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A framework to evaluate dynamic social and ecological interactions between offshore wind energy development and commercial fisheries in a changing climate: A US West Coast perspective

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Abstract

Offshore wind energy (OWE) planning is occurring alongside efforts to understand the potential effects of long-term environmental variability and climate change on social-ecological systems. To minimize potential conflicts between current and new ocean-use sectors, there is a need to identify tradeoffs between OWE development and other ocean users under dynamic environmental conditions. Here, we present a framework for evaluating the risk of groundfish fisheries being displaced from traditional fishing grounds by the designation of proposed OWE areas (OWEAs) and how risk may be affected by climate change impacts on targeted species. Specifically, we use fishery-dependent catch data from three groundfish fisheries to derive annual fishing “footprints” for port groups along the U.S. West Coast (1994–2020). We calculate the historical risk of these fleets being displaced from fishing grounds that have been proposed as sites for OWE development using an exposure-vulnerability framework. Risk varies across fishing fleets, but generally corresponds to a fleet’s target species and distance to proposed OWEAs. We then use existing climate-driven projections to map the spatial distribution of targeted species biomass for each of the three fisheries from 2020 to 2100. In some cases, future target species biomass indices have higher predicted values inside proposed OWEAs compared to outside OWEAs, indicating that incorporating climate change impacts may increase the

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perceived risk of displacement for these fleets. These results indicate that tradeoffs between commercial fishing and OWE development will not be fully understood unless the effects of climate change are incorporated into marine spatial planning and efforts to develop appropriately scaled mitigation measures.

Introduction

Climate change is impacting the structure, function, and economies of social-ecological systems across the globe (e.g., [1–3]). Current and predicted impacts include changes to atmospheric, terrestrial and oceanographic features (e.g., wind speeds, temperatures, precipitation, sea levels, ocean acidity), the productivity of individual species and entire food supply systems (e.g., shifts in spatial distribution of predators and prey), and regional patterns of migration and distribution of human populations [4–7]. These climate change impacts have prompted the need to develop multiple solutions to reduce greenhouse gas emissions and our dependence on fossil fuels.

One solution is the development and deployment of renewable energy technologies that can replace carbon-based sources. These technologies include solar, wind, bioelectricity, geothermal, and hydropower, and have increased their share of energy markets, increased economic activity with new jobs and infrastructure, and decreased commercial and domestic electricity costs [7–9]. Planning, technological development, and deployment of offshore wind energy (OWE) projects have rapidly increased in recent years to help meet the needs for energy independence and clean-power goals for dozens of countries [10–12]. Wind resources in offshore marine environments provide a relatively strong and consistent source of electricity-generating power, including during evening and nighttime hours and during cloudy and rainy periods when generating energy from other renewable sources is reduced.

In the United States, federal and state processes to pursue OWE development in the Atlantic and Pacific Oceans and the Gulf of Mexico have been underway in recent years. The Bureau of Ocean Energy Management (BOEM) is the lead regulatory agency for OWE leasing and development; however, the overall planning process is generally driven by a partnership of state and federal regulatory agencies with the goal of identifying areas that can meet stated energy-generating goals, while simultaneously minimizing overlap and potential conflict with existing ocean-use sectors and ecological resources. On the U.S. West Coast, all proposed OWE development aims to use floating-platform technology due to depths > 60m across most of the continental shelf. The configuration of floating platforms anchored to the bottom and transmission cables suspended in the water column will most likely create areas that operationally exclude most existing ocean-users, including commercial fisheries. Thus, in order to maintain safe, sustainable markets of locally-sourced seafood and to utilize carbon-free sources of energy from our oceans, it will be important for the OWE planning process to adequately avoid, minimize, and mitigate potential impacts to fisheries and the communities that depend on them (e.g., [13–14]).

Fishery harvests represent one of the most important and traditional ecosystem services provided by the marine environment [15–16]. Impacts from OWE to fisheries and fishing communities may include indirect effects (e.g., bottom-up oceanographic changes that affect local and regional productivity, trophic interactions, and the availability of target and bycatch species) and direct effects (e.g., the spatial exclusion from historically utilized fishing areas, or wind farms acting as fish aggregation or avoidance devices) [13,17-21]. Many of the indirect effects are yet to be understood and will be untested until floating OWE is operational. However, determining the extent of direct impacts due to displacement from fishing grounds and developing a framework that can identify the relative magnitude of impact and appropriate mitigation measures to existing ocean user groups can be addressed during the OWE planning process.

Current efforts to identify locations in the ocean for OWE development have relied on various marine spatial planning efforts to map the spatial distribution of wind resources, existing ocean uses, and important ecological resources (e.g., protected species, essential habitats). These data have been used to identify areas in U.S. federal waters that are suitable for OWE and minimize overlap with other ocean users and important ecological resources [22–23]. However, efforts to date have only considered interactions with historical distributions of existing ocean use sectors and ecological resources and have not considered the likely interactions that are predicted to occur in the future as a result of anticipated climate change.

Species and suitable habitat for many harvested species are predicted to shift poleward and/or change depth distributions [24–26], though the uncertainty in large-scale model predictions can be notable and is often inconsistently communicated [27–28]. Fish and fishery responses to these changes are complex and will vary across fleets, ports, and even individual vessels depending on the strength and direction of species distributional shifts [28–33]. Despite these complexities, estimates of uneven redistribution of fisheries-related benefits, losses, adaptive fishing practices, and even global declines in fisheries revenue have been attributed to climate change effects on the spatial distribution of various fisheries species [26,33-35]. Estimates of overlap and impacts of OWE to fisheries based on historical data alone may significantly mischaracterize the importance of OWE planning areas to future fishery operations if anticipated spatial shifts in harvested species are not accounted for, potentially leading to increased conflicts over fishing rights and access to fishery resources [29]. Therefore, a holistic understanding of distributional shifts is important for supporting OWE marine spatial planning efforts [36], climate-ready fisheries management [37], multi-sector marine scenario planning [38], and the development of renewable energy in such a way that minimizes resource use conflicts and unintended consequences of OWE [39].

In this study, we examine three groundfish trawl fisheries along the U.S. West Coast as a case study to determine whether accounting for the effects of climate change on species distributions alters the degree of potential displacement risk to fisheries from OWE development. Specifically, we first create port-level spatial footprints of historical fishing activity for each fishery ("fleets" from here on) and measure the risk of displacement from proposed OWE areas (OWEAs). Second, we use projected changes in target species' distributions to examine how proposed OWEAs may become more or less important to each fleet after accounting for anticipated climate-change driven distribution shifts. This study provides a novel framework for considering the importance of future climate change effects on planning and mitigation efforts for OWE development. Our framework can readily incorporate ongoing and future work that builds on our assumptions and understanding of how species, individual vessels, and fishing fleets are likely to respond and adapt to climate change. Understanding historical and potential future interactions between fisheries and OWE development will be key in meeting the goals of generating clean energy from offshore wind resources while simultaneously maintaining access to sustainable seafood and promoting co-use of our oceans and climate-ready fisheries and fishing communities.

Methods

Overview

We examined the question of how climate change might alter the perceived risk of groundfish fishing displacement due to proposed OWEAs within a risk assessment framework. First, we calculated risk based on historical fishing activity following the general approach defined by the Intergovernmental Panel on Climate Change (IPCC; [40]), and more recently applied to fisheries/climate change-focused questions [33,41]. Namely, risk is a function of two primary axes: the level of exposure to a stressor and the vulnerability of the subject to that stressor. For the exposure axis, we calculated the degree of spatial overlap between historical fishing activity (1994–2020) and proposed OWEAs. For the vulnerability axis, we calculated the product of each port's adaptive capacity and sensitivity to losing these fishing grounds. Adaptive capacity was measured as a function of fishing site fidelity (i.e., the interannual variability in a port's fishing footprint), and sensitivity was measured as the proportion of targeted-species landings captured within OWEAs. Second, we used projected changes in the spatial distribution of harvested species to identify how the risk of displacement for each fleet might change in the future based on comparisons of biomass indices inside and outside proposed OWEAs. We use the term "fishing fleet" to refer to data from a group of fishing vessels participating in each sub-fishery and delivering landings to specific ports. All code used in this analysis is available on GitHub [42].

Fishing fleet descriptions

The groundfish fishery on the U.S. West Coast is one of the region's most economically important fisheries, generating approximately $117M USD in revenue and supporting approximately 1,700 jobs in 2023 [43]. Vessels participating in the groundfish fishery operate off the coasts of California, Oregon, and Washington, harvesting over 87 species under a variety of permit structures (e.g., open access, recreational, limited entry, catch shares) and gear types (e.g., longlines, trawls, pots). For the purposes of this analysis, we focused on three distinct sub-fisheries based on target species and gear type: (1) bottom trawl fishing targeting the DTS complex (**D**over sole *Microstomus pacificus*, **T**hornyheads *Sebastolobus* spp., and **S**ablefish *Anoplopoma fimbria*); (2) bottom trawl fishing targeting non-DTS species including, but not limited to, arrowtooth flounder *Atheresthes stomias*, petrale sole *Eopsetta jordani*, English sole *Parophrys vetulus,* and Pacific cod *Gadus macrocephalus*; and (3) midwater trawl fishing targeting rockfish species, primarily yellowtail and widow rockfish (*Sebastes flavidus* and *S. entomelas*). Vessels participating in these sub-fisheries range in size, scale of operations, and have a range of cross-participation in other U.S. West Coast fisheries (e.g., crab, shrimp, etc.) that affects fishing location choices and operational costs [44]. The bottom trawl groundfish fisheries collectively generate approximately $20M USD in annual revenues from ~75 participating vessels [33], most of which also participate in other fisheries [45]. The DTS subfishery had just under 40 participating vessels in 2020, generating $5.8M in annual revenues (down from closer to 100 vessels generating $37.7M in 2010) [46]. The number of vessels participating in the non-DTS subfishery has ranged from 35-58 participating vessels generating $8-17M in annual revenues from 2010-2020 [46]. The midwater trawl fishery targeting rockfishes has generated $0.5-10M in annual revenues from its 5–25 participating vessels from 2012-2020 [46]. Over the study period, the midwater trawl fleets targeting rockfish had the fewest number of vessels participating in the fishery and in many years had less than three vessels participating as a result of several years of greatly-reduced quotas for widow rockfish (2002–2014; [47]), though participation and landings revenue could increase in the future as species continue to rebuild, evidenced by increasing harvest in recent years [47–48]. Vessels participating in the three sub-fisheries operated with an average of 2 crew members over the study period [46]. These groundfish fisheries were the focus of this study due to the wide range of depths and higher degrees of site fidelity in the targeted species that likely results in higher potential for consistent overlap and conflict with new ocean-uses, though this framework could be applied in the future to other fisheries.

Offshore wind energy areas

Planning for offshore wind energy development (OWED) along the U.S. West Coast has been underway in recent years, with proposed development sites in federal waters off the states of California and Oregon, and an unsolicited bid request off the coast of southern Washington. Specifically, two OWE Call Areas were proposed in 2022 offshore from the ports of Coos Bay and Brookings, OR, while two Wind Energy Areas (WEA) have been identified, divided into five lease areas, and leased to developers offshore from the ports of Eureka and Morro Bay, CA (Fig 1; [49–50]). The Coos Bay Call Area

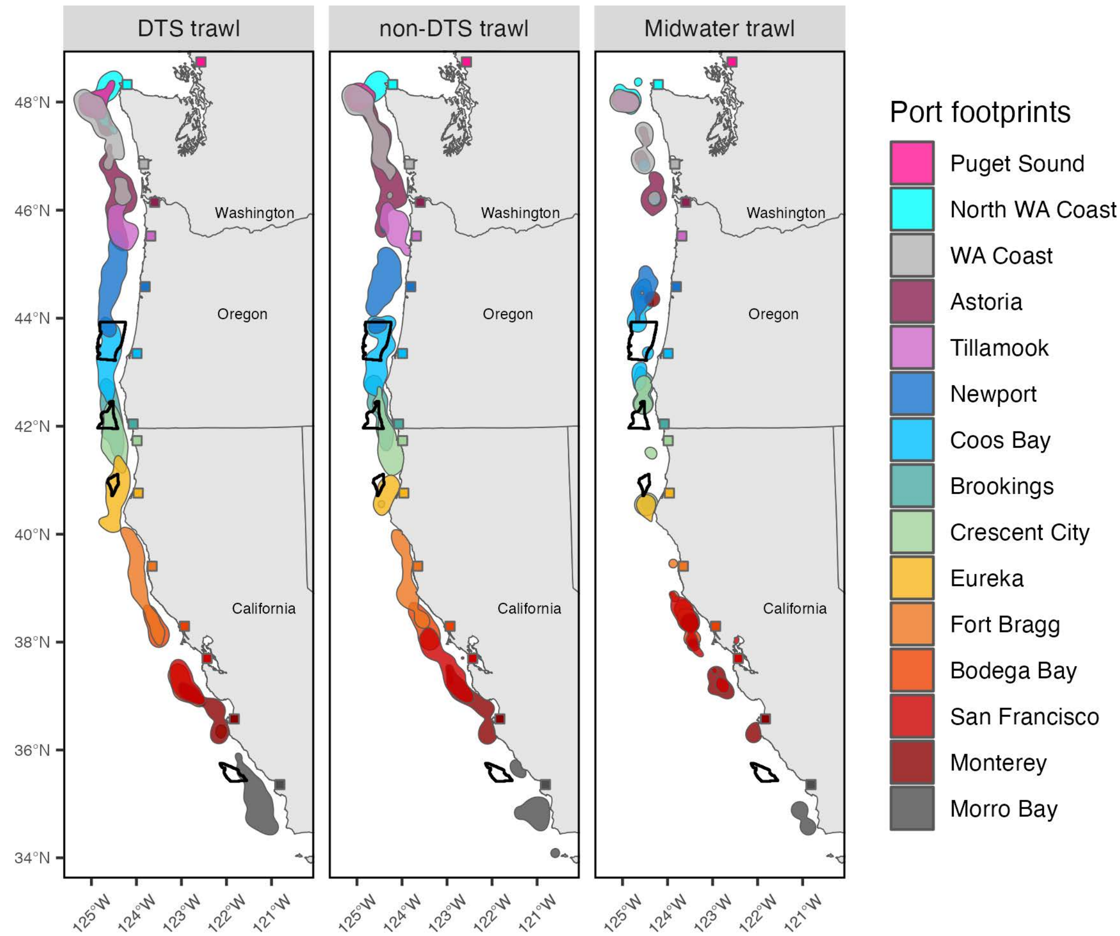

Fig 1. Overlap of historical cumulative fishing footprints (1994-2020) with proposed offshore wind energy areas (black outlines, [49–50]; https://www.boem.gov/renewable-energy/state-activities/Oregon, https://www.boem.gov/renewable-energy/state-activities/California) for three groundfish trawl fisheries that deliver catches to respective ports (colored squares) across the U.S. West Coast. Footprints represent the top 75% volume contour of all landed catch by weight. Wind energy planning areas from north to south are: Coos Bay Call Area, Brookings Call Area, Humboldt Wind Energy Area and Morro Bay Wind Energy Area. Coastal outline created using Natural Earth.

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occupies approximately 3500 km^2 of ocean space, starting ~22 km offshore and extending to ~105 km offshore with a range of water depths between ~120–1300 m. The Brookings Call Area occupies approximately 1150 km^2, starting ~22 km offshore and extending to ~73 km offshore with water depths ranging from ~125–1150 m. The Humboldt WEA off the coast of Eureka, CA has been divided into two lease areas that occupy a combined ~535 km^2 and is 34–57 km offshore to a maximum depth of ~1100 m. The Morro Bay WEA occupies ~975 km^2 and is ~ 32 km offshore, extending to a maximum depth of ~1300 m.

The process of identifying areas to lease to OWE developers in the U.S. consists of several steps generally governed by BOEM and its Intergovernmental Renewable Energy Task Force. This task force is a partnership between BOEM and members of local, state, and tribal governments and other federal agencies. BOEM and the Task Force work through a series of steps to identify "Planning Area(s)", "Call Area(s)", "Wind Energy Area(s)" and finally, "Lease Area(s)". Each stage in the process includes multiple levels of data gathering, spatial analysis, requests for public comment, and engagement with relevant managers and stakeholders. BOEM uses the collected information and analyses to identify areas of the ocean that are feasible for OWED and that avoid and/or minimize the magnitude of potential impacts and interactions with existing ocean user groups and environmental resources. The pace of this planning process has been moving faster than the pace of most scientific research efforts to identify and test for potential impacts, so it is important to develop analytical frameworks that can be quickly deployed to identify potential interactions through a variety of risk analyses or management strategy evaluations.

Calculating potential risk of displacement

Exposure. We estimated the exposure of groundfish fishing activity to OWED as the annual spatial overlap between fishing activity and proposed OWEAs in three steps. First, we summarized fishery-dependent location and landings data for vessels operating in California, Oregon, and Washington from logbook and fish ticket data from 1994 (the beginning of the Limited Entry program for catcher vessels; [51]) to 2020, available from the Pacific Fisheries Information Network (PacFIN; http://pacfin.psmfc.org). Despite the changes in groundfish fishery management regulations over this period, we chose to include data across this longer time frame to encapsulate the wide range of potential changes in regulatory decisions, market forces, or institutional arrangements that could occur in the future and affect fleet fishing locations. Logbook entries were processed for quality control (e.g., we removed ~5% of hauls with obvious erroneous tow times, set coordinates, or depths using the same methods as in [33]). We used fishing gear type ("GRID" in PacFIN) and landings species composition to attribute each haul to one of the three groundfish sub-fisheries described above. If the gear type was identified as midwater trawl and the sum of yellowtail and widow rockfish landings was greater than landings of Pacific hake *Merluccius productus*, we assigned those hauls to the midwater trawl rockfish fishery (as distinct from the midwater hake trawl fishery). For all other hauls, we grouped and summed the landed weight (metric tons; mt) of species according to each sub-fishery's target species: "DTS" = sum of Dover sole, longspine and shortspine thornyhead, and sablefish; "midwater trawl" = sum of yellowtail and widow rockfish; and, "non-DTS" = sum of all other species (S1 Table). These hauls were then assigned to a sub-fishery based on which group of species had the largest proportion of landings. We then used the landing port name ("PCID" in PacFIN) to aggregate each haul into IO-PAC port groups [52]. These IO-PAC port groups were used here because some ports represent relatively small communities with a smaller number of vessels delivering landings or with a single processor, and aggregating at the IO-PAC port-group level allows for the inclusion of more data relative to confidentiality standards and creates data that can be tied to broader environmental conditions, management regulations, and economic indices [52]. Data processing and presentation adhered to all data confidentiality standards, which sometimes resulted in removing individual years of data from figures, but cumulative statistics and calculated values for all fisheries-specific port groups met confidentiality requirements. Summary statistics (Table 1) were generated using these logbook-based location-specific records of landings.

Second, we defined annual fishing footprints that capture the spatial extent of fishing activity for each fishing fleet as a bounded representation of fishing activity to align with species distribution model projections (as in [33]). To accomplish this, in short, we created a kernel density surface [37] of annual fishing activity based on landed weight and the geocoordinates of trawl set points aggregated for each fishing fleet using the same rules as above. To create each annual fishing fleet footprint, we calculated the kernel densities (using the density.ppp function in the *sp* package in R; [53–54]) using a percent volume contour (PVC; using the getvolumeUD function in the *adehabitatHR* package version 0.4.21 in R; [55]) to define the area that contains 75% of the kernel density distribution (i.e., upper 75% of landings weight). We examined the sensitivity of results to the choice of kernel density PVC (i.e., 50%, 75%, 95%) (S2 Text).

Third, we used the sf package in R (version 1.0-16, [53]) to calculate the area of spatial overlap between each fishing fleet's footprints and each of the four proposed OWEAs for all years in which fishing occurred. We then summed the areas of intersection across all OWEAs and calculated the annual proportion of each footprint's spatial overlap with proposed OWEAs. We report results on fishing fleets whose footprints overlapped with OWEAs ≥ 5 years during this period and focus the remaining analyses on these fishing fleets.

Table 1. Summary statistics and relative risk levels for three groundfish fishing fleets in each IO-PAC port group that operated within proposed offshore wind energy areas (OWEAs) between 1994-2020. "DTS" = groundfish bottom trawl fishery targeting dover sole, thornyheads and sablefish; "nDTS" = groundfish bottom trawl fishery targeting non-DTS groundfish species; "MDT" = midwater trawl fishery targeting widow and yellowtail rockfish; "OWEA landings" = landings removed from areas within proposed OWEAs. All other column variables are relative to the operation of the entire fishery, regardless of overlap with OWEAs. All metrics, with the exception of "Relative risk", were based on individual fishing events and their geocoordinates in the logbook and fish ticket data, while "Relative risk" integrates information from both individual fishing events (e.g., sensitivity component of the vulnerability axis) and estimated fishing footprints (e.g., exposure axis and the adaptive capacity component of the vulnerability axis). Relative risk has a maximum possible value of ~1.7.

Port group	Fishery	Total landings (mt)	OWEA landings (mt)	# years fished	# years landings overlap	# years footprints overlap	Total hauls	Total trips	Unique vessels	Relative risk
Newport, OR	DTS	70457	9826	27	27	21	28827	5144	78	0.60
Newport, OR	nDTS	40898	3314	27	27	20	25305	4686	75	0.47
Newport, OR	MDT	13639	258	20	10	6	1328	815	54	0.24
Coos Bay, OR	DTS	80781	40935	27	27	27	23895	5806	76	0.95
Coos Bay, OR	nDTS	38201	12612	27	27	27	18663	5069	68	0.67
Coos Bay, OR	MDT	342	28	13	5	10	62	41	17	0.22
Brookings, OR	DTS	42885	13887	27	27	27	12006	2630	45	0.72
Brookings, OR	nDTS	7371	1123	27	23	27	3783	1241	40	0.37
Brookings, OR	MDT	891	324	9	8	8	177	106	13	0.55
Crescent City, CA	DTS	23623	4382	23	22	22	12262	3067	68	0.58
Crescent City, CA	nDTS	8089	390	22	13	14	10821	3016	59	0.40
Crescent City, CA	MDT	711	169	11	7	8	120	85	14	0.28
Eureka, CA	DTS	82944	9042	26	26	26	25445	6899	71	0.66
Eureka, CA	nDTS	27780	505	26	18	26	15131	5345	60	0.66
Eureka, CA	MDT	1083	0	13	0	7	201	129	26	NA
Morro Bay, CA	DTS	16800	145	23	13	9	7455	1760	38	0.37
Morro Bay, CA	nDTS	5527	0	26	0	0	9157	3027	41	NA
Morro Bay, CA	MDT	90	0	7	0	0	40	23	7	NA

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Adaptive capacity

Adaptive capacity is the first component of the vulnerability axis in our risk calculation. This metric seeks to capture the potential ability of each fishing fleet to adapt to being displaced from the proposed OWEAs. The ability to move and seek out new resources from new fishing grounds may be captured in the variation observed in each fishing fleet's footprints. We assumed that fleets with lower levels of interannual spatial overlap in their annual fishing footprints indicate an inherent flexibility in choosing their fishing locations during routine operations, and this would suggest an increased ability to choose alternative fishing grounds if displaced by OWED.

We calculated 'fishing site fidelity' to capture this historical spatial variation in each fishing fleet's operations. We defined fishing site fidelity as $F_{ij}/(F_i + F_j)$ [56], where F_{ij} is the spatial intersection between fishing footprints in years *i* and *j* and $(F_i + F_j)$ is the spatial union of fishing footprints (i.e., total space utilized) in years *i* and *j*. This calculation was performed and summary statistics were calculated across all combinations of years in the study period for each fleet.

Sensitivity

Sensitivity is the second component of the vulnerability axis in our risk calculation. In order to represent the relative economic importance of fishing areas inside and outside proposed OWEAs, we focused this component on only the targeted species for each fleet, with the assumption that targeted species are the most important component of total catch for each fishing fleet. Using the same logbook and fish ticket data used to calculate exposure, we used the geocoordinates of each haul and spatially joined the haul-level data to each of the proposed OWEA boundaries. We then subsetted and summed the amount of landings (mt) across all targeted species for each fleet (see *Fisheries descriptions* above), and calculated the annual proportion of targeted species' landings from hauls that occurred inside versus outside of the proposed OWEAs. We used the means and standard deviations across these annual proportions as the sensitivity values for each fleet. Using the haul-level data as compared to the 75% PVC footprint-level data for the sensitivity component allowed for higher spatial resolution specificity for this axis of vulnerability. We chose landed weight (instead of landed revenue or fishing effort) to calculate sensitivity independent of changes in species-specific market prices over time, though this could be explored in future work.

Risk calculation

We integrated the measurements of historical exposure, sensitivity, and adaptive capacity to evaluate the relative levels of risk of displacement from OWEAs (based on historical behavior) for vessels participating in each of the three trawl fisheries. Using the IPCC risk framework that defines risk as a function of exposure and vulnerability (e.g., [40]), we calculated vulnerability as the Euclidean distance from the origin to each paired sensitivity and adaptive capacity value:

$$V_f = \sqrt{(AC_f^2 + S_f^2)}$$

where $V_{f,}$ $AC_{f,}$ and S_f are the vulnerability, adaptive capacity, and sensitivity values, respectively, for fishing fleet *f*. In the final step, we calculated relative risk of displacement, $Risk_f$, by calculating the Euclidean distance in the same manner using paired vulnerability and exposure, $E_{f,}$ values for each fleet:

$$Risk_f = \sqrt{(V_f^2 + E_f^2)}$$

It should be noted that the vulnerability, adaptive capacity, and sensitivity that go into the calculation of risk are per capita (vessel) indices. They do not reflect the collective risk of displacement or economic losses aggregated across all vessels in each fleet or port group.

Influence of climate change on potential future risk of displacement

To examine how anticipated climate change may affect potential exposure to proposed OWEAs for each fishing fleet, we used species distribution model (SDM) predictions developed by Liu et al. [26,57]. In short, Liu et al. [26,57] used modeled bottom temperature and bottom oxygen as covariates in fitting Generalized Linear Mixed Models to biomass density observations ("biomass index" from here on). Environmental covariates were extracted from a historical reanalysis (1980–2010) derived from an implementation of the Regional Ocean Modeling System (ROMS) for the California Current region [58–59]. Data on groundfish occurrence and density used in the SDMs came from the West Coast Groundfish Bottom Trawl Survey, a long-term, standardized trawl survey conducted by the National Oceanic and Atmospheric Administration (NOAA)'s Northwest Fisheries Science Center. After fitting to the historical data, Liu et al. [26,57] projected groundfish species distributions for each year out to 2100 using a projected version of the California Current ROMS model [59] that was forced with output from three Earth System Models contributing to phase 5 of the Coupled Model Intercomparison Project (CMIP): Geophysical Fluid Dynamics Laboratory (ESM2M), Hadley Center (HADL), and Institut Pierre Simon Laplace (IPSL) CM5A-MR. These three models were selected to capture the overall variation in physical and biogeochemical variables predicted across the CMIP5. This approach of predicting an index of biomass onto a grid is commonly used in fisheries assessments to estimate historical changes in biomass [26]. In addition, the use of an ensemble of models has been a preferred quantitative framework that offers the ability to explore and quantify uncertainty and the variability attributed to model parameterization [27–28].

For each target species available, we averaged the three projected biomass index values for each projection model and summed all targeted species for each respective sub-fishery for each year (2020–2100) and spatial location (0.1° resolution) (see S1 Text and S1 Table for species that have SDMs and were included in each sub-fishery's targeted species summation). For visualization of the changes in predicted biomass indices, we calculated the percent change in the summed biomass index for each year, spatial location, and sub-fishery using 2020 values as the baseline for comparison. We calculated the mean and standard error of the biomass index predictions that occurred within portions of each fishing fleet's historical (1994–2020) fishing footprint that were either inside or outside the boundaries of the proposed OWEAs. Finally, we calculated the ratio of the mean biomass index inside to the mean biomass index outside proposed OWEAs to visualize how the relative importance of historical fishing grounds contained within proposed OWEAs may change in the future.

It is important to acknowledge the uncertainty inherent at multiple stages of examining the future potential effects of climate change in marine systems [27-28,60]. Structural model uncertainty, parametric uncertainty, linguistic uncertainty, environmental variability, and choice of climate scenario among other sources of uncertainty all impact projection results and can challenge making inferences about meaningful, policy-relevant effects. Additionally, our approach in applying these biological projections to a socio-economic system also makes a few important assumptions. First, it assumes that the major drivers of fishing behavior (e.g., fuel prices, fisheries management regulations, market prices and demands) will be similar in the future to what they have been in the past. Second, it assumes that the outcomes of said behavioral choices (e.g., where, how, when, and which species to target) will also be similar in the future. Third, we assume that the institutional arrangements that affect fishing communities as social-ecological systems will remain stable and intact. Though there is evidence that past fishing locations are a strong predictor of future fishing locations [61–62], we recognize that the elements underlying these assumptions are dynamic and complex and difficult to project over long time horizons. The drawbacks and inherent and inevitable uncertainty of predicting the ecological and socioeconomic impacts of climate change are outweighed by the potential value of identifying broad-scale patterns and trends and proactive planning in support of maintaining resilient fishery resources and communities.

Results

Exposure: overlap between fishing footprint and OWEAs

During the historical period (1994–2020), six port groups from the three groundfish fisheries of interest had ≥ 5 annual footprints that overlapped with proposed OWEAs: Newport, Coos Bay, and Brookings in Oregon, and Eureka, Crescent City, and Morro Bay in California (Table 1; Fig 1). The cumulative fishing footprints varied in the degree of spatial overlap with OWEAs by fishing fleet (Fig 1). Across all port groups, the DTS and non-DTS trawl fisheries had similar historic levels of cumulative footprint overlap with the proposed OWEAs (~15%), while the midwater trawl fishery had the lowest amount of overlap (~6%).

At the port-group level, footprints from fishing activity making landings into Coos Bay, Brookings, and Crescent City had the greatest amount of overlap with OWEAs across all three fisheries. The Coos Bay port group footprints had the highest average annual overlap with OWEAs for all three fisheries, averaging 46% (±7% SD) for the DTS trawl fishery, 31% (±10% SD) for the non-DTS trawl fishery, and 11% (±14% SD) for the midwater trawl fishery (Fig 2). The least amount of overlap was seen in the Morro Bay DTS trawl (1 ± 2%), Crescent City non-DTS (3 ± 3%), and the Newport midwater trawl (1 ± 2%) fishery footprints. Temporal variability was highest for the midwater trawl fishery for each port group with the exception of Brookings, in which the non-DTS fishery was most variable. Temporal trends in overlap were evident for several fleets. Overlap with OWEAs began increasing after ~2004 for the Newport DTS and non-DTS trawl footprints, and throughout the historic study period for the Eureka DTS trawl footprint. Overlap decreased over the historical period for the Brookings and Crescent City DTS trawl footprints. Overlap between non-DTS trawl footprints and OWEAs generally declined for Coos Bay, Brookings and Crescent City, although the Coos Bay fleet has had increased use of OWEAs in the

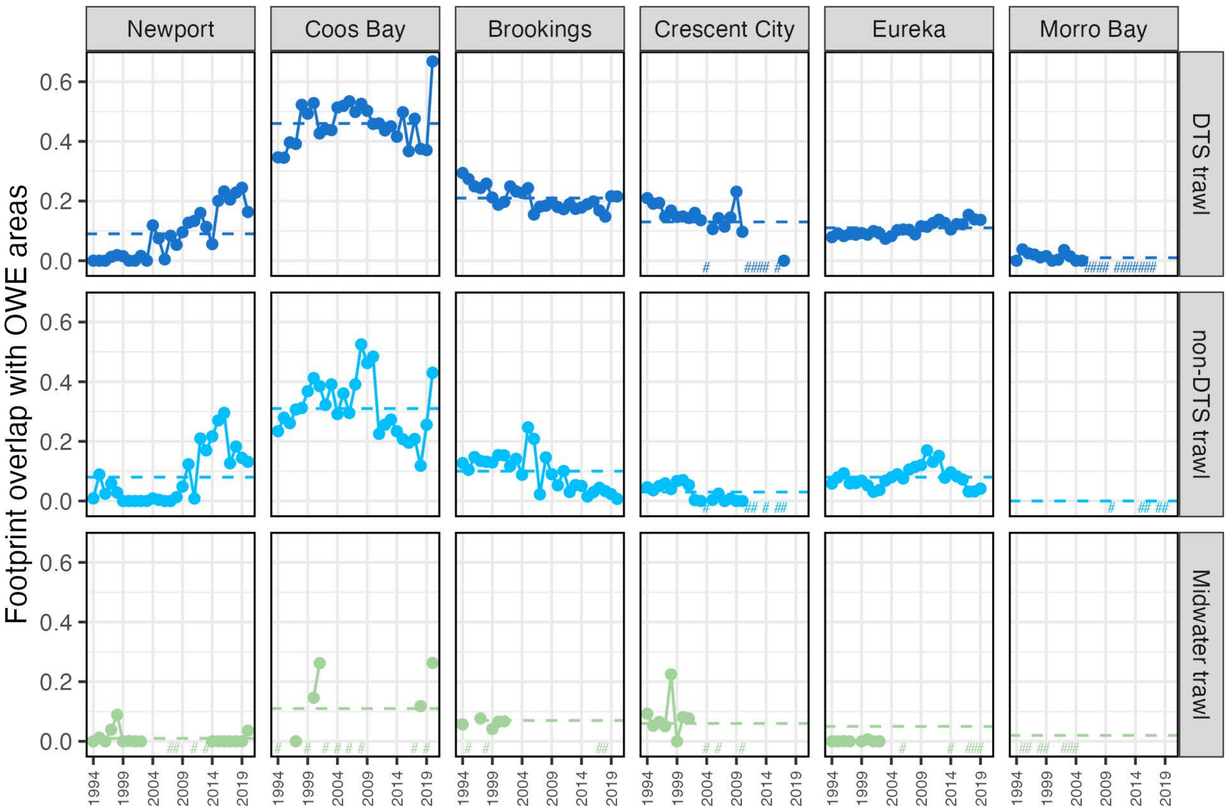

Fig 2. Exposure: annual proportional area of overlap between fishing footprints and proposed offshore wind energy areas (OWEAs) for each of three groundfish trawl fisheries (rows) and their respective ports of landing (columns). Dashed lines = mean values across all years (1994-2020). Proportional values of 0 = fishery operated but had no overlap with OWEAs. Some year-fishery-port group values have been removed from the figure due to confidentiality requirements (years with #'s in the plot rug; 17 DTS, 11 non-DTS and 31 midwater trawl values), leading to differences with Table 1, but all values were included in the mean calculations (dashed lines) shown here.

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most recent years. Other trends were either more mixed and variable (e.g., Coos Bay DTS, Eureka non-DTS), or were difficult to display due to data confidentiality issues (e.g., most midwater trawl footprints).

Adaptive capacity: fishing site fidelity

Similar to the overlap of footprints, the degree of fishing site fidelity varied by fishing fleet. Specifically, fishing site fidelity was highest (and the lowest coefficient of variation) in almost all ports for the DTS trawl fishery, ranging from 0.37 (± 0.17) in Morro Bay, CA to 0.65 in Eureka, CA (± 0.1) and Coos Bay, OR (± 0.13). Fishing site fidelity was lowest (with the greatest amount of variation) for the midwater trawl fishery, ranging from 0.07 (± 0.11) in Coos Bay to 0.34 (±0.31) in Eureka (Fig 3). Fishing site fidelity for the non-DTS trawl fishery ranged from 0.32 (±0.17) in Brookings, OR to 0.65 (±0.11) in Eureka, which was the port with the highest average site fidelity across all three sub-fisheries (Fig 3).

Sensitivity: proportion of target species landings within OWEAs

Coos Bay and Brookings, OR had the largest proportion of targeted species harvested from within proposed OWEAs, amounting to 0.51 (± 0.07) and 0.33 (± 0.05) for the DTS and 0.31 (± 0.12) and 0.11 (± 0.10) for the non-DTS trawl fisheries, respectively. Morro Bay and Eureka had the lowest proportion of targeted species harvested from within proposed OWEAs for the DTS trawl fishery (Fig 4). Interannual variability in these values was higher than variation observed in the overlap of footprints.

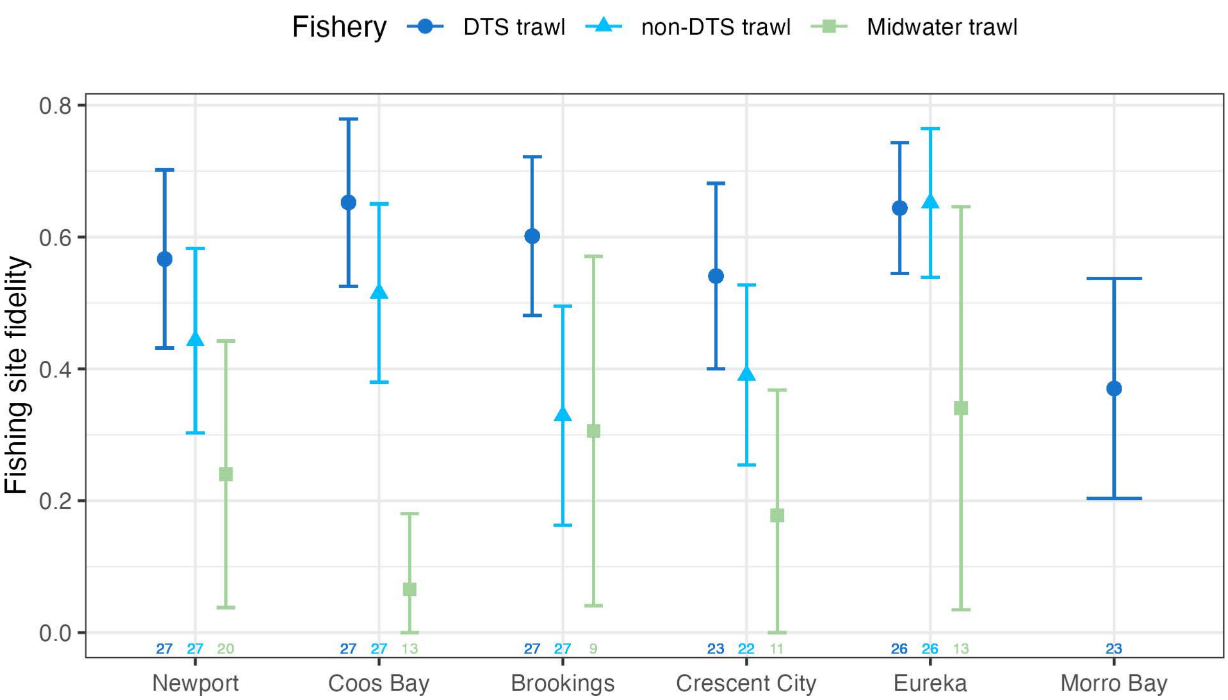

Fig 3. Adaptive capacity: mean (± SD) fishing site fidelity across all annual fishing footprint combinations (1994-2020) for each fishing fleet that overlapped with proposed offshore wind energy areas (OWEAs). Values along the x-axis show the number of years the fishing fleet operated (regardless of overlap with proposed OWEAs) and the number of years of data used to calculate fishing site fidelity.

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Risk of fisheries to potential displacement

The integration of measures of exposure, adaptive capacity, and sensitivity revealed a wide range of relative levels of risk across fishing fleets (Fig 5, Table 1). The Coos Bay DTS trawl fishery showed the highest level of relative risk (Euclidean distance = 0.95; max value possible = ~1.7) to being displaced from OWEAs. The next highest levels of risk of displacement were Brookings DTS, Coos Bay non-DTS, Eureka DTS and Eureka non-DTS fisheries. Five of the top seven highest levels were observed for the DTS fishery, with only the Morro Bay DTS fishery having low levels of risk relative to other DTS or non-DTS fisheries. Risk of displacement for midwater trawl fisheries was relatively low across all combinations, with only the Brookings midwater trawl fishery having a relative risk value greater than a subset of the DTS or non-DTS fisheries. The variability in these facets of risk is depicted in units of standard deviation, which can be seen as a representation of the uncertainty in risk of displacement for a given fishing fleet and generally shows higher variation in annual levels of risk for the midwater rockfish fishery.

Influence of climate change on species distributions

Overall, the aggregated SDM predictions from Liu et al. [26,57] show that the DTS fishery target species are expected to shift into deeper habitats in the future (averaged across years 2050–2100 relative to 2020), resulting in higher biomass estimates further offshore and lower biomass estimates inshore (Fig 6a); biomass estimates for non-DTS trawl target species were predicted to increase within intermediate depths and decrease at deeper depths (Fig 6b); and midwater trawl target species' biomass estimates were predicted to decrease broadly across much of the West Coast where OWEAs are proposed (Fig 6c).

The relative magnitude of changes in projected biomass across portions of fishery footprints inside and outside of proposed OWEAs varied across port groups and fisheries (Fig 7). Projected biomass indices were nominally greater

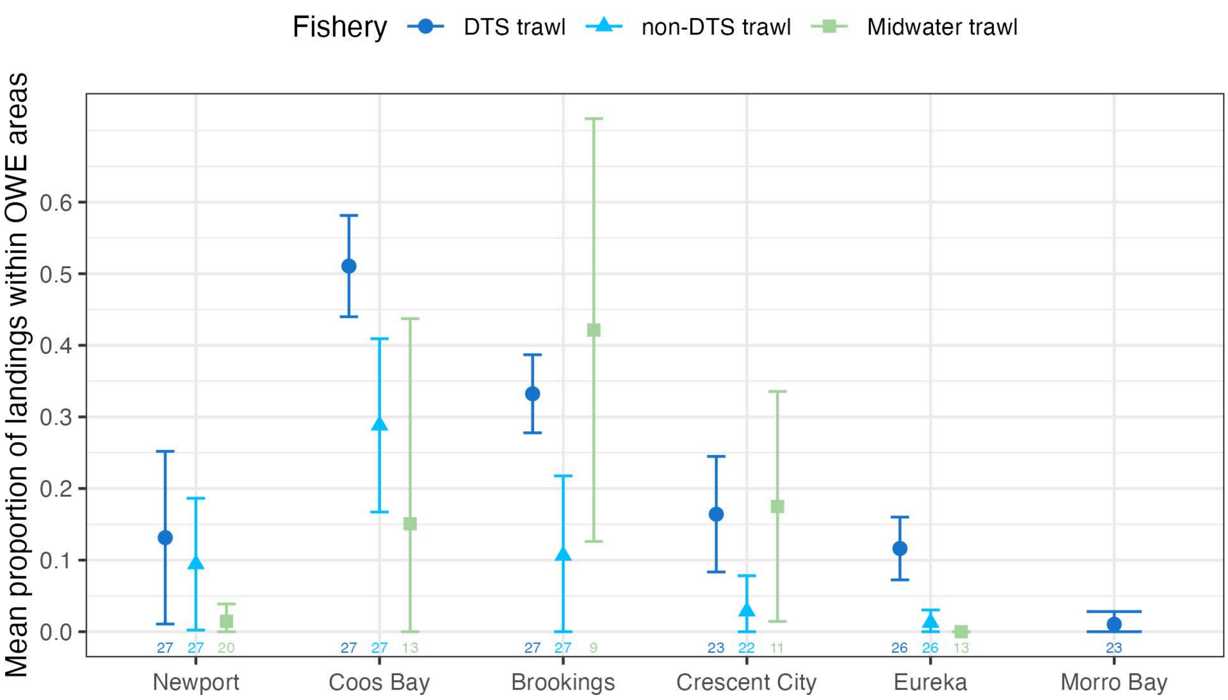

Fig 4. Sensitivity: mean (± SD) proportion of targeted-species landings by weight harvested from within proposed offshore wind energy areas (OWEAs) from 1994 to 2020 for each of three groundfish trawl sub-fisheries and their respective port of landing. Values along the x-axis show the number of years the fishing fleet operated (regardless of overlap with proposed OWEAs) and the number of years of data used to calculate sensitivity.

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inside the OWEA portions of fishing footprints for four of the six DTS trawl port groups (Brookings, Crescent City, Eureka and Morro Bay) and were nominally similar inside and outside OWEAs for Newport and Coos Bay. For the non-DTS trawl fishery, Brookings and Crescent City had higher biomass indices inside OWEAs by the end of the century, while the other three port groups showed some slight trends but were generally equal inside and outside OWEA portions of their footprints. Across all port groups of the midwater trawl fishery, biomass indices were generally greater in the portions of their footprints outside OWEAs in the near term, but showed decreasing trends in the indices through the end of the century.

The ratio of biomass indices inside versus outside OWEA portions of fishing footprints showed three main patterns (Fig 8). The ratios for the DTS trawl port groups were relatively consistent from 2020 to 2100, with increased uncertainty beginning in ~2050. In contrast, nearly all non-DTS port groups showed increasing trends in the inside:outside ratio through the end of the century. The ratios for the midwater trawl fishery showed a general pattern of both areas becoming more equal in the latter half of the century.

Discussion

In this study, we examined the contemporary risk of displacement from fishing grounds due to the siting of OWE development for three groundfish fisheries and their respective port group fleets, and coupled this with the potential influence of climate change on the perception of that risk. Based on our modeling assumptions and past fishing activity (1994–2020), we found that vessels delivering landings (particularly DTS and non-DTS species) into Coos Bay and Brookings, OR, and Eureka, CA have the greatest potential risk of displacement due to a higher degree of operational overlap with proposed OWEAs and higher proportions of targeted species harvested from within proposed OWEAs, and inherently higher levels

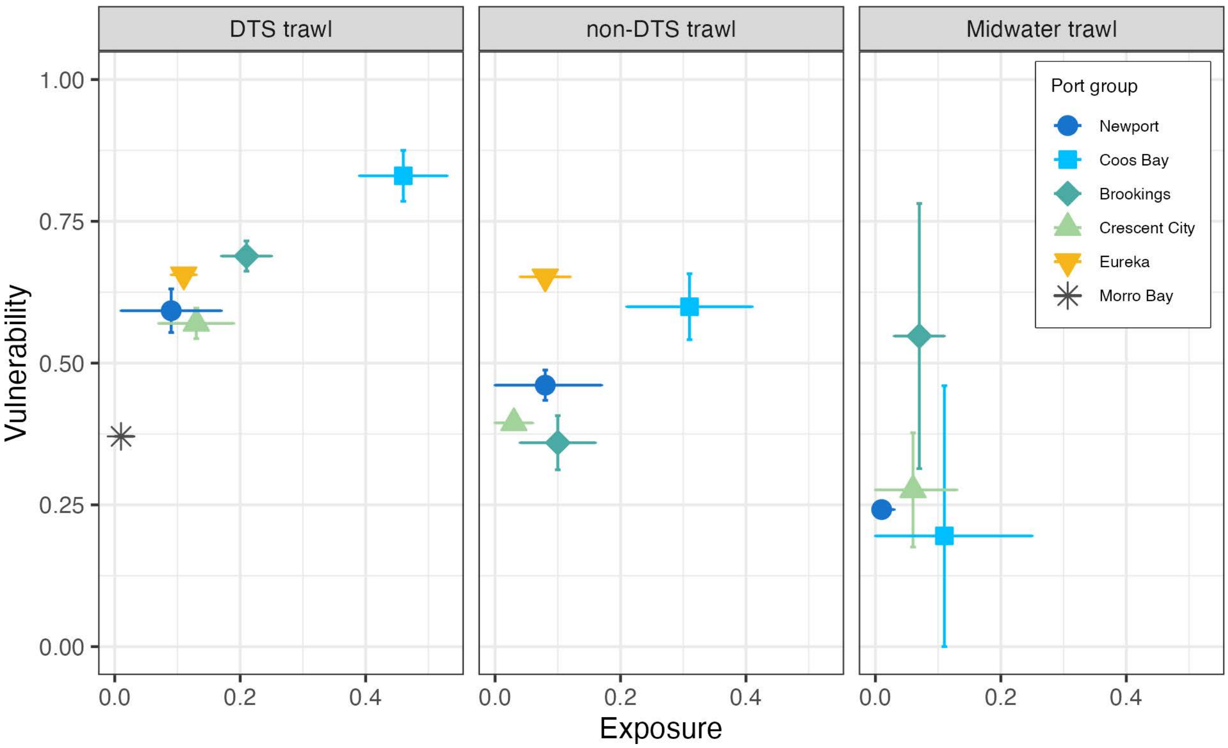

Fig 5. Relative levels of risk to the potential displacement from historical fishing grounds due to the siting of offshore wind energy developments for three groundfish trawl fisheries and their respective port groups. The Exposure axis is the mean (± SD) proportional spatial overlap of annual fishing footprints (1994-2020; Fig 2) with proposed offshore wind energy areas. The Vulnerability axis is the mean (± SD) Euclidean distance calculated from respective adaptive capacity (Fig 3) and mean sensitivity (Fig 4) values.

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of fishing site fidelity. However, historical levels of overlap with OWEAs varied across fleets and are likely to change in the future due to climate-related shifts in target species distributions, particularly for the non-DTS trawl fleets. These results highlight the importance of considering anticipated climate change effects during planning and mitigation processes for renewable energy development, which has been largely overlooked to date. The process for identifying new OWEAs is generally moving faster than the pace of scientific research, but the analytical framework presented here can be adapted when OWEAs are proposed or altered and as we gain additional mechanistic insights and refined hypotheses as to how species distributions and fishing behavior will change. Our framework can be applied to other coastal areas to inform the OWEA siting process and examine the potential socioeconomic impacts of marine renewable energy development on coastal communities.

Influence of exposure on risk

The risk of displacement by offshore wind energy development for a given fishing port community depends largely on the degree of spatio-temporal variability in fishing activity, which is driven by several factors. The fleets examined here had varying degrees of overlap with potential OWE development, mostly dependent on distance from port to OWEAs. We also found temporal trends in the use of these areas. For example, the DTS and non-DTS fleets delivering to Newport, OR had relatively low levels of overlap between their fishing footprints and OWEAs across the entire historical period, however, the proportion of overlap has been consistently increasing over the last 10–15 years. In contrast, the footprints from vessels

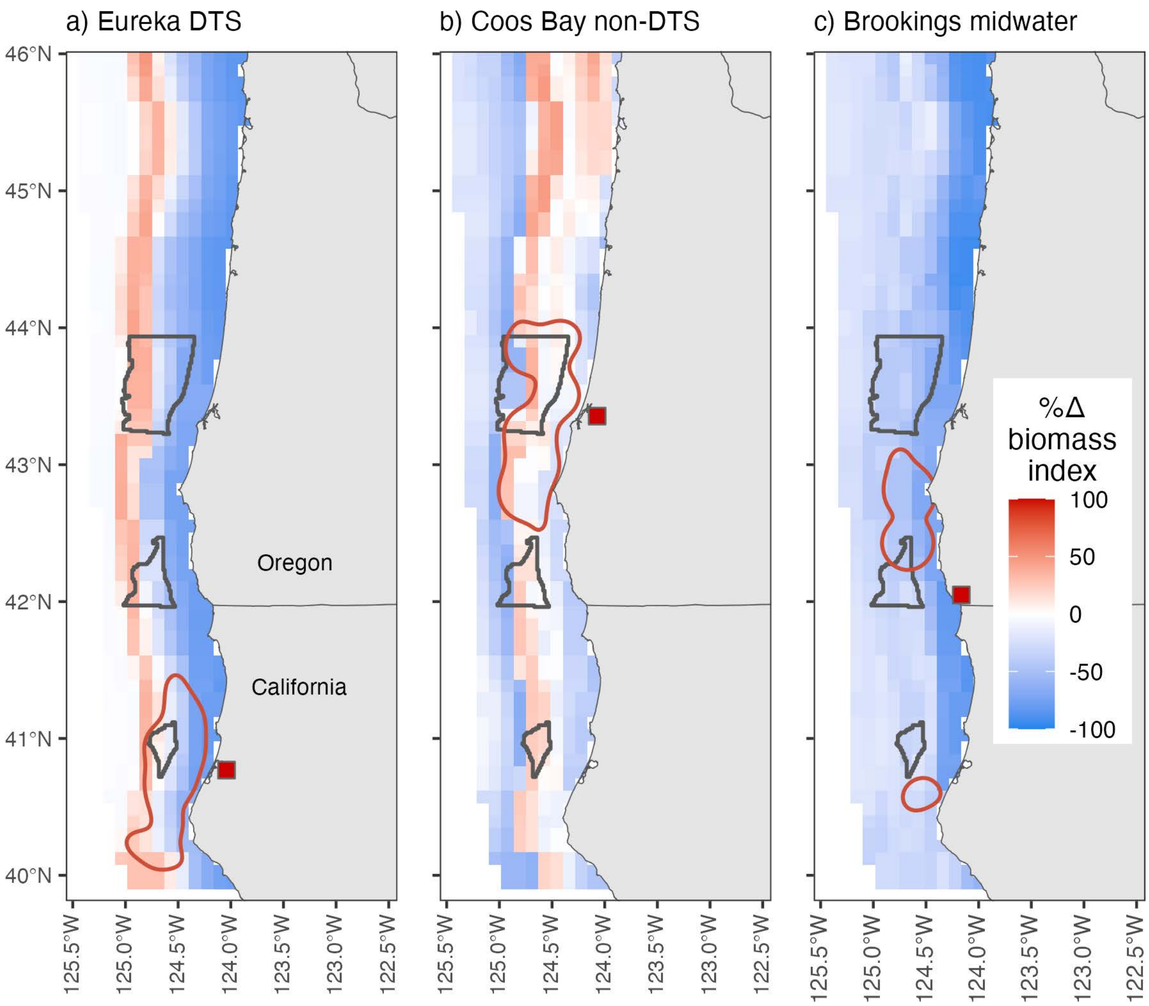

Fig 6. Proposed offshore wind energy Call Areas in Oregon and Wind Energy Areas in California (black outlines, [49–50]; https://www.boem.gov/renewable-energy/state-activities/Oregon, https://www.boem.gov/renewable-energy/state-activities/California), cumulative fishing footprints calculated from commercial landings from 1994 to 2020 (red outlines), and the average percent change in projected biomass index of targeted species (gridded heatmap) for three example fishing fleets. Changes in biomass index values are differences between the average from 2050-2100 compared to a baseline of 2020. Red squares = respective port group location. Coastal outline created using Natural Earth.

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delivering non-DTS species to Coos Bay, Brookings, and Crescent City have decreased in their overlap with OWEAs over time. Identifying the factors driving these specific changes in fishing activity is beyond the scope of this manuscript, but could include broadscale changes in fisheries management (e.g., annual quota levels, limited entry program in 1994, buyback program in 2003, and the implementation of catch shares and individual fishing quotas in 2011; [51]), diversification of harvest portfolios [45,63], adaptive fishing strategies by individual vessels or vessel groups [33], port-specific processing capacity, and changing target species market prices. Trends and changes in spatio-temporal patterns of fishing footprints will continue for U.S. West Coast fishing fleets in the future, and new constraints on accessing targeted species (i.e., operational closures due to the presence of other ocean-use sectors) will decrease the flexibility of fleets to adapt to changing climate, management, and market forces [64–66]. Thus, future models that examine interactions among fishery footprints, OWEAs, and shifting target species distributions may need to incorporate additional assumptions or functional relationships that can account for fleet behaviors.

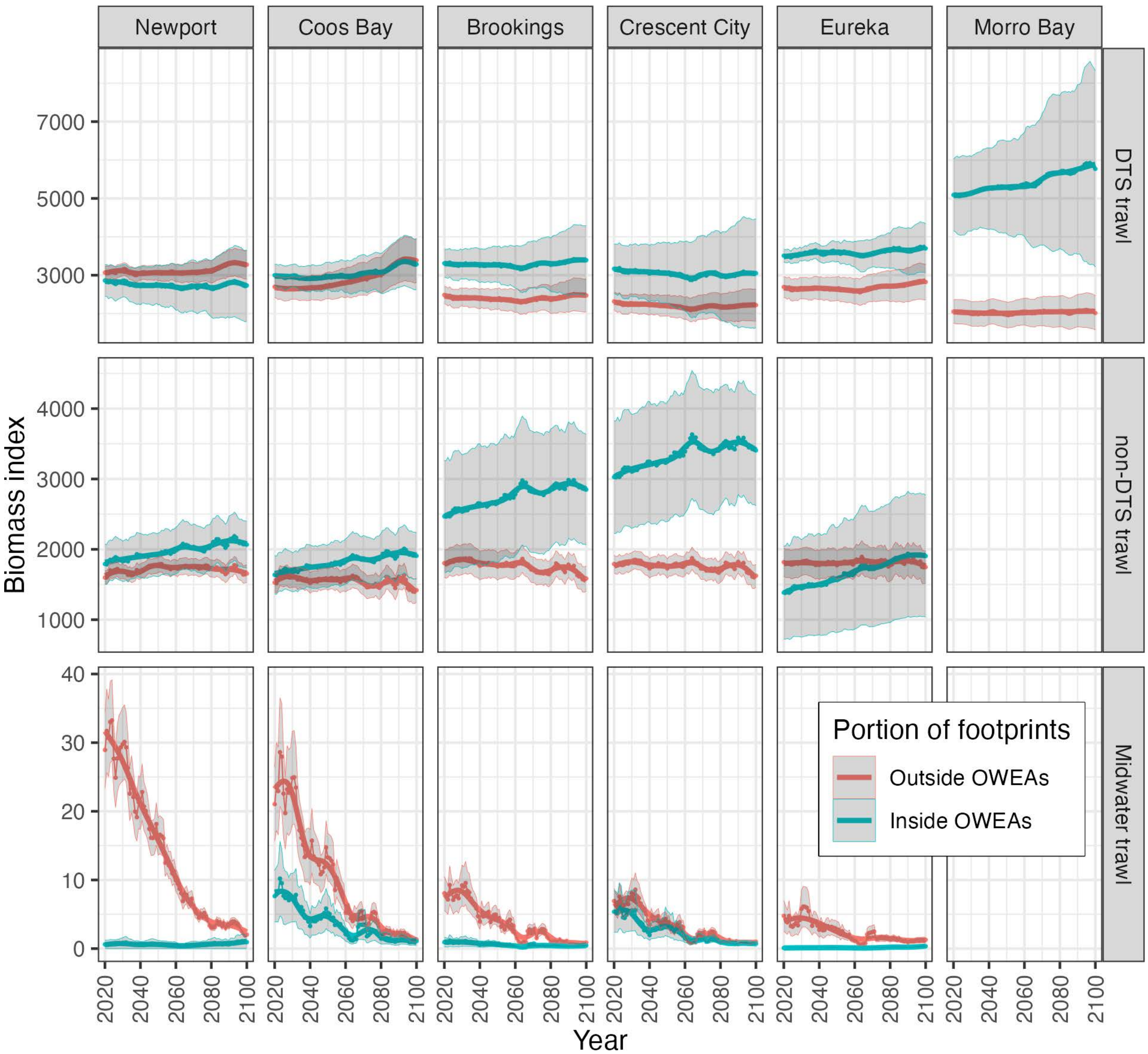

Fig 7. Projected mean (points) and SE (shading) of biomass index for target species (5-yr running average; thick lines) within portions of each fleet's historical fishing footprints (1994-2020) that were inside or outside the boundaries of proposed offshore wind energy areas (OWEAs). The biomass index (kg/km^2) for each fleet was calculated from species distribution models fitted to catch-per-unit-effort data collected by the Northwest Fisheries Science Center's groundfish bottom trawl survey (2003-2010; [26]).

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Influence of sensitivity on risk

The sensitivity component of our risk calculation used the proportion of targeted species landed within OWEAs to measure how sensitive a fleet might be to the economic impacts of these areas becoming operationally closed to these fisheries. Overall, these values were relatively similar to the degree of spatial overlap between footprints and the OWEAs (i.e., exposure) with notable exceptions for at least two of the midwater trawl fleets. The Brookings, OR and Crescent City, CA midwater trawl fleets had much higher sensitivity values compared to their respective exposure values, and, in general, midwater trawl fleets were more variable in each component of the risk calculation. The differences in these two metrics suggest much higher levels of variance in the spatial adherence of targeted species to fine-scale habitat locations, as opposed to the

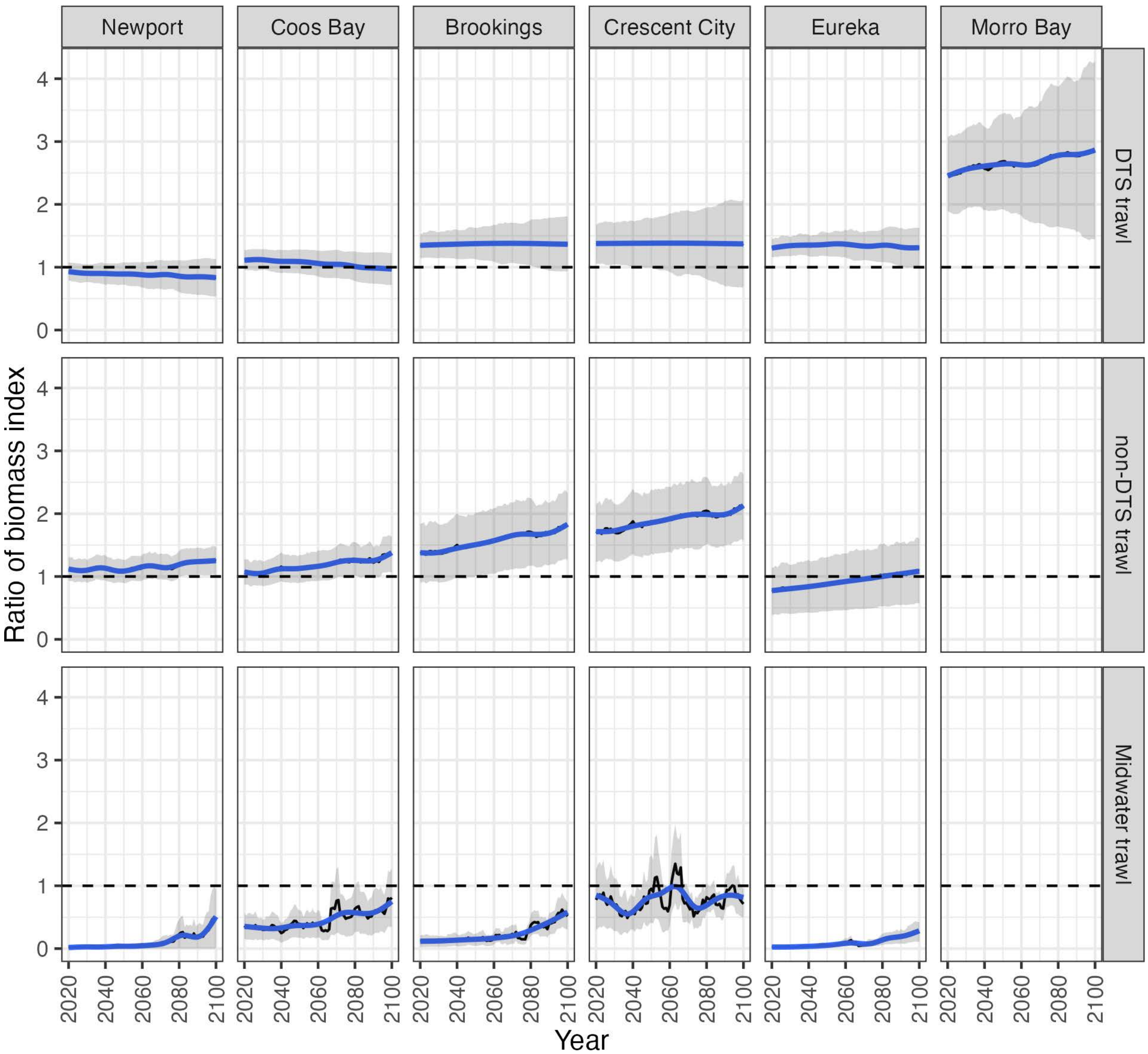

Fig 8. Ratio (±SE) of projected biomass index values inside compared to outside proposed offshore wind energy areas (OWEAs) for each fishing fleet. Values > 1 represent years when the average biomass index from areas of historical fishing footprints inside OWEAs was projected to be greater than areas outside OWEAs.

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bottom-oriented species targeted by the DTS and non-DTS fisheries. The midwater trawl fleets target widow and yellowtail rockfish, which may form dense aggregations in response to highly dynamic oceanographic and prey conditions [67]. These environmental conditions could result in mismatches between the timing of fishing activities and fish aggregations, resulting in some highly productive and unproductive years. These characteristics suggest that these fleets operate more sporadically than the DTS and non-DTS fleets, potentially resulting in greater variability and sensitivity to operational disruptions.

Influence of adaptive capacity on risk

We used fishing site fidelity as a proxy for understanding the potential adaptive capacity component of the risk calculation across fleets. For most port groups, DTS fleets showed the highest levels of fishing site fidelity in their annual footprints, followed by non-DTS fleets and midwater fleets. These patterns of fishing ground use likely reflect the relatively higher association of DTS and non-DTS targeted species with finer-scale benthic habitat characteristics than the dynamic pelagic habitats associated with the target species of the midwater trawl fishery [68]. The consistent use of the same fishing grounds suggests that DTS fleets may have relatively higher reliance on specific locations for harvesting targeted species, and may be less mobile or less flexible than non-DTS and midwater fleets in relocating their operations due to a variety of financial, market, or port-specific infrastructure conditions [31,69].

Influence of climate change on perception of risk

Finally, we examined how the distribution of target species biomass is anticipated to shift within historical footprints due to climate change both inside and outside proposed OWEAs to provide insight as to whether these respective areas might become more or less important to specific fleets in the future (and therefore an increased or decreased risk of displacement). We found that biomass indices are projected to be greater *within* the portion of fishing footprints that overlaps with OWEAs for at least 6 of the 14 fleets, indicating that these areas of overlap will continue to be areas of relatively high productivity for the targeted species. This represents a potential tradeoff between OWED and fishing opportunities for these fleets in the future. Notably, the increasing trends in the ratio of biomass inside versus outside OWEAs observed for the non-DTS fleets suggests that areas of overlap would likely become more important and would increase their level of risk in the future compared to the risk calculated from their historical footprints alone. These spatial shifts in target species' biomass complicate any analysis to determine whether a fleet could make up lost harvest and revenue from newly closed areas over the long term (e.g., [70–71]). In contrast, we found the ratio of biomass indices for DTS species inside and outside of OWEAs remained relatively stable through the end of the century, suggesting that climate-induced shifts of targeted species may not alter our perception of relative risk for these fleets.

Implications for fishing communities and OWE planning

It is challenging to identify all of the tradeoffs in stakeholder costs and benefits when making decisions about the permanent placement of renewable energy sites in dynamic ecosystems [72–76], and it is even more difficult to incorporate and identify tradeoffs under future climate scenarios [77]. Our results shed first light on the potential changes to a fishing fleet's level of risk of being displaced from historical fishing grounds when future climate change effects are considered. The projected differences in biomass indices of targeted species inside and outside proposed OWEAs suggest that some fisheries and ports will be at greater risk in the future due to respective changes in spatial fishing opportunities. For example, the Brookings, OR and Crescent City, CA non-DTS fleets had two of the lowest relative risk values across all fleets based on historical fishing footprints, but when spatial shifts in their targeted species distributions were considered, we found that biomass indices were projected to be higher, and will continue to increase, inside the OWEA portions of their footprints in the future, suggesting that these fleets may have to significantly increase fishing effort or identify adequate, new fishing grounds in order to maintain current harvest levels. In contrast, the Coos Bay, OR DTS fleet had the highest level of risk based on historical fishing footprints, but anticipated climate change effects suggest that biomass of targeted species will slightly increase outside the OWEA portions of their footprints towards the end of the century; thus, this fleet may be able to make up for lost fishing opportunities inside the OWEAs by shifting fishing effort to these areas of increasing biomass that will still be accessible outside the OWEAs.

The ability of a fishing community to adapt to climate change depends on its flexibility or mobility to access new fishing locations [33,69]. Fishing behavior is often assumed to follow a profit-maximizing strategy, with adaptive capacity being affected by fisher values, habits, access to capital, willingness to invest in switching gear or target species, and perception of costs and constraints, among other factors [66,78]. Changes in fishing behavior due to exclusion from historical fishing grounds (e.g., due to the designation of marine reserves or installation of renewable energy infrastructure) can range from expansion into new fishing grounds to "follow the fish" [37,79], "fishing the line" to capitalize on potential increased biomass near reserve areas [79–80], changing target species or gear type [81], or leaving the fishery entirely [82]. These decisions will likely be driven by context- and port-specific adaptive capacity, knowledge, real and perceived changes in costs, and existing restrictions on the fishery [66]. On the U.S. West Coast, previous research suggests that port-level climate risk is geographically variable, and will depend on fishers' ability to 'adapt in place' by altering catch portfolios to adjust to the changing mix of available species, or 'adapt on the move' by following climate-driven distribution shifts of target species [33]. Our results corroborate and extend these findings by focusing on the risks associated with spatial displacement as a result of OWE development. Overall, it is clear that the diversity of target species and types (i.e., surface, midwater, benthic, fishes, crustaceans, mollusks, etc.), vessel sizes, gear types, and fishing strategies employed by U.S. West Coast fishers make predictive inference challenging and require data-driven management mechanisms that can adapt to future changes in fishery resources and ongoing spatial management decisions.

Predicting future vulnerability (and therefore resilience to potential displacement by OWED) is difficult not only due to complex socio-economic factors that are unique to a given fishing community, but also to the dynamic environment in which they operate. The spatio-temporal distribution and biomass of species targeted in groundfish fishing activities can be strongly affected by oceanographic variability and food web dynamics. Additionally, research is ongoing in terms of how OWE infrastructure (e.g., turbines, platforms) may affect the spatio-temporal availability of target species due to physical changes in wind strength and upwelling [21,84], attraction/avoidance to new substrates, or by virtue of the area acting as a *de facto* marine reserve and therefore potentially becoming a net source of biomass [73,80,83]. Some fishers alter which fisheries they participate in response to management actions, climate impacts, or human-health concerns, altering the structure of entire fishing communities [45,63]. This type of response to OWED could significantly affect the resiliency of specific ports or change which mitigation measures will best alleviate the impacts of renewable energy development. Ultimately, our results suggest predicted climate change-induced shifts in target species distributions would alter our relative understanding of the interactions between commercial fishing fleets and the OWE sector if fishing behavior remains similar to observed behavior over the last 20^+ years.

The results presented here are based on historical fishing activity at the fishery level (rather than the entire portfolio of a vessel or owner operator) and do not fully encapsulate the complex suite of issues that drive vulnerability to displacement, sensitivity, and adaptive capacity for individual vessels. Additionally, it is important to note that our approach of examining the degree of overlap between fishing footprints and OWEAs does not account for the fact that a given degree of overlap represents a different potential impact depending on a particular port area's expected revenue from that fishery. For example, a 50% overlap between DTS trawl fishing activity and an OWEA would be less impactful to a port with a larger proportion of revenue from a different fishery. Ultimately, port-specific characteristics (e.g., number of participating vessels, fishery participation, processing capacity, distance to fishing areas, etc.) will matter when applying or refining this framework to make operational decisions or develop mitigation strategies. There is a dearth of quantitative assessments of fishing displacement [85], and some of these issues could be investigated for this fishery in the future using fishing behavior or location-choice models that account for the whole portfolio of the vessel or the entire port-based community to determine thresholds for financially viable fishery participation. Future work could also examine localized environmental predictors of changes in fishing activity [86] that could either reduce or exacerbate potential overlap depending on prevailing oceanographic conditions. A robust fishing behavior model that also incorporates climate-induced shifts in target species could more accurately estimate future fishing location choices given potential changes in the drivers of fishing behavior, behavioral outcomes, and institutional arrangements that we assume to remain constant over the projected time horizon.

Conclusion

OWE could be an important component of achieving goals to reduce fossil fuel-based electricity production (e.g., [87–88]), and it is important to understand the risk of this development to current ocean users over the multi-decadal life expectancy of these projects. This study presents a framework for including the interactive effects of future climate change scenarios and proposed OWED on the vulnerability of commercial fisheries and their associated coastal communities being displaced from historical fishing grounds. The differential effects of climate change on target species' distributions could create complex interactions within and across fisheries and port communities. The framework we have used here could be applied to other fisheries or regions where the siting of new ocean-use sectors, including marine renewable energy or offshore aquaculture, overlaps with other recreational or commercial natural resource uses. Though the assumptions in this work (e.g., that drivers of fishing behavior and behavioral outcomes will remain constant in the future) may limit our ability to more precisely predict true potential risk of displacement by OWED, this work highlights the importance of incorporating climate change into the marine spatial planning process to ensure that tradeoffs and appropriately scaled mitigation measures (in both time and space) are considered during the decision-making process.

Supporting information

S1 Text. Target species defining sub-fisheries.
(DOCX)

S2 Text. Sensitivity to choice of kernel density percent volume contour.
(DOCX)

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