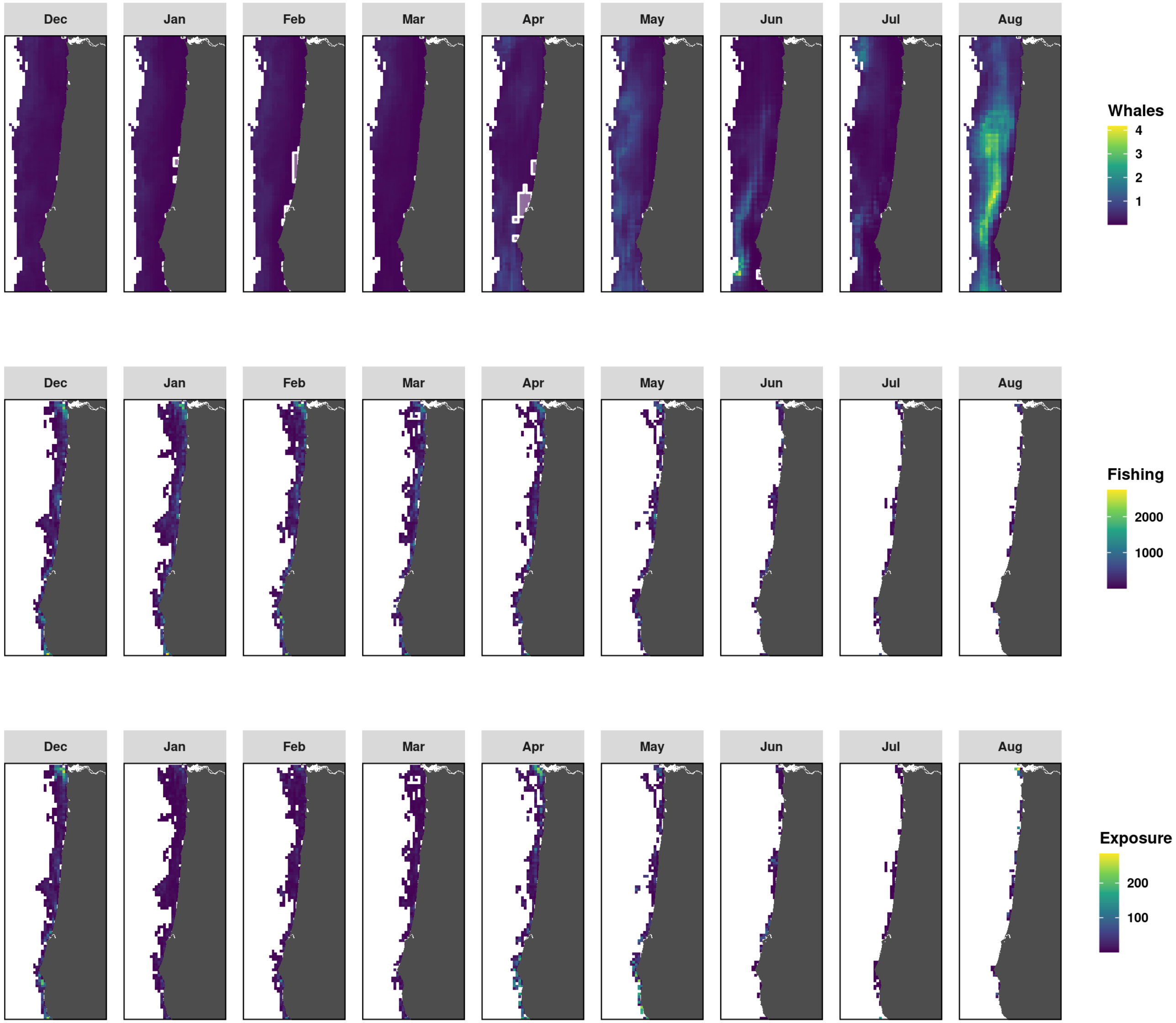

Figure S4: Monthly spatial layers for crab season 2013-2014. A) Whale densities in number of whales predicted by 5 x 5 km grid cell overlayed with white polygons representing the areas of extrapolation. B) Commercial Dungeness crab fishing effort. C) Exposure to entanglement risk.

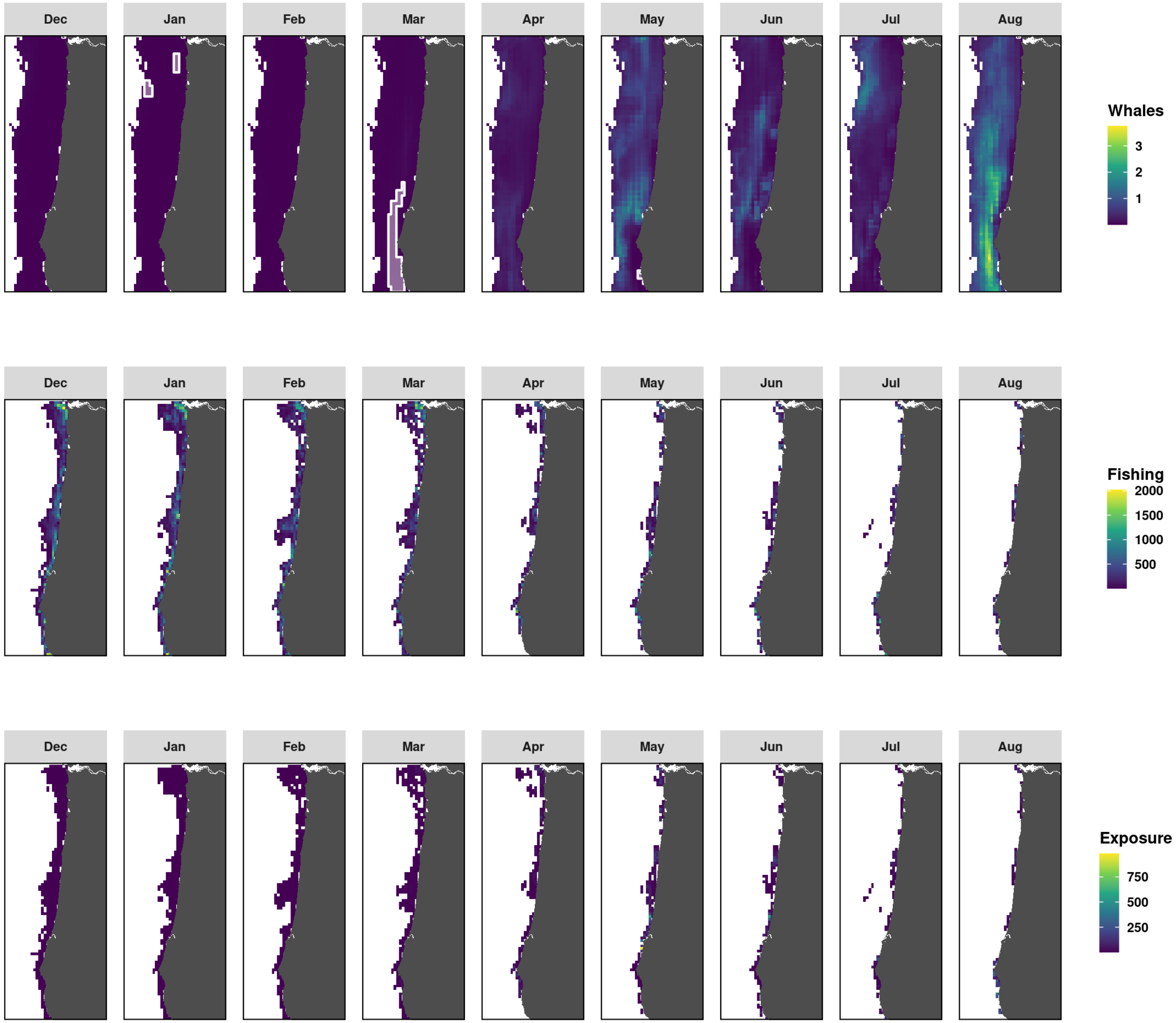

Figure S5: Monthly spatial layers for crab season 2014-2015. A) Whale densities in number of whales predicted by 5 x 5 km grid cell overlayed with white polygons representing the areas of extrapolation. B) Commercial Dungeness crab fishing effort. C) Exposure to entanglement risk.

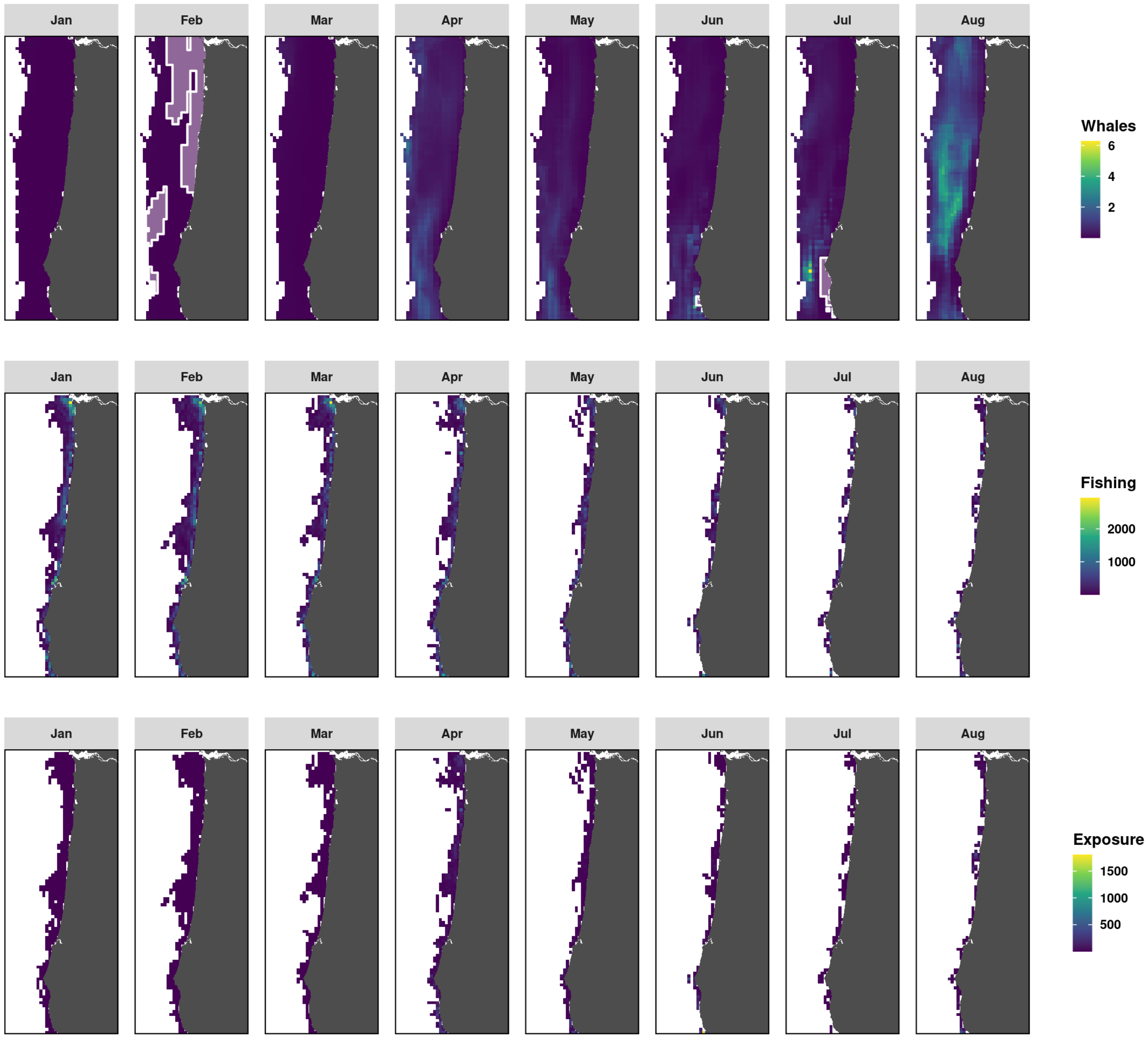

Figure S6: Monthly spatial layers for crab season 2015-2016. A) Whale densities in number of whales predicted by 5 x 5 km grid cell overlayed with white polygons representing the areas of extrapolation. B) Commercial Dungeness crab fishing effort. C) Exposure to entanglement risk.

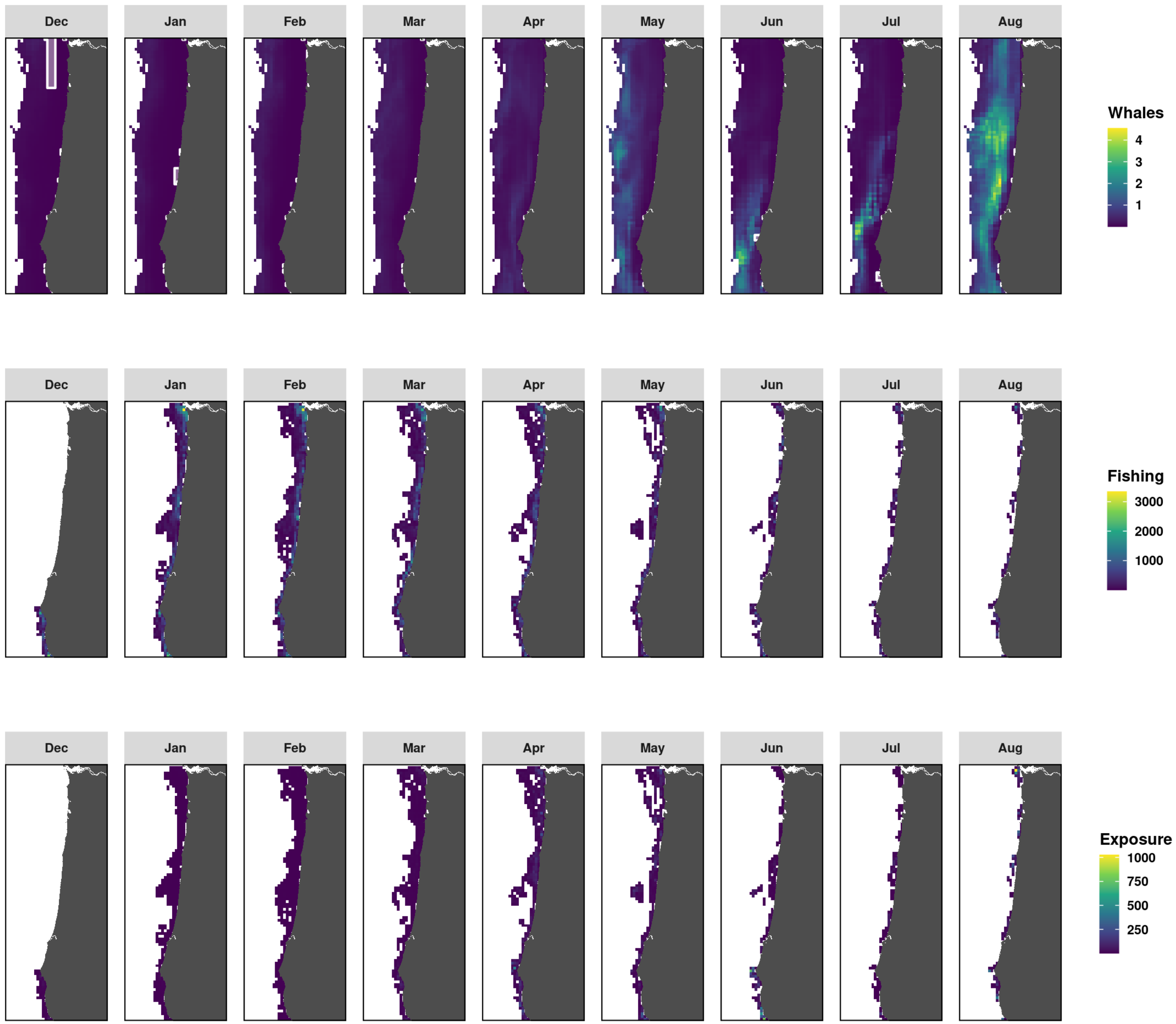

Figure S7: Monthly spatial layers for crab season 2016-2017. A) Whale densities in number of whales predicted by 5 x 5 km grid cell overlayed with white polygons representing the areas of extrapolation. B) Commercial Dungeness crab fishing effort. C) Exposure to entanglement risk.

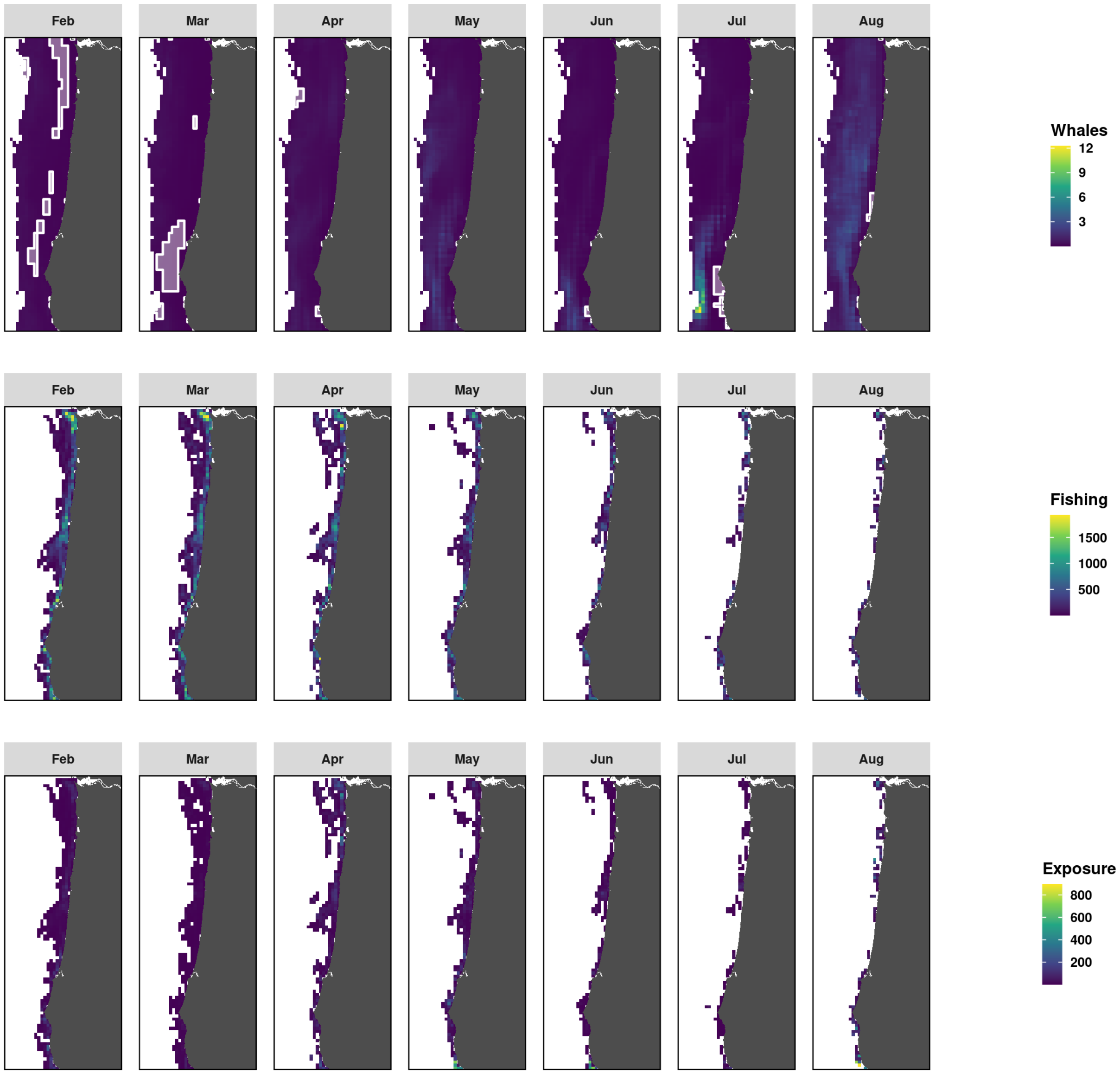

Figure S8: Monthly spatial layers for crab season 2017-2018. A) Whale densities in number of whales predicted by 5 x 5 km grid cell overlayed with white polygons representing the areas of extrapolation. B) Commercial Dungeness crab fishing effort. C) Exposure to entanglement risk.

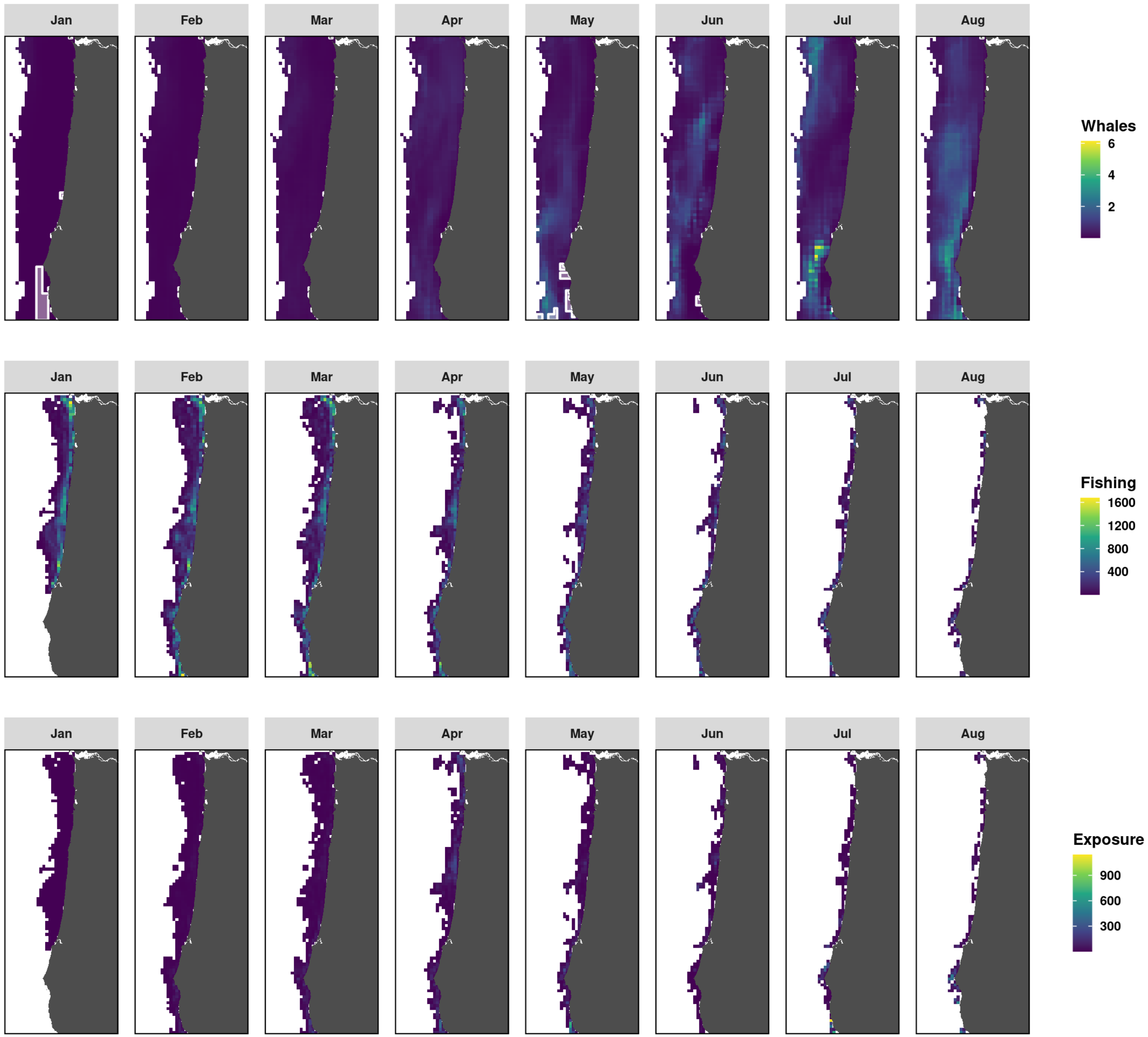

Figure S9: Monthly spatial layers for crab season 2018-2019. A) Whale densities in number of whales predicted by 5 x 5 km grid cell overlayed with white polygons representing the areas of extrapolation. B) Commercial Dungeness crab fishing effort. C) Exposure to entanglement risk.

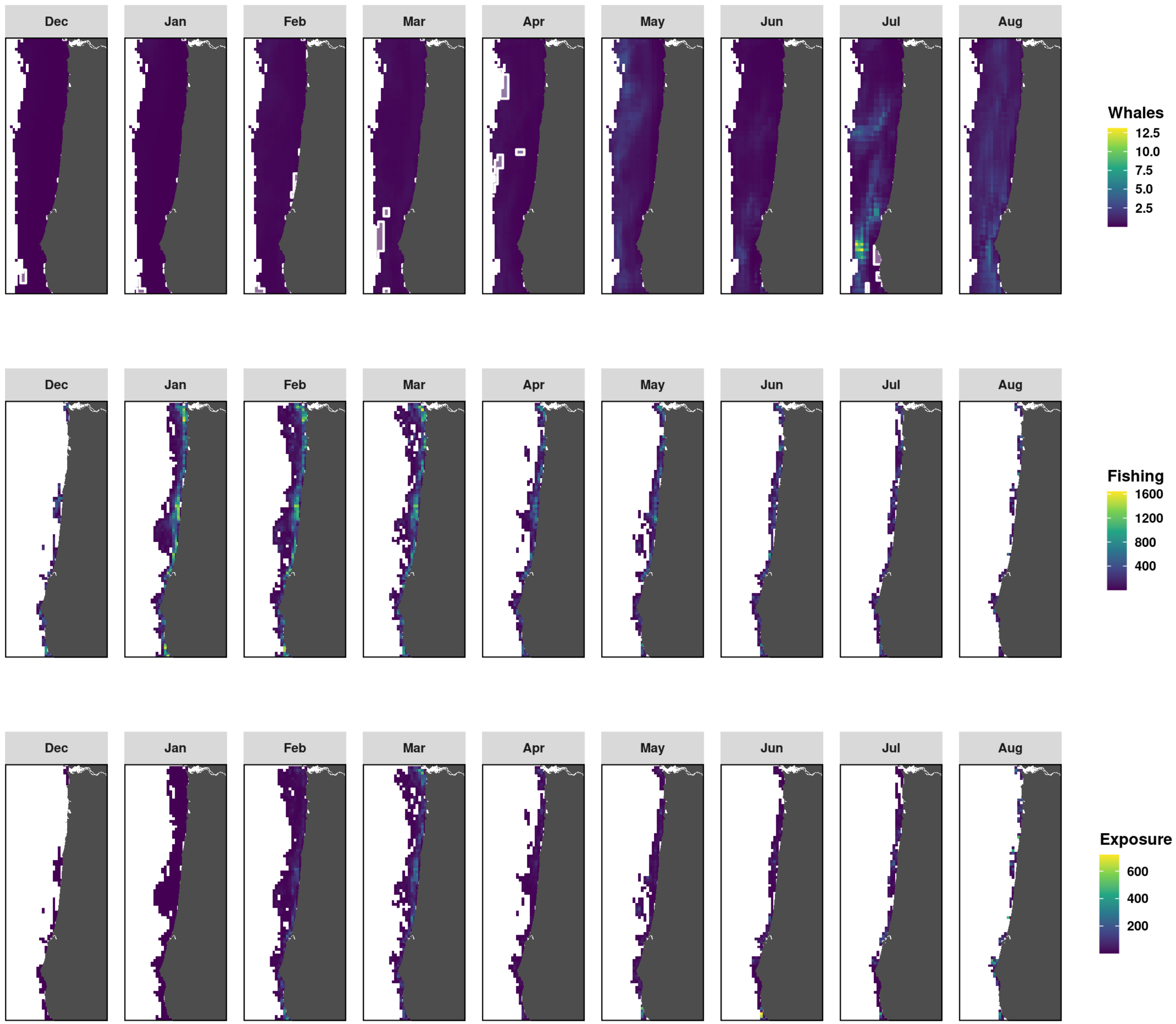

Figure S10: Monthly spatial layers for crab season 2019-2020. A) Whale densities in number of whales predicted by 5 x 5 km grid cell overlayed with white polygons representing the areas of extrapolation. B) Commercial Dungeness crab fishing effort. C) Exposure to entanglement risk.

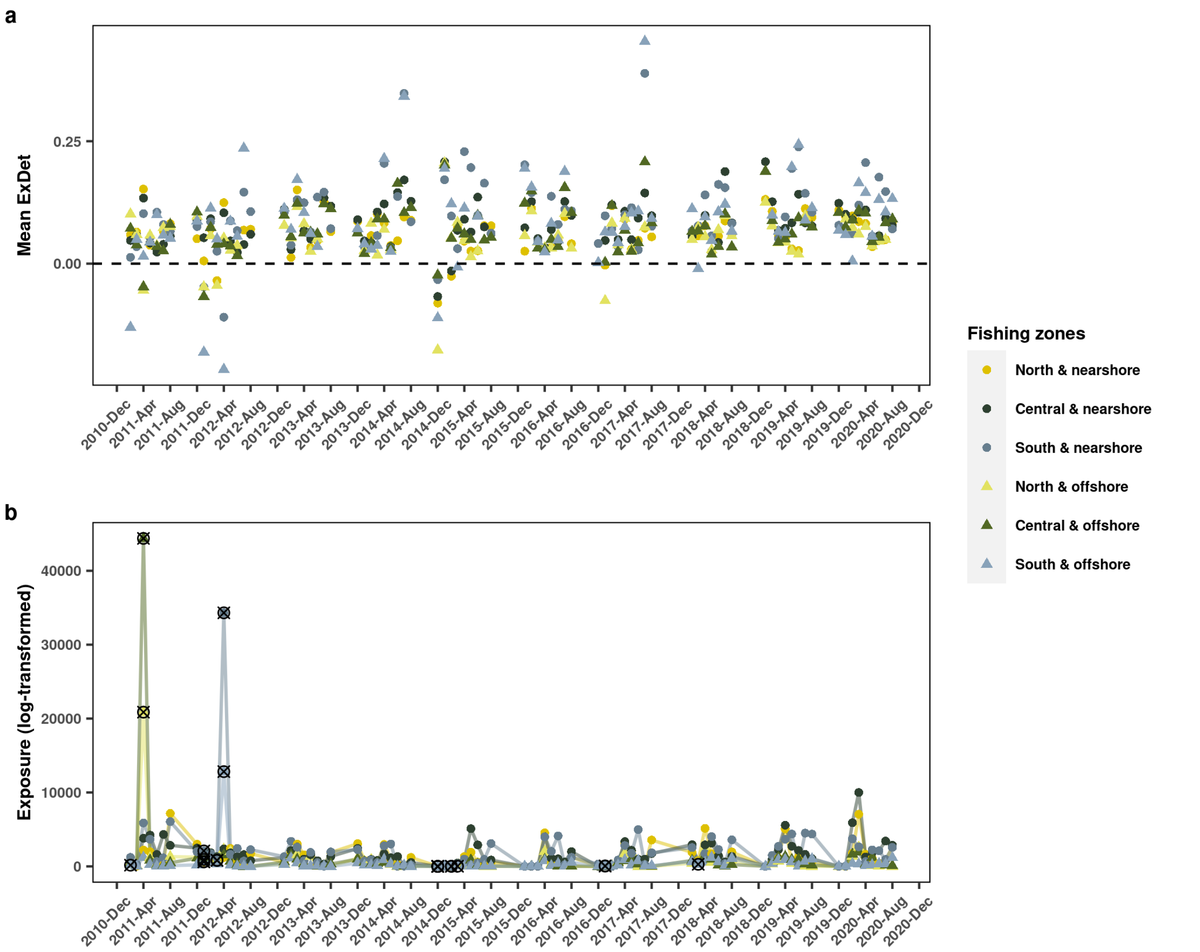

Figure S11: a) Mean ExDet (Extrapolation Detection) per fishing zone x month. ExDet below the dashed line indicate that whale density would be predicted in non-analogous conditions. B) Mean exposure per fishing zone x month. Black crosses (n = 23) indicate zones x month combinations that were removed prior to modeling the variations of exposure to avoid extrapolation of whale densities to non-analogous conditions. Note that removing the zones x month where extrapolation occurred resulted in filtering out some anomalously high exposure values (e.g., April 2011, April 2012).

Supplementary tables

Table S1: Description of confirmed entanglement events involving humpback whales and Oregon Dungeness crab fishing gear when the general area of gear set location was estimated from interviews with gear owners. Data provided by NMFS WCR, April 2021. Report locations: WA = Washington, CA = California, MX = Mexico.

Report year	Report month	Report location	Crab season gear set	Estimated gear set location off oregon	Estimated gear set depth
2014	5	WA	2013-2014	Just south of the Columbia River	30-40 fathoms
2015	7	CA	2014-2015	Off Cape Meares	20 fathoms
2019	4	MX	2018-2019	Around Coos Bay	>50 fathoms
2020	6	CA	2019-2020	Just south of Florence	95 fathoms