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# Stay or go? Geographic variation in risks due to climate change for fishing fleets that adapt in-place or adapt on-the-move

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## Abstract

From fishers to farmers, people across the planet who rely directly upon natural resources for their livelihoods and well-being face extensive impacts from climate change. However, local- and regional-scale impacts and associated risks can vary geographically, and the implications for development of adaptation pathways that will be most effective for specific communities are underexplored. To improve this understanding at relevant local scales, we developed a coupled social-ecological approach to assess the risk posed to fishing fleets by climate change, applying it to a case study of groundfish fleets that are a cornerstone of fisheries along the U.S. West Coast. Based on the mean of three high-resolution climate projections, we found that more poleward fleets may experience twice as much local temperature change as equatorward fleets, and 3–4 times as much depth displacement of historical

level logbook, landings, and registration data may be acquired by direct request from the California, Oregon, and Washington Departments of Fish and Wildlife, subject to a non-disclosure agreement.

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environmental conditions in their fishing grounds. Not only are they more highly exposed to climate change, but some poleward fleets are >10x more economically-dependent on groundfish. While we show clear regional differences in fleets' flexibility to shift to new fisheries via fisheries diversification ('adapt in-place') or shift their fishing grounds in response to future change through greater mobility ('adapt on-the-move'), these differences do not completely mitigate the greater exposure and economic dependence of more poleward fleets. Therefore, on the U.S. West Coast more poleward fishing fleets may be at greater overall risk due to climate change, in contrast to expectations for greater equatorward risk in other parts of the world. Through integration of climatic, ecological, and socio-economic data, this case study illustrates the potential for widespread implementation of risk assessment at scales relevant to fishers, communities, and decision makers. Such applications will help identify the greatest opportunities to mitigate climate risks through pathways that enhance flexibility and other dimensions of adaptive capacity.

## Introduction

Climate change is shaping the availability of nature's benefits to people and will continue to do so for generations [1,2]. While global-scale projections provide coarse, qualitative expectations for how climate impacts will manifest in different regions and sectors, there is much more limited understanding of risks due to climate change at local scales. Yet regionally-specific information about the effects of biophysical changes on natural resource-dependent industries and communities is critical for adaptation planning and strategic responses from resource management agencies [3–5]. For communities that rely upon harvest of natural resources for their lives and livelihoods, the scale and intensity of expected environmental change in customary use areas for agriculture, fisheries, forestry, and other industries is especially important [6,7]. A clear challenge lies in determining how adaptation within or outside of these areas can enhance climate resilience, using tractable, resonant, and scalable approaches.

Environmental change is spatially heterogeneous and will intersect with dynamic social factors to determine risk due to climate change [3,8,9]. For instance, it is already apparent that rates of warming at the poles exceed those toward the equator [10], patterns of historical variability in local physical forcing will interact with anthropogenic climate change to determine future conditions [11–14], and short-term extreme events fueled by climate change, as well as long-term gradual change, can create localized hotspots of impact [15,16]. In the ocean, warming waters can cause shifts in species' ranges or alterations in target species productivity that lead to changes in local abundance that vary over space [17–19]. This heterogeneity will fuel divergent ecological responses of species to create spatial variability in the exposure of human communities to these impacts [20].

Social vulnerability of human communities, based on their sensitivity and adaptive capacity to respond to biophysical changes, also varies geographically. For fisheries and fishing communities, the potential to adapt to change–whether driven by climate, markets, regulations, or other factors–differs enormously based on a variety of historical contingencies as well as contemporary circumstances [21–26]. For example, the diversity of species a fishing community has access to or other potential sources of non-fishing revenue can act as buffers during times of ecological or financial volatility [27]. The ability to cope, adapt, and transform fishing practices in response to climate change [28] is influenced strongly by variation across domains of adaptive capacity, which include assets, flexibility, organization, learning, and agency [20,29–31]. A recurrent challenge lies in determining how to measure and manage these different domains of adaptive capacity in tangible ways. Coupled social-ecological analyses of a fishing community's risk due to climate change integrate the magnitude of environmental change it will experience, the sensitivity to such change, and adaptive capacity.

The flexibility domain of adaptive capacity (e.g., occupational multiplicity, technological diversity; [30]) is especially pertinent to fishing communities. The potential for spatial redistribution of target species due to changing ocean conditions encourages particular focus on two of the more tangible, and non mutually-exclusive, attributes of flexibility: fisher or fleet mobility and species diversification. More mobile fishers and fleets can 'adapt on-the-move', responding to changes in the availability of target species by changing where they fish [32], while more diversified fishers may 'adapt in-place', continuing to operate in historical fishing grounds while switching species [33]. Scientific advice that captures variability in mobility and diversification provides effective support for decision makers managing fisheries in the face of climate change [29].

In much of Europe and North America, groundfish fishing fleets that use bottom trawl gear to target demersal species have formed the backbone of fishing communities for decades to centuries. Many of the most well-developed future projections of the impacts of climate change for fisheries are rooted in predictions of declining abundance of groundfish species (e.g., [17,34–36]), which tend to be characterized by high-quality, fishery-independent data, strongly influenced by environmental forcing, and prone to overfishing due to their life-history characteristics. Surprisingly, however, there are relatively few studies that explicitly connect climate change to coupled social-ecological risk for groundfish fishing fleets. On the U.S. West Coast, this gap in understanding is a crucial one, as the groundfish fishery in this region is a cornerstone of the commercial fishing industry and economies of entire fishing communities [37–39]. Groundfish are caught by bottom trawl off of the coasts of California, Oregon, and Washington, including catch by some vessels participating in state-managed bottom trawl fisheries that capture federally-managed groundfish incidentally. Most catch is managed under the Pacific Coast Groundfish Fishery Management Plan by the Pacific Fishery Management Council (PFMC). This federally-managed fishery consists of nearly 100 species that include rockfishes (*Sebastes* spp.), roundfishes (e.g., sablefish), and flatfishes (e.g., Dover sole). The bottom trawl groundfish fishery once generated >$100M USD (2021 USD) and engaged >400 vessels across all three US West Coast states (Fig 1A and 1B). As of 2019, these values have fallen by a factor of five or more, with annual revenues at just over $20M USD and fewer than 75 vessels remaining in the fleet despite consistency in the number of port groups buying bottom trawl groundfish over the same time period (Fig 1C and 1D).

While several West Coast groundfish stocks were rebuilt during the last two decades [40] and total allowable catches have been increasing [41], utilization of many species remains low [42], and much of the revenue generated from this fishery is now concentrated within fewer ports, primarily in Oregon (Fig 1E). These patterns coincide with declines in the number of fish buyers, reduced processing capacity, and increased spatial consolidation of processing, which in turn may impact the magnitude and distribution of fishing effort [37,43,44]. Together, these trends suggest that port-level bottom trawl groundfish fishing fleets (hereafter, groundfish fleets) are a useful set of fleets on which to focus because each is subject to the same regulations and market forces, operates within a similar geographic area, experiences environmentally-driven change in species' availability, and therefore shares common opportunities and challenges.

The confluence of long-term declines in revenue and participation along with increased geographic consolidation (Fig 1E) suggests that the risk due to climate change for U.S. West

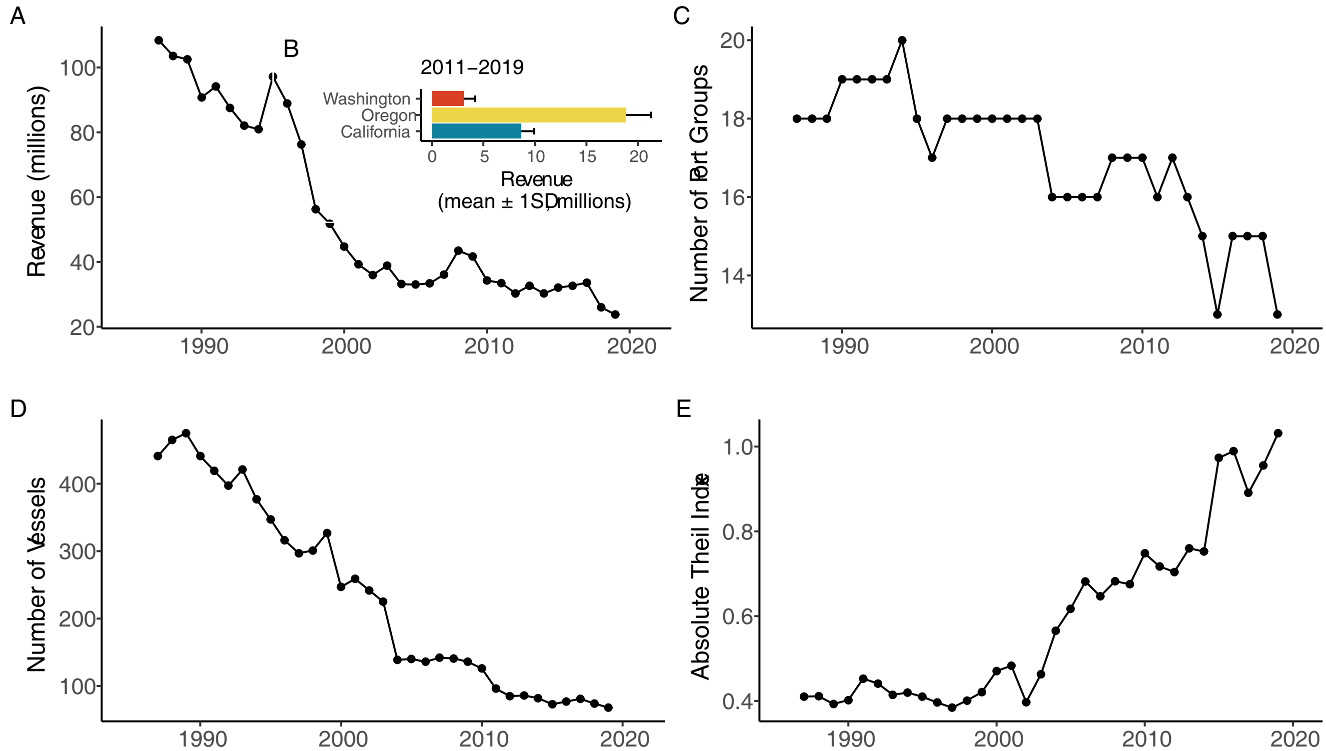


**Fig 1. Historical changes in the groundfish fishery.** (a) Ex-vessel revenue coastwide, (b) mean (±SD) annual ex-vessel revenue by state for 2011–2019, (c) number of port groups, (d) number of vessels, and (e) revenue consolidation (estimated with the absolute Theil Index, calculated for each port group; [45]). A port group represents a collection of individual ports; these groups were developed by the Pacific Fisheries Management Council (S1 Table). All revenue data were adjusted for inflation to 2021 USD. See S1 Text for methodological details.

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Coast groundfish fleets may be high and heterogeneous, yet neither these risks nor regional variability in the potential for these fleets to mitigate risk has been rigorously explored. To close this knowledge gap, we assessed the coupled social-ecological risk of groundfish fleets along the U.S. West Coast to climate change. We focused this assessment on projected environmental change within present-day fishing grounds, in combination with quantitative analyses surrounding the economic dependence of the fleets on groundfish and the fleets' relative mobility and capacity to diversify into other fisheries, based on past fishing behaviors. We hypothesize that regional variation in the magnitude of future ocean change will create geographically variable exposure. In addition, we predict that consolidation of the groundfish fleet over time has concentrated economic dependence on bottom trawl-caught groundfish in fewer places, altering sensitivity to future changes in groundfish fisheries. Finally, we expect that fleet composition and fisheries portfolios vary from place to place, causing inconsistency in the capacity for fleets to cope with risk posed by climate change across the coast.

## Methods

### Overview

We approached the question of what climate change portends for groundfish fleets on the U.S. West Coast using a coupled social-ecological approach. We define coupled social-ecological risk due to climate change as the combination of exposure to projected environmental or

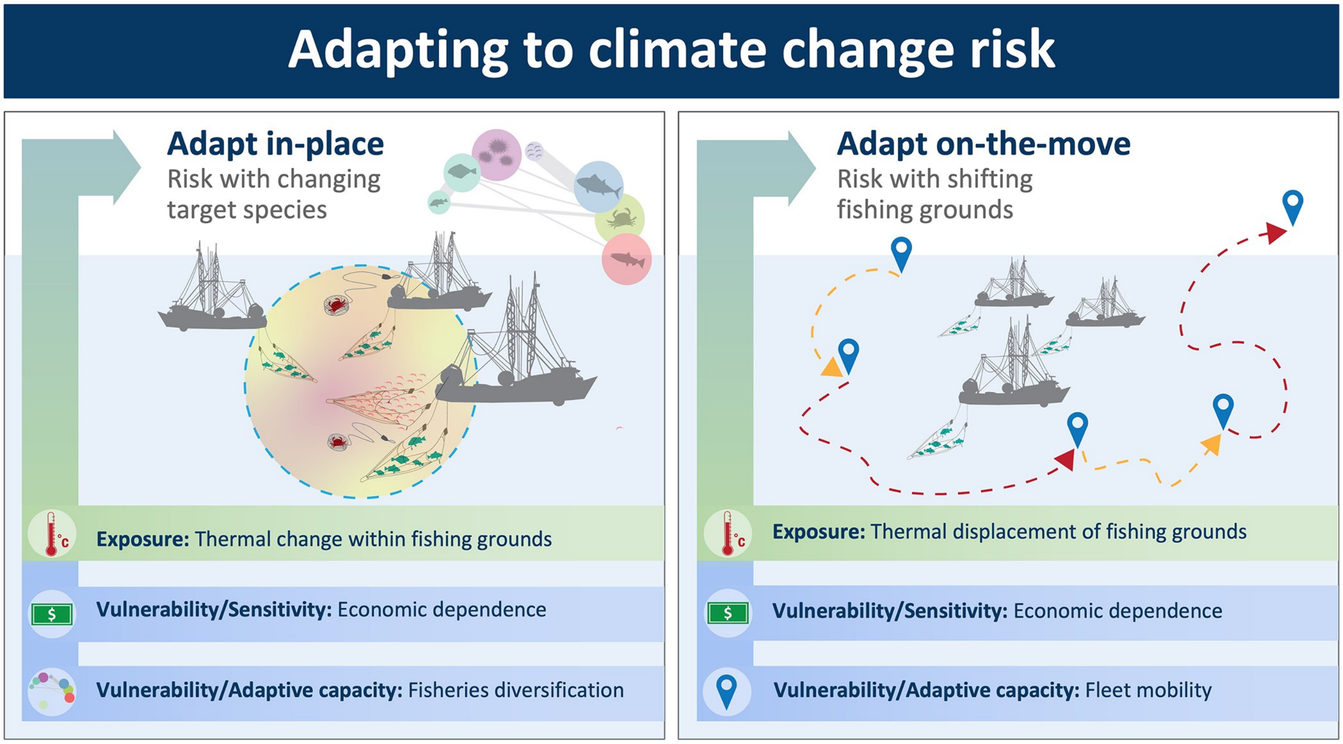


**Fig 2. Conceptual framework to consider coupled social-ecological risk due to climate change.** (a) Assuming fleets change target species while remaining in current fishing grounds (adapt in-place); (b) assuming fleets shift fishing grounds while targeting current species (adapt on-the-move). We define coupled social-ecological risk due to climate change as the combination of exposure to projected environmental or ecological change and the sensitivity and adaptive capacity (i.e., social vulnerability) of the affected community, or more formally, Risk = $(\text{Exposure}^2+\text{Vulnerability}^2)^{1/2}$ (Eq 7) where Vulnerability = $(\text{Sensitivity}^2+(\text{Lack of Adaptive Capacity})^2)^{1/2}$ (Eq 6). This approach is adapted from frameworks in [3,20]. In both panels, redder colors indicate higher exposure due to warming.

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ecological change and the social vulnerability of the affected community. Social vulnerability is defined in terms of sensitivity and adaptive capacity. We assessed fleet-specific risk in two ways (Fig 2). First, we evaluated risk if fleets change target species while continuing to fish in current fishing grounds (the *adapt in-place* assessment). Second, we assessed risk if fleets shift fishing grounds while targeting current species (the *adapt on-the-move* assessment). This evaluation builds on the general framework of the Intergovernmental Panel on Climate Change (IPCC) [3], and more recent reviews and developments introduced by [9,26,46–48]. We define each groundfish fleet as the collection of vessels landing groundfish caught using bottom trawl gear and delivered to buyers in the same port group (S1 Table). We note that this definition of a groundfish fleet is inclusive of vessels with federal permits for the fishery and vessels participating in state-managed bottom trawl fisheries that capture federally-managed groundfish incidentally.

For the adapt in-place assessment, we estimated exposure as the amount of thermal change expected between the periods 1990–2020 and 2065–2095 within the present-day fishing grounds used by each fleet. We estimated the flexibility dimension of adaptive capacity based on an index of diversification, defined as realized opportunities to participate in multiple fisheries in each port group from 2011–2019, and encompassing a recent period of consistent management regulations [37].

For the adapt on-the-move assessment, we estimated exposure as the projected extent of horizontal (change in latitude and/or longitude) and vertical (change in depth) displacement of near-bottom isotherms representative of present-day fishing grounds for each fleet between the periods 1990–2020 and 2065–2095 (S1 and S2 Figs; [49]). We estimated the flexibility dimension of adaptive capacity based on an index of mobility, defined based on documented distances of fishing grounds from landing ports during 2011–2019.

For both the adapt in-place and adapt on-the-move assessments, we defined sensitivity as the economic dependence of each groundfish fleet on bottom trawl groundfish relative to total commercial fishing revenue, including pink shrimp, Dungeness crab, and Pacific whiting, generated by those fleets within the U.S. Exclusive Economic Zone and state waters during the period of 2011–2019. This approach assumes that more economically-dependent fleets are more susceptible to harm if climate change negatively affects bottom trawl groundfish. To estimate overall risk due to climate change for groundfish fleets, we calculated a social vulnerability index based on the sensitivity and adaptive capacity estimates, and combined it with estimates of exposure. We describe these calculations in detail below.

## Defining fishing footprints

The foundation of this risk assessment is the location of fishing grounds for each groundfish fleet. We defined the spatial footprints of each of 14 fleets based on fishery-dependent catch data available from logbooks from 2011–2019 in Washington, Oregon, and California. We retrieved these data from the Pacific Fisheries Information Network (PacFIN; http://pacfin.psmfc.org). To connect these data with specific fishing communities, we associated footprints with port groups of landing for each bottom trawl tow in the database (following [50,51]; S1 Table). There are nearly 300 ports where groundfish are landed and the distinction between ports can often be as small as two different sides of a small bay. The port groupings were developed by the PFMC for biennial groundfish harvest specifications. In addition, aggregating individual ports into port groups is necessary to provide a feasible set of geographic areas for a coastwide climate risk analysis. Finally, analysis at the individual port-level would violate confidentiality requirements, because there are often fewer than three buyers in any one port.

We pre-processed the logbook data to remove problematic hauls prior to development of footprints (https://zenodo.org/record/7916821). Specifically, we included hauls lasting at least 0.2 hours but not more than 24 hours, and removed hauls with coordinates outside of the U.S. EEZ, and those on land or outside of a customary catch depth (>2,000 m) or area (defined based on locations of bottom trawl tows during the period 2010–2015). We evaluated the depth reported for each haul using the *Imap* R package (https://github.com/John-R-Wallace-NOAA/Imap), which overlays hauls with the National Geophysical Data Center (NGDC) bathymetry (at a resolution of 3 arc-seconds, or ~90m at the Equator) [52–54]. We retained hauls reporting a depth within 250 m of the NGDC depth, assuming accurate reported haul locations. However, we assumed that if reported depths were inaccurate by >250 m, the haul locations were likely to be similarly erroneous. Finally, we assumed that failure to report depth was not indicative of positional error, but a simple misstep on the skipper's part, so we acquired the missing depth from NGDC based on the geocoordinates of the set (start) point for each haul. Combined, these filters reduced the size of the logbook dataset by ~4% across all years (S2 Table).

For each fleet, we extracted all tows from the period 2011–2019 from the logbook data, excluding fleets with fewer than 3 vessels reporting logbook data during that time period. We used the summed weight of landed catch of all groundfish species actively managed or listed as ecosystem component species in the groundfish fishery management plan used by the PFMC (Tables 3–1, 3–2 in https://www.pcouncil.org/documents/2016/08/pacific-coast-groundfish-fishery-management-plan.pdf/), along with the geocoordinates of trawl set points, to create a kernel density surface [33]. We calculated kernel density with a 10 km bandwidth, using the density.ppp function in the *sp* package in R [55]. The kernel density allowed us to define the footprint of each fleet, using a percent volume contour that represents the boundary of the area that contains 75% of the volume of the kernel density distribution. The percent volume contour was determined using the getvolumeUD function in the *adehabitat* package in R [56]. The position of each fleet's footprint on the coast was relatively unchanged by the choice of the 50, 75, 90, or 95 percent volume contour (S4 Fig), and would not influence the rank order exposure of fleets, or the relationships between exposure and latitude, described below given the large-scale patterns of projected bottom temperature change, horizontal displacement, and vertical displacement (S1 and S2 Figs).

## Exposure

Poor ocean bottom conditions are the most relevant hazard for the life stages of groundfish species caught with bottom trawl gear, and temperature is an established predictor of groundfish species' range shifts [57]. We obtained projected bottom temperatures–the basis for a regional assessment of hazard–from an ensemble of regional downscaled ocean projections [11] produced using the Regional Ocean Modeling System (ROMS; S1 Fig). The ROMS domain spans the California Current ecosystem from 30˚-48˚N latitude and from the coast to 134˚W longitude at 0.1˚ degree (~7–11 km) horizontal resolution with 42 terrain-following vertical layers. The regional projections were forced with output from three Earth System Models (ESMs) contributing to phase 5 of the Coupled Model Intercomparison Project (CMIP5): Geophysical Fluid Dynamics Laboratory (GFDL) ESM2M, Hadley Center HadGEM2-ES (HADL), and Institut Pierre Simon Laplace (IPSL) CM5A-MR. While we only used the high-emissions Representative Concentration Pathway (RCP) 8.5 scenario, which is the highest-emission scenario and one which appears to be increasingly unlikely [58], the ESMs were chosen to bracket the spread of potential future change. Specifically, GFDL and HADL represent low and high ends of the spectrum, respectively, for the projected magnitude of warming in the CMIP5 ensemble [11,59]. The relatively weak warming in GFDL under RCP8.5 is comparable to the CMIP5 ensemble mean warming under RCP4.5. We focused on 30-year historic (1990–2020) and future (2065–2095) periods to best capture interdecadal variability [59] in ocean conditions characteristic of the California Current ecosystem.

We estimated exposure based on analysis of projected bottom temperatures within each fleet's fishing footprint. For the adapt in-place assessment, we calculated exposure $e_{adaptin-place,p}$ for each fleet operating out of port group $p$ as the thermal state change normalized by historic thermal variability within each fishing footprint, addressing the question: if the footprint of fishing effort for a fleet remains stationary, how much will the environment change within it relative to the scale of variability it normally experiences?

To obtain estimates of $e_{adaptin-place,\ ESM,p}$ for each ESM we spatially joined bottom temperature projections to the fleet footprints (using the *sf* library in R; [60]), and calculated the mean and standard deviation in bottom temperature during the historic period, $t_{historic,ESM,p,c}$ and $\sigma_{historic,ESM,p,c}$, respectively, and the mean bottom temperature during the future period, $t_{future,ESM,p,c}$, for each ROMS cell $c$ within each footprint. We estimated exposure as the difference in the average future and historic temperatures across all cells within each footprint, $\bar{t}_{future,ESM,p}$ and $\bar{t}_{historic,ESM,p}$, divided by the average standard deviation in historic bottom temperature across all cells within each footprint, $\bar{\sigma}_{historic,ESM,p}$, or

$$e_{adaptin-place,ESM,p} = \frac{\bar{t}_{future,ESM,p} - \bar{t}_{historic,ESM,p}}{\bar{\sigma}_{historic,ESM,p}}. \quad (1)$$

Therefore, the units for this exposure metric are essentially standard deviations of temperature change relative to the historic baseline.

For the adapt on-the-move assessment, we calculated exposure for each fleet based on horizontal (change in latitude and/or longitude) and vertical (change in depth) displacement of isotherms representative of present-day fishing grounds (S2 Fig). Displacement is a metric that characterizes environmental change in terms of the minimum distance that must be traveled to track constant temperature contours [49], addressing the question: if the footprint of fishing effort for a fleet moves to find a future environment that matches the historical one, how far will it have to go? In the case of bottom temperature, we calculated both horizontal and vertical displacement for each ROMS cell. We excluded ROMS cells in which >10% of their area was inaccessible to the trawl fishery due to presence of untrawlable habitat or the most recent spatial fishery regulations (2020-present; S2 Text, S3 Fig). Sensitivity analysis revealed that the choice of the 10% threshold for inaccessible habitat did not qualitatively change conclusions. To capture movement on finer spatial scales than the 0.1˚ degree resolution of the ROMS output, displacements were interpolated to capture the minimum distance required (i.e., it is not necessary to move a full 0.1˚ degree to the next grid cell if a partial movement would account for the temperature change). As with $e_{adaptin-place,ESM,p}$, we joined the summaries of displacement to the fleet footprints, and calculated the average value of horizontal and vertical displacement for each fleet and ESM, or $e_{adapton-the-move,ESM,Hd,p}$ and $e_{adapton-the-move,ESM,VD,p}$, respectively. The units for the horizontal and vertical displacement metrics are in kilometers that would have to be shifted to maintain an isotherm.

## Sensitivity

We calculated sensitivity in the same way for both the adapt in-place and adapt on-the-move assessments, focusing on the economic dependence of fleets on bottom trawl groundfish. To obtain information on fisheries landings by port group, on 3 October 2022 we downloaded data for all bottom trawl groundfish vessels for the period 2011–2019 from PacFIN's comprehensive fish tickets table. We calculated sensitivity *s* of vessel *v* in year *y* to changes in revenue *r* (adjusted for inflation to 2021 USD) from the bottom trawl-caught groundfish *gbt* in port group *p* in relation to all fisheries *f* and port groups in which it participates as

$$s_{f=gbt,p,y,v} = \frac{r_{f=gbt,p,y,v}}{\sum_{p=1}^{P} \sum_{f=1}^{F} r_{f,p,y,v}}. \tag{2}$$

We calculated annual sensitivity of each fleet $S_{f\,=\,gbt,p,y}$ based on the median value of $s_{f\,=\,gbt,p,y}$ across vessels for each year and port group as

$$\overline{S_{f=gbt,p,y}} = median(s_{f=gbt,p,y,v}). \tag{3}$$

## Adaptive capacity

Adaptive capacity is a complex and multifaceted concept, defined by the Intergovernmental Panel on Climate Change as "[t]he ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" ([61], p. 9). Evaluating adaptive capacity comprehensively requires assessment of multiple domains, including assets, flexibility, organization, learning, and agency [29–31]. Here we focused on the flexibility domain as it pertains to coping capacity, the "ability to react to and reduce the adverse effects of experienced hazards" ([62], p. 72). Specifically, we quantified diversification and mobility within the groundfish fleets, equating reduced diversification and mobility with reduced capacity to cope and adapt.

**Adapt in-place: Diversification.** For the adapt in-place assessment, we quantified present-day fisheries diversification within each of the port groups associated with each groundfish fleet in terms of opportunities to participate in other fisheries from 2011–2019. For this analysis, we selected a measure that invites consideration of the full cross-section of a port group (e.g., processors, deckhands, owners, captains, etc.) that may offer resilience to a groundfish fleet should it experience negative impacts of climate change. We did not subset to only those vessels that participated in the bottom trawl groundfish fishery, as we wanted to reflect the potential for future adaptation within a port group given current fishing opportunities defined as broadly as possible.

Specifically, we generated an annual fisheries participation network [25,38] for each port group to derive an edge density metric. In these networks, different fisheries are depicted as nodes, while pairs of nodes are connected by lines, called edges, that integrate information about vessels participating in both fisheries (S5 Fig; further methodological details provided in [63]). Edge density of a network is defined as the ratio of the number of edges present to the total possible edges in the network [64]. Higher edge density implies that fishers in these ports have, on average, access to a greater range of alternative fishing opportunities if one node (fishery) is compromised because of poor stock availability, a fishery closure, or other regulatory actions [25,38]. Edge density scales with network size (it is easier to achieve a high density in a low complexity network), so comparisons across networks of different sizes should be made with the knowledge that port groups with fewer fisheries will necessarily have more diversification potential than those with more fisheries.

We created annual fisheries participation networks using species landings data retrieved from PacFIN's comprehensive fish tickets table on 29 December 2021. These networks represent the most recent available data for the period 2011–2019 [63], and are summarized annually from week 46 in one year through week 45 in the following year (e.g., November 2018 to November 2019) to capture the beginning of the Dungeness crab (*Metacarcinus magister*) fishing season, a fishery in which many bottom trawl groundfish vessels also participate. We classified nodes based on the species groupings described by [65]. We report diversification as the annual edge density value of each port group's fisheries participation network.

**Adapt on-the-move: Mobility.** For the adapt on-the-move assessment, we characterized each fleet's mobility based on documented changes in the distance of fishing grounds to port from 2011–2019. This approach assumed that fleets from port groups fishing farther from port were more mobile, while acknowledging that many factors influence this metric (e.g., bathymetry, stock availability, vessel size and gear, spatial closures, substrate, etc.). We calculated mobility $m_{p,y,v}$ of vessel $v$ in year $y$ based on its landings-weighted distance from port. For each vessel $v$ in year $y$, we calculated the straight-line distance $d$ from the set location $l$ of each haul to the port of landing $p$, then weighted each distance calculation by the groundfish landings associated with that haul before selecting the median value for each vessel in each year:

$$m_{p,y,v} = median(d_{p,y,v,l}) \tag{4}$$

We calculated annual mobility of each fleet $\overline{M_{p,y}}$ based on the median value of $m_{p,y,v}$ for each year and port

$$\overline{M_{p,y}} = median(m_{p,y,v}), \tag{5}$$

and report the 95th percentile of $\overline{M_{p,y}}$ as our annual index of mobility. This approach assumes each vessel contributes equally to fleet mobility, rather than weighting mobility by each vessel's landings, and captures the upper limit of mobility for each fleet.

## Assessment of risk due to climate change

We integrated measures of exposure, sensitivity, and adaptive capacity of the groundfish fleets on the U.S. West Coast to evaluate coupled social-ecological risk to climate change. Our definitions follow those of the IPCC [62], such that high exposure to climate change, given the hazard of projected warming bottom temperatures [11], and high vulnerability, together imply high risk. Vulnerability is defined broadly as "the propensity or predisposition to be adversely affected" ([3], p. 5), and here we calculate it by integrating our measure of sensitivity (economic dependence) with our measures of adaptive capacity (diversification or mobility).

Specifically, we calculated median exposure values based on thermal change relative to historic variability, horizontal displacement, and vertical displacement across the 3 ESMs for each fleet, and rescaled the median exposure values to index values of $E^*_{p,\ thermal\ change}$, $E^*_{p,\ horizontal\ displacement}$, and $E^*_{p,\ vertical\ displacement}$ such that their minimum values were 0 and their maxima were 1 (the maximum thermal change relative to historic variability, horizontal displacement, and vertical displacement expected across all fleets). We calculated the average value of $\overline{S_{f=gbt,p,y}}$ across 2011–2019 and rescaled it to create a sensitivity index $S^*_p$ with a minimum value of 0 and a maximum value of 1, with 1 reflecting the maximum observed across all fleets. For each of the measures of adaptive capacity, we calculated their average annual values across 2011–2019, and rescaled the resultant quantities such that their minimum values were 0 and their maxima were 1, with 1 reflecting the minimum diversification or mobility observed across all fleets. This reversal of scale converted these indices into measures of a relative lack of capacity to cope and adapt, due to a relative lack of diversification $D^*_p$ and relative lack of mobility $M^*_p$.

We calculated vulnerability of each fleet under the adapt in-place assessment $V_{p,\ adapt\ n\text{-}place}$ and under the adapt on-the-move assessment $V_{p,\ adapt\ on\text{-}the\text{-}move}$, as the Euclidean distance to the origin of the location represented by sensitivity $S^*_p$ and either $D^*_p$ or $M^*_p$ values, such that

$$V_{p,adapt\ in-place} = ({S^*_p}^2 + {D^*_p}^2)^{1/2} \tag{6A}$$

and

$$V_{p,adapt\ on-the-move} = ({S^*_p}^2 + {M^*_p}^2)^{1/2}. \tag{6B}$$

With this calculation, we assume vulnerability to be equally affected by sensitivity and adaptive capacity. Following [46] (their Fig 2, right), we represented this vulnerability to climate change visually, and used it to distinguish between fleets of greater or lesser concern and those that are potential adapters or have high latent risk.

Our ultimate interest was in the combined risk due to climate change of each fleet under the adapt in-place assessment $R_{p,\ adapt\ in\text{-}place}$ and under the adapt on-the-move assessment $R_{p,\ adapt\ on\text{-}the\text{-}move}$. Specifically, we defined this integrated measure of exposure and vulnerability as the Euclidean distance to the origin of the location associated with each value of $E^*_{p,i}$ and vulnerability $V_{p,j}$,

$$R_{p,adapt\ in-place} = ({E^*_{p,thermal\ change}}^2 + {V_{p,adapt\ in-place}}^2)^{1/2}. \tag{7A}$$

$$R_{p,adapt\ on-the-move} = ({E^*_{p,vertical\ displacement}}^2 + {V_{p,adapt\ on-the-move}}^2)^{1/2}. \tag{7B}$$

With these calculations, we assume risk to be equally affected by exposure and vulnerability, and interpret fleet risk relative to other fleets in this analysis, rather than capturing an absolute measure of risk.

### Geographical patterns

To evaluate whether there were geographical patterns in the exposure, sensitivity, adaptive capacity, and risk metrics, we conducted regressions of these variables against latitude. Specifically, we used the *glmmTMB* package to evaluate (i) the fixed effects of latitude on thermal change relative to historic variability, horizontal displacement, or vertical displacement for each ESM separately; (ii) the fixed effect of latitude and the random effect of year on sensitivity, diversification, and mobility; and, (iii) the fixed effect of latitude on each of the risk metrics. In all of the models, we weighted the regressions by the number of vessels composing each fleet. For the sensitivity and diversification models, we used a logit link and the ordered beta family because the data represent proportions. For the mobility model, we used a log link and the Gaussian family to adequately capture the long tail in the distribution of landings-weighted distance from port across fleets, and included splines (number of knots = 3). All other models used an identity link and the Gaussian family. While the convention when plotting regressions is to have the explanatory variable on the x-axis, we decided to plot latitude on the y-axis because it provides a more intuitive representation of poleward and equatorward shifts in fishing fleets operating off the U.S. West Coast. To evaluate the leverage of individual fleets in these analyses, we re-ran the regressions described above using leave one out cross validation (LOOCV; see S3 Text for details).

## Results

We found that the sensitivity of groundfish fleets along the U.S. West Coast, based on their share of earnings from the groundfish fishery, varied substantially from close to zero to near complete dependence (Fig 3). The more equatorward San Francisco, Santa Barbara, and Los Angeles fleets derived <10% of their revenue from the bottom trawl groundfish fishery during 2011–2019, while the more poleward fleets landing in Puget Sound, Astoria, and Fort Bragg captured ≥80% of their revenue from the bottom trawl groundfish fishery (Fig 3). Overall, though there was a fair amount of interannual variability in the relationship, sensitivity increased significantly with latitude ($p < 0.001$; Fig 3, S3D Table). The Santa Barbara fleet had high leverage, but did not modify the positive relationship observed in the full data set (S15 Fig). These estimates of sensitivity based on economic dependence of groundfish fleets on bottom trawl groundfish were used in both the adapt in-place and adapt on-the-move risk assessments.

We centered our analysis of exposure to climate change within present-day fishing footprints (Fig 4A) of U.S. West Coast groundfish fishing fleets. These footprints indicate extensive fishing along the coast, particularly off Washington and Oregon (Fig 4B) where fishing grounds overlapped considerably more and generally occupied larger areas, compared with the fishing footprints of fleets landing catch in California-based port groups (Fig 4C and 4D). The landings-weighted depth of the catch, while highly variable for some port groups, was generally shallower for fleets landing catch in ports south of Point Conception, California, than those farther north (S6 Fig). In addition, these equatorward fleets tended to be composed of smaller-size vessels (S7 Fig).

On average across the three ESMs, we estimated that between the historic (1990–2020) and projected (2065–2095) periods, there would be one standard deviation or more of near-bottom ocean warming within present-day fishing footprints, ~5km of horizontal displacement of

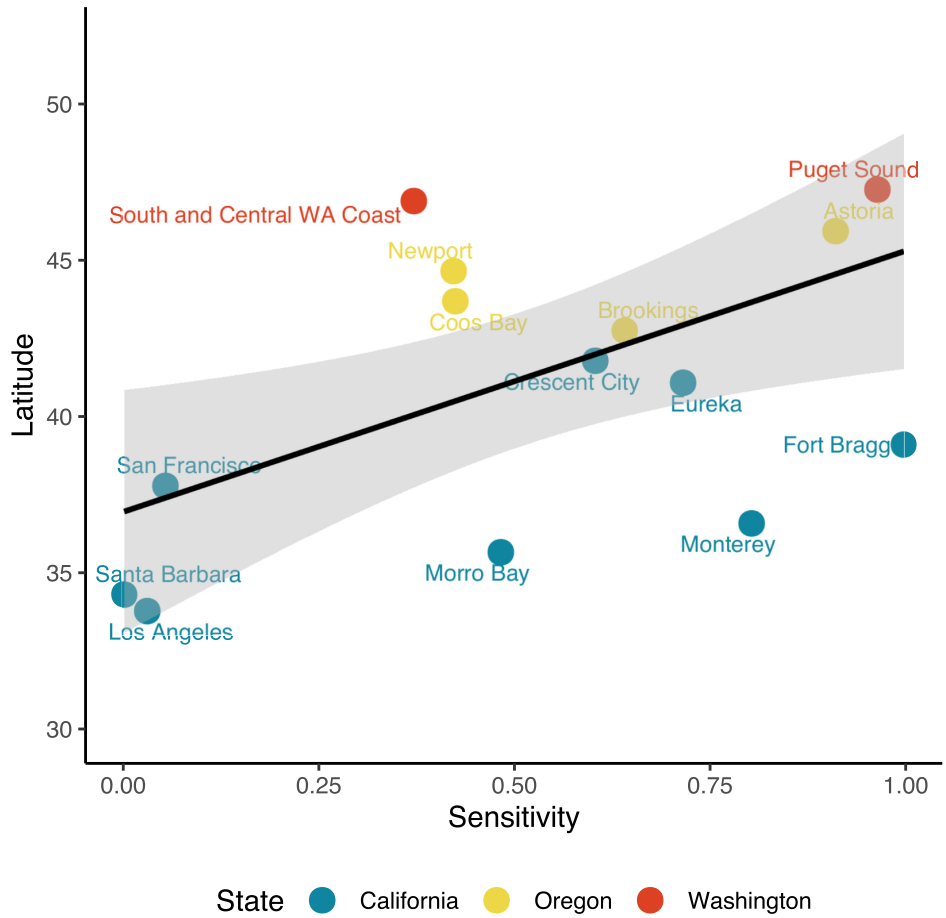


**Fig 3. Economic dependence, as a measure of sensitivity, of U.S. West Coast groundfish fleets to changes in the fishery, in relation to latitude.** The black line represents the relationship between mean economic dependence (2011–2019; proportion of groundfish revenue relative to revenue from all commercial fisheries) and latitude, while grey shading indicates the SE of this relationship, which was statistically significant ($p < 0.001$, S3 Table). Colors correspond to the state in which each port occurs (blue: California, yellow: Oregon, red: Washington).

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bottom isotherms, and 10s to 100s of meters displacement of bottom isotherms into deeper waters (vertical displacement). We also found that exposure under adapt in-place and adapt on-the-move strategies increased significantly with latitude (S3A–S3C Table). Compared to more equatorward fleets, we found that poleward fleets will experience twice as much local temperature change within present-day fishing footprints (Fig 4E), relative to historic variability, and 3–4 times as much vertical thermal displacement if they move to follow thermal profiles of present-day fishing footprints (Fig 4F). The Puget Sound, Astoria, Santa Barbara, and Los Angeles fleets had high leverage in the regressions with both measures of exposure (S9–S14 Figs), but did not modify the positive relationship observed in the full data set (except for the IPSL-based regression of local temperature change within present-day fishing footprints, which was highly uncertain; S11 Fig). Horizontal displacement of bottom isotherms in present-day fishing footprints is more uncertain across the ESMs and its association with latitude varied in sign depending on the ESM (S8 Fig). Because the sign of the association between horizontal displacement and latitude varied between ESMs, we did not calculate an average horizontal displacement across ESMs to include in the overall risk estimates reported below.

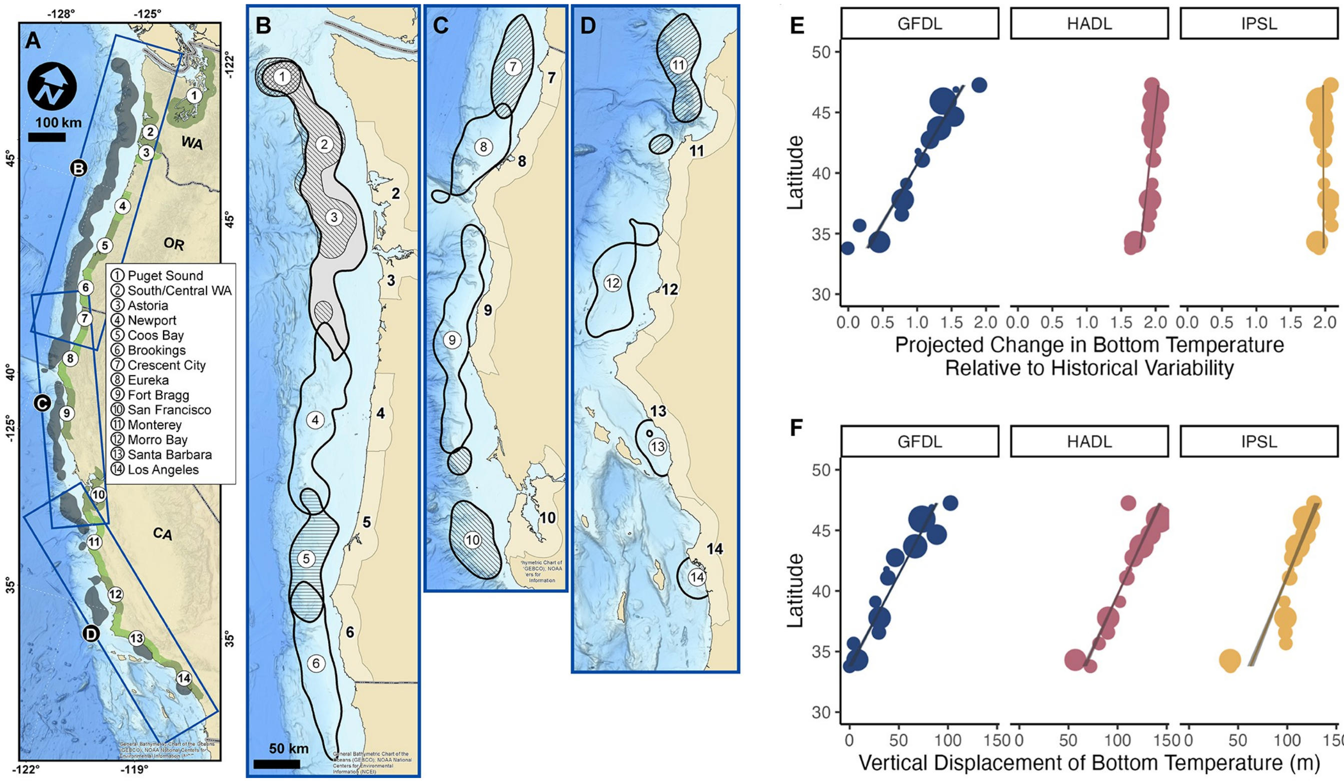


**Fig 4. Fishing footprints and geographic exposure to climate change within fishing footprints.** (a) Fishing footprint from 2011–2019 (dark gray regions) for U.S. West Coast groundfish fleets. Alternating light/dark green regions on land delineate the 14 port groups, which are numbered with corresponding names listed in inset legend. Three enlargement maps to the right show the 14 port groups landing bottom trawl-caught groundfish on land (numbered), but with distinct, individually delineated fishing footprints (corresponding circled numbers) associated with fleets fishing off Oregon and Washington (b) and California (c, d). Estimates of exposure of these fleets to climate change based on comparison of 30-year historic (1990–2020) and future (2065–2095) periods for (e) bottom temperature change relative to historic variability, and (f) vertical displacement of bottom isotherms. In (e) and (f), point size scales with the number of vessels in each fleet and these relationships were statistically significant ($p < 0.001$, S3 Table). GFDL, HADL and IPSL correspond to the three Earth system models used to develop dynamically downscaled projections of bottom temperature. GEBCO 2023 (NOAA NCEI Visualization) base map (https://noaa.maps.arcgis.com/home/item.html?id=8050bfc4eb4444758f194db95f817184). Credit: General Bathymetric Chart of the Oceans (GEBCO); NOAA National Centers for Environmental Information (NCEI).

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Our two measures of the adaptive capacity of the groundfish fishing fleets showed contrasting changes with latitude (Fig 5). Diversification, which we used as a proxy for the potential to adapt if fleets continue to fish where they are now (adapt in-place), declined significantly with increasing latitude (Fig 5A, S3E Table; $p<0.001$). While statistically significant, the differences in diversification between poleward and equatorward fleets due strictly to latitudinal position were small and uncertain in absolute magnitude (S16 Fig) and unlikely to be especially impactful to fleet-specific vulnerability (65–75% of potential edges were realized in most networks). In addition, the Puget Sound and Santa Barbara fleets had high leverage (S16 Fig). In contrast, fleets in poleward ports generally caught groundfish farther from ports of landing (~80km-250km) compared to ports in more equatorward California (in most cases <50km). Therefore fleet mobility (interquartile range of mobility: 40–90 km), which we use as a proxy for the potential for fleets to adapt by moving to new fishing grounds (adapt on-the-move), increased significantly with increasing latitude (Fig 5B, S3F Table; $p<0.001$). The Puget Sound fleet had high leverage in the regression of mobility against latitude, but did not modify the positive relationship observed in the full data set (S17 Fig).

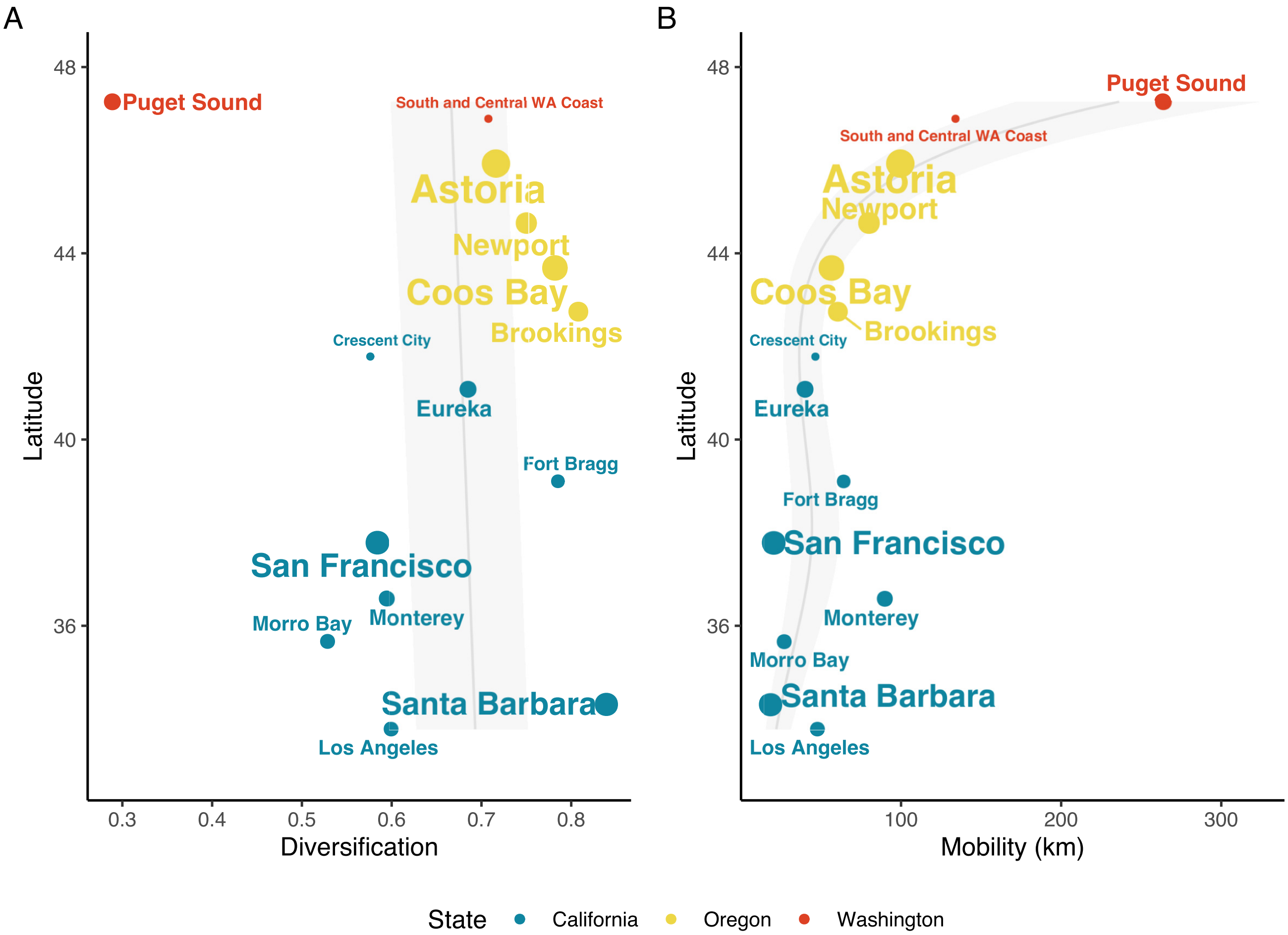


**Fig 5. Geographic variation in fleet fisheries diversification and fleet mobility.** Relationships between the latitude of ports of landings for U.S. West Coast groundfish fleets and two elements of the flexibility dimension of adaptive capacity: (a) diversification based on edge density of fisheries participation networks; and (b) mobility based on landings-weighted distance from port to fishing grounds. Points indicate averages across 2011–2019, point size scales with the number of vessels in each fleet, and these relationships were statistically significant (diversification: $p = 0.015$, mobility: $p < 0.001$, S3 Table). Colors correspond to the state in which each port occurs (blue: California, yellow: Oregon, red: Washington).

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Collectively, we found that the coupled social-ecological risk of poleward groundfish fishing fleets was elevated compared to more equatorward fleets (Fig 6, S19 Fig). Sensitivity created the greatest variation in vulnerability ($y$-axes in S18 Fig), which tended to be highest for fleets landing at ports in northern California, Oregon, and Washington. Under an adapt in-place strategy, risk was greatest for more poleward fleets because of their greater exposure and higher sensitivity (Fig 6A). Under an adapt on-the-move strategy, the greater exposure and sensitivity of more poleward fleets to climate change was dampened by their greater mobility, and fleets had similar risk scores from either being more vulnerable or more exposed, but not necessarily both more vulnerable and more exposed simultaneously (S19 Fig). Overall, latitude had a greater effect on risk of groundfish fleets to climate change under an adapt in-place strategy (compare slopes in S3G and S3H Table, risk scores in S19 Fig).

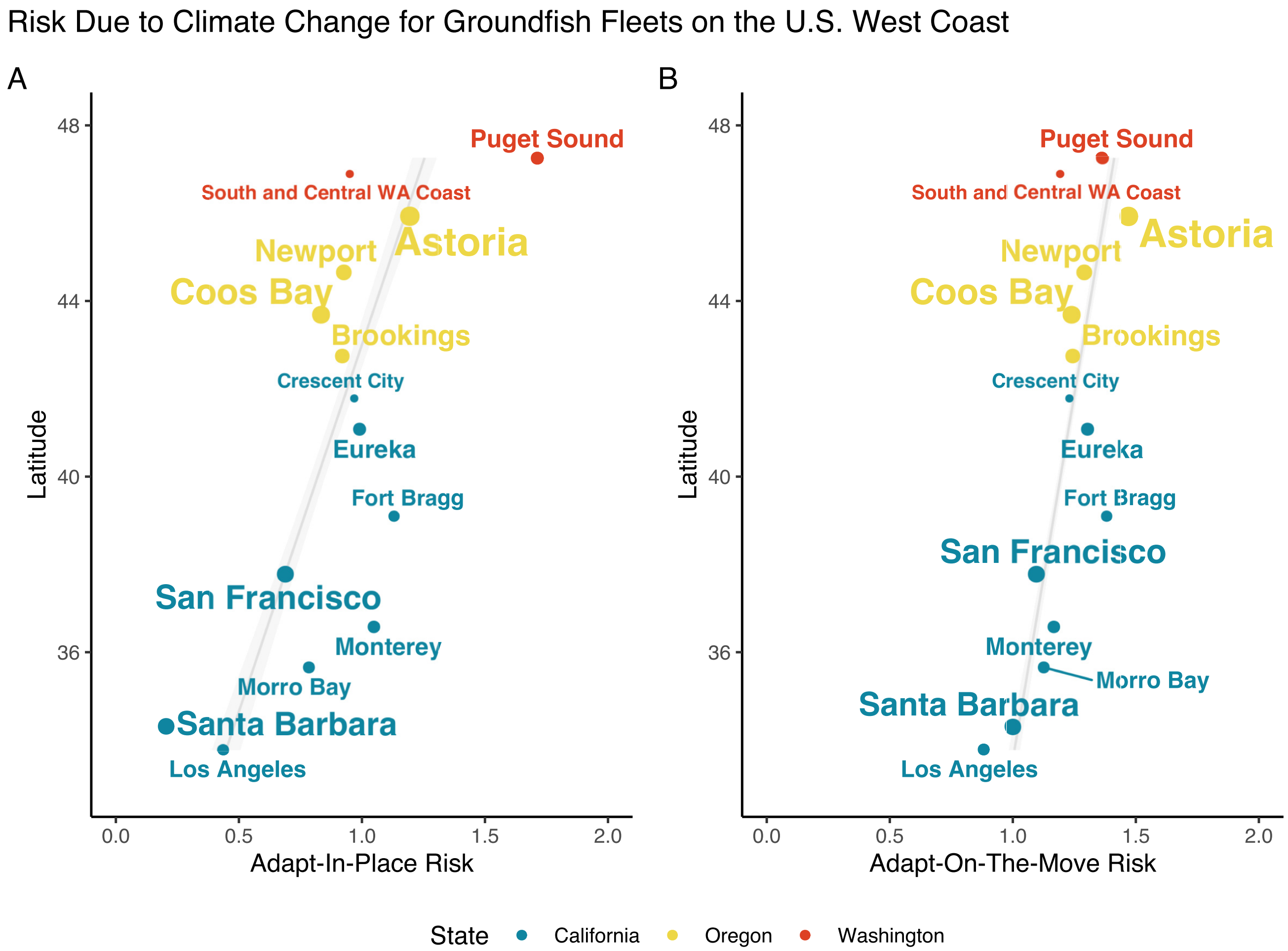


**Fig 6. Coupled social-ecological risk due to climate change for groundfish fleets on the U.S. West Coast.** (a) Assuming fleets change target species while remaining in current fishing grounds (adapt in-place); (b) assuming fleets shift fishing grounds while targeting current species (adapt on-the-move). Larger points and font sizes indicate fleets composed of a greater number of vessels, and these relationships were statistically significant ($p < 0.001$, S3 Table). Colors correspond to the state in which each port occurs (blue: California, yellow: Oregon, red: Washington).

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## Discussion

The translation of global-to-local projected impacts of climate change can facilitate strategic planning that helps resource-dependent communities and industries take a proactive role in their futures. One form this translation can take is climate risk assessments that are performed at scales relevant to individuals, communities, and decision makers [4]. Such steps increase the reliability and relevance of information by representing important social and biophysical processes more accurately and providing user-specific context. Focusing on the bottom trawl groundfish fishery along the U.S. West Coast, we found that more poleward fleets face greater risk due to climate change because of higher exposure and greater sensitivity in the form of economic dependence on groundfish. Specifically, we showed that poleward risk was greater if fleets rely on existing groundfish fishing grounds, which necessitates diversifying to other species and can come at a cost (e.g., investment in additional permit and gear types), rather than shifting fishing grounds and maintaining current catch composition. This result suggests that an adapt on-the-move strategy will better mitigate risk than an adapt in-place strategy for high-latitude fleets, assuming that the variable costs of fishing (e.g., due to changes in fuel prices and labor wages) relative to ex-vessel revenues remain similar to the present. These general inferences emerge from application of one indicator for each dimension of risk, which is an oversimplification, but also offers transparency and the potential for replicability for other fleets and regions. Our findings contrast with similar work in other parts of the world, such as Europe, where lower-latitude fleets and fisheries are expected to face greater climate risk [35,36,66]. While existing within-fishery flexibility on the U.S. West Coast provides some promise for coping with, reacting to, and adapting to projected impacts of climate change [67], our analysis highlights how further development of this and other dimensions of adaptive capacity could enhance resilience of these fishing fleets.

## Building climate resilience for fishing fleets

Parsing risk into its constituents (exposure, sensitivity, and adaptive capacity, under two contrasting adaptation strategies) suggests different types of interventions that can be implemented to reduce risk. Communities may have similar risk scores, but contrasting sources of risk, and therefore may respond favorably to customized interventions. Mitigating risk may require more proactive efforts to improve adaptive capacity, such as fisheries portfolio diversification or enhancing fleet mobility, or to reduce sensitivity through expansion of revenue streams, among other solutions [29,46,68]. For example, in California, there are existing precedents for enhancing adaptive capacity for fleets with latent risk (low sensitivity and low adaptive capacity). For instance, following the implementation of individual fishing quotas in 2011, members of the Fort Bragg, Morro Bay, Monterey, and Santa Barbara fleets organized quota risk pools with the support of local government and non-government organizations to navigate bycatch constraints, thereby enhancing resilience within the new regulatory environment [69].

In contrast, the suite of interventions for fleets that are potential adapters (because they have higher adaptive capacity and sensitivity, e.g., Fort Bragg or Astoria) are more likely to focus on a reduction in sensitivity. Livelihood diversification (e.g., through mariculture or tourism activities) can dampen sensitivity while also improving adaptive capacity in-place, whereas improving access to fish for other target species and in new (or previously closed) fishing grounds are more exclusively directed at reducing sensitivity [46,68]. Finally, there are interventions that could rescale the risk landscape across all fleets, such as recent efforts to create increased market share for groundfish [70]. Increased consumer demand for a diversity of groundfish could increase profit margins, augment financial safety nets for fishers, and provide an opportunity to take advantage of currently underutilized and abundant stocks. However, creation of market demand in specific areas requires resolution of mismatches between locations of fishery landings, seafood processing, and seafood markets (e.g., through accurate mapping of seafood supply chains and rescuing of stranded capital; [71]). In addition, market demand interventions may exacerbate ecological risk if they incentivize localized depletion of stocks to meet growing local demand [68,72].

Historical contingencies in management, market, and ecological forces provide important context for evaluating the most useful interventions, regardless of whether risk due to climate change is higher or lower for these fleets. These forces create a geography of pre-existing vulnerability, akin to that documented in other regions where shrinkage and disappearance of fishing communities has occurred [73] or where implementation of new management measures has set the stage for responses to subsequent shocks [25,74]. For the bottom trawl groundfish fishery on the U.S. West Coast, revenue has become more concentrated within fewer fleets over the last several decades, a trend that continued throughout the 2011–2019 period we focused on in this study. Furthermore, the narrower continental shelf available to California fleets has led to smaller fishing footprints (areal extent) and a lower projected exposure to expected ocean warming for equatorward groundfish fleets (Fig 4), which also tend to be composed of smaller, less mobile vessels (Fig 5 and S7 Fig, [73]). These trends are a result of the biogeographic context in which each fleet operates, a changed regulatory environment, historical impacts to more equatorward groundfish stocks [75], and various other factors (e.g., geographic locations of buyers, processors, and associated infrastructure; [37,45]). As in other fisheries (e.g., Dungeness crab; [76]), practices that level the playing field for the many smaller vessels composing equatorward groundfish fleets may help to reduce their climate risk. In contrast, for more poleward groundfish fleets that have high sensitivity, it may be more effective to employ approaches that bolster other dimensions of adaptive capacity such as organization, e.g., via social capital building to create cooperatives [46]. Each fleet's history complicates the many possible paths forward, but potential futures are made less opaque with the information we have provided here on climate risk.

## Future directions for assessing climate risk in fisheries

Our approach to understanding spatial heterogeneity in climate risk for fishing fleets in general, and on the U.S. West Coast in particular, highlights opportunities for future research. The data and methods we used to estimate exposure, sensitivity, and adaptive capacity, and to combine them into a risk index, deserve further examination. For instance, we found that estimates of exposure based on horizontal displacement of bottom isotherms are highly uncertain (S8 Fig). This result underscores the challenge of generating expectations about future ocean conditions and use, and brings into question how other environmental factors that affect species distributions, such as dissolved oxygen [77,78] may change and interact with the behavior of fishing fleets [79–82]. Another avenue of future research is integrating expectations for other fisheries in the participation networks (S5 Fig, [38,63]) that are likely to experience climate effects, which will add complexity to estimates of adaptive capacity. For example, Dungeness crab fisheries at higher latitudes may be negatively impacted by ocean acidification effects by the late 21st Century [51], and numerous Pacific salmon (*Oncorhynchus* spp.) populations along the U.S. West Coast are highly vulnerable to climate impacts at multiple life history stages [83]. An extension of this work could connect species distributions projected using dynamically downscaled ESM outputs (e.g., [84–86]) to fishing footprints directly, using expected changes in the resources themselves within customary use areas to derive estimates of exposure. Such an approach could capture the potential for more equatorward species moving into footprints while others move out ([87–89]; but see [90]), and would also need to address the potential for fleets to capitalize on these changes under existing regulations. There is also the question of how best to identify fishing areas, or footprints, for estimating exposure. Here we identified the primary fishing grounds where the majority of harvested biomass is extracted based on vessel landings by port. Alternative approaches could use metrics such as revenue [91], fisher days [33], or could define fishing areas specific to vessel home ports [23].

There are also alternative approaches for describing sensitivity and adaptive capacity. For example, rather than focus solely on economic dependence on a target species relative to all other commercial fisheries, it would be informative to quantify the economic dependence of fleets on target species relative to all other income streams including those outside of commercial fisheries. Such data are not necessarily widely available, though household survey research in small-scale fisheries provides a template for pursuing this line of inquiry [92–94]. Additionally, the sensitivity and adaptive capacity of crew on fishing vessels may be quite different than for captains or owners. Strong social identity related to participation in particular fisheries could affect fishers' willingness or ability to adapt by shifting to new fisheries or livelihood activities [95,96]. Ideally, future work to understand risk of fishing communities will embrace a participatory approach in which notions of community, vulnerability, and adaptive capacity are co-developed [97] and considered alongside perceptions of other risks beyond climate change [98]. Approaches such as fisheries learning exchanges may have the added benefit of building trust amongst stakeholders to allow for increases in flexibility in response to climate change, without jeopardizing ecological sustainability [99].

While we chose to analyze fleets defined by common fishing grounds and ports of landing as one type of community, there are other units of community analysis that are equally or more compelling (e.g., communities-of-place defined shoreside, [100,101]; and fisher networks emergent as communities-of-practice [102,103]). Different rubrics for describing communities may lead to greater or lesser emphasis on mobility and diversification as primary metrics to index adaptive capacity. Being able to fish a larger portfolio of species can buffer fishers' revenues against change and high variability [65]–but doing so often requires owning multiple permits, which may be cost prohibitive for many participants or difficult to manage given current jurisdictional boundaries [104]. This insight could lead to deeper exploration of geographic gradients in the assets dimension of adaptive capacity.

We do not know whether current levels of diversification and mobility are at an upper bound or if there is room for further adjustment given current costs (fuel consumption, insurance, etc.; [105]). Fishing new species may be constrained by fisheries regulations that are slow to adapt to shifting species distributions [21]. Specifically, for the bottom trawl groundfish fishery, some quota categories are restricted to certain geographic regions, which would be problematic if stocks move out of the designated areas [104]. Similarly, mobility may be limited for smaller-vessel fleets and larger-vessel fleets with more diversified catch, as has been demonstrated on the U.S. East Coast [73]. Diversification and mobility aspects of flexibility are underpinned by enabling conditions that intersect with other domains of adaptive capacity such as assets (e.g., financial resources), learning (e.g., access to knowledge, adaptable skill sets), and organization (e.g., community cohesion), all of which may vary across different community typologies [29,30,46]. Future work to explore these issues, for example through retrospective evaluation of community changes associated with adaptive capacity measures existing prior to a disruptive event [25,74], would be illuminating.

Assessments of risk due to climate change can be used to communicate potential impacts to people, regions, or sectors at local scales [5], and in so doing can provide rationale for medium- to long-term policy decisions intended to improve resilience. This case study provides a practical implementation of the widely-used IPCC risk assessment framework at a geographic scale that is relevant to fishers, communities, and U.S. federal fisheries managers. It achieves this appropriately-scaled outcome by integrating climatic, ecological, and socio-economic data from a regionally large-volume, relatively profitable, lynchpin fishery. These kinds of data are commonly available from many of the largest-volume, greatest-value fisheries globally. However, given that these data were also available for the relatively small fleets we assessed here, this framework may be viable for smaller-scale fisheries as well, especially with creative approaches to generating information streams (e.g., improving understanding of fishing grounds, economic dependence on target species, and mobility via structured surveys and participatory workshops; [97]). Similar analyses for fleets in other regions, coupled with scenario planning efforts [106,107], can provide more comprehensive insight into the risks of climate change for fisheries. This insight can be used to identify regions with the greatest potential to improve resilience to climate change through government-based regional action plans, self-determined actions, and via new legislation for fishery disaster responses (e.g., in the U.S. via the Fishery Resource Disasters Improvement Act) [26,29].

The contrasts observed here among U.S. West Coast groundfish fleets have explanations ranging from physics to market forces, and contingencies fueled by historical and present-day regulations. They add to evidence from the U.S. that more poleward fishing fleets may be at greater risk due to climate change [51,86], in contrast to expectations for greater equatorward risk in other parts of the world, such as Europe [35,36,66]. While the potential for the adapt on-the-move strategy to mitigate greater poleward risk exceeded that for the adapt in-place strategy, our results imply that neither of these within-fisheries flexibility measures are sufficient to disrupt fundamental geographic patterning of risk. Rather, alternative adaptation approaches that build out other attributes of flexibility, including those external to commercial fisheries, and alternative dimensions of adaptive capacity not addressed here, may prove most fruitful for ameliorating latitudinal patterns of climate risk. For example, increased agency for fishers to access new target species entering their fishing grounds, introduction of greater flexibility to shift fishing permits quickly, and organizational support to develop new markets are all aspects of adaptive capacity that can reduce climate risk. Evaluations of climate risk and adaptation approaches that capture these other types of issues need not be more complex, but instead can strive for transparency, replicability, and comparability with this one. While the insights presented here are specific to the U.S. West Coast, they suggest that coupled social-ecological risk assessments like this one offer a promising path forward for evaluating climate adaptation options in other regions around the world.

## Supporting information

**S1 Fig. Bottom temperature change, horizontal displacement of bottom temperature, and vertical displacement of bottom temperature projected by three dynamically downscaled Earth System Models (GFDL, HAD, IPSL) for the period 2025–2055 and 2065–2095.**
(TIFF)

**S2 Fig. Schematic of thermal displacement calculation.** (a) Historical (1990–2020) bottom temperature, (b) bottom temperature change between historical and future (2065–2095) bottom temperatures, and (c) future bottom temperature and thermal displacement. The thermal displacement calculation is illustrated for an example location at 124.2˚W, 43.9˚N. At that location the historical mean temperature was 10.1˚C and the projected bottom temperature increase is 2.2˚C. In the future period, moving from the future temperature (12.3˚C) to the historical temperature (10.1˚C) requires an offshore horizontal displacement of 25 km, with an associated 98 m increase in bottom depth (vertical displacement). This example uses projections forced by the IPSL Earth Systems Model, assuming Amendment 28 bottom trawl fishery closures.
(TIFF)

**S3 Fig. Contextual map, indicating the landing ports and port groups for groundfish fleets on the U.S. West Coast, as well as fishery closure areas and untrawlable habitat.** Landing ports are represented by white squares, while hatched regions show areas closed to bottom trawl fishing and red regions show untrawlable habitat. Green shading reflects 20km inland buffer for each of the 14 IO-PAC port groups. Left map shows fishery closures under Amendment 19, from ~2003–2019, and right map shows fishery closures from 2020 to present under Amendment 28 which were used for thermal displacement calculations. GEBCO 2023 (NOAA NCEI Visualization) base map (https://noaa.maps.arcgis.com/home/item.html?id=8050bfc4eb4444758f194db95f817184). Credit: General Bathymetric Chart of the Oceans (GEBCO); NOAA National Centers for Environmental Information (NCEI).
(TIFF)

**S4 Fig. Fishing footprints from 2011–2019 for U.S. West Coast groundfish fleets, using the 50, 75, 90, and 95 percent volume contour.**
(TIFF)

**S5 Fig. Example fisheries participation networks for 3 port groups on the U.S. West Coast.** Example fisheries participation networks for the Puget Sound (left), Coos Bay (middle), and Morro Bay (right) port groups on the U.S. West Coast (2019). Each fishery is depicted as a node, while pairs of nodes are connected by lines, called edges, that integrate information about vessels participating in both fisheries. In these examples, Coos Bay and Morro Bay have higher edge densities than Puget Sound, implying that fishers in these port groups have access to a greater range of alternative fishing opportunities if one node (fishery) is compromised because of poor stock availability, a fishery closure, or other regulatory actions.
(EPS)

**S6 Fig. Groundfish fleet depths.** Landings-weighted depth of fishing grounds for U.S. West Coast groundfish fleets from 2011–2019 (median with 95% confidence interval).
(TIFF)

**S7 Fig. Groundfish fleet vessel lengths.** Vessel lengths for U.S. West Coast groundfish fleets from 2011–2019 (median with 95% confidence interval).
(TIFF)

**S8 Fig. Horizontal displacement of fishing footprints.** Estimates of exposure of U.S. West Coast groundfish fleets to climate change based on comparison of 30-year historic (1990–2020) and future (2065–2095) periods for horizontal displacement of bottom isotherms. Note that the direction of the association between horizontal displacement and latitude varied between the three Earth System Models (GFDL, HADL, IPSL).
(TIFF)

**S9 Fig. Leave one out cross validation for regression of exposure based on bottom temperature change relative to historical variability using the GFDL Earth System Model against latitude.** Points and error bars represent estimates of the coefficient of this regression (±2 SE) with the corresponding fleet removed from the data, red line indicates the mean estimate of the coefficient with all fleets included in the analysis. Changes in sign of the coefficient indicate a difference in the qualitative directional relationship between exposure based on bottom temperature change relative to historical variability and latitude.
(TIFF)

**S10 Fig. Leave one out cross validation for regression of exposure based on bottom temperature change relative to historical variability using the HADL Earth System Model against latitude.** Points and error bars represent estimates of the coefficient of this regression (±2 SE) with the corresponding fleet removed from the data, red line indicates the mean estimate of the coefficient with all fleets included in the analysis. Changes in sign of the coefficient indicate a difference in the qualitative directional relationship between exposure based on bottom temperature change relative to historical variability and latitude.
(TIFF)

**S11 Fig. Leave one out cross validation for regression of exposure based on bottom temperature change relative to historical variability using the IPSL Earth System Model against latitude.** Points and error bars represent estimates of the coefficient of this regression (±2 SE) with the corresponding fleet removed from the data, red line indicates the mean estimate of the coefficient with all fleets included in the analysis. Changes in sign of the coefficient indicate

a difference in the qualitative directional relationship between exposure based on bottom temperature change relative to historical variability and latitude.
(TIFF)

**S12 Fig. Leave one out cross validation for regression of exposure based on vertical displacement of bottom temperature using the GFDL Earth System Model against latitude.** Points and error bars represent estimates of the coefficient of this regression (±2 SE) with the corresponding fleet removed from the data, red line indicates the mean estimate of the coefficient with all fleets included in the analysis. Changes in sign of the coefficient indicate a difference in the qualitative directional relationship between exposure based on vertical displacement of bottom temperature and latitude.
(TIFF)

**S13 Fig. Leave one out cross validation for regression of exposure based on vertical displacement of bottom temperature using the HADL Earth System Model against latitude.** Points and error bars represent estimates of the coefficient of this regression (±2 SE) with the corresponding fleet removed from the data, red line indicates the mean estimate of the coefficient with all fleets included in the analysis. Changes in sign of the coefficient indicate a difference in the qualitative directional relationship between exposure based on vertical displacement of bottom temperature and latitude.
(TIFF)

**S14 Fig. Leave one out cross validation for regression of exposure based on vertical displacement of bottom temperature using the IPSL Earth System Model against latitude.** Points and error bars represent estimates of the coefficient of this regression (±2 SE) with the corresponding fleet removed from the data, red line indicates the mean estimate of the coefficient with all fleets included in the analysis. Changes in sign of the coefficient indicate a difference in the qualitative directional relationship between exposure based on vertical displacement of bottom temperature and latitude.
(TIFF)

**S15 Fig. Leave one out cross validation for regression of economic dependence, as a measure of sensitivity, against latitude.** Points and error bars represent estimates of the coefficient of this regression (±2 SE) with the corresponding fleet removed from the data, red line indicates the mean estimate of the coefficient with all fleets included in the analysis. Changes in sign of the coefficient indicate a difference in the qualitative directional relationship between economic dependence and latitude.
(TIFF)

**S16 Fig. Leave one out cross validation for regression of diversification against latitude.** Points and error bars represent estimates of the coefficient of this regression (±2 SE) with the corresponding fleet removed from the data, red line indicates the mean estimate of the coefficient with all fleets included in the analysis. Changes in sign of the coefficient indicate a difference in the qualitative directional relationship between diversification and latitude.
(TIFF)

**S17 Fig. Leave one out cross validation for regression of mobility against latitude.** Points and error bars represent estimates of the coefficient of this regression (±2 SE) with the corresponding fleet removed from the data, red line indicates the mean estimate of the coefficient with all fleets included in the analysis. Changes in sign of the coefficient indicate a difference in the qualitative directional relationship between mobility and latitude.
(TIFF)

**S18 Fig. Social vulnerability of groundfish fleets on the U.S. West Coast.** We assume that fleets either (a) adapt in-place by changing target species while remaining in current fishing grounds, or (b) adapt on-the-move by shifting fishing grounds while targeting current species. Font size and color scales with projected exposure to climate change. Vertical and horizontal lines represent median values across fleets.
(EPS)

**S19 Fig. Social vulnerability of groundfish fleets on the U.S. West Coast relative to exposure to climate change.** Social vulnerability, defined as sensitivity relative to adaptive capacity, in relation to exposure to climate change for U.S. West Coast groundfish fleets, under the assumption that fleets (a) adapt in-place by changing target species while remaining in current fishing grounds, or (b) adapt on-the-move by shifting fishing grounds while targeting current species. Font size, point size, and Euclidean distance from the origin scales with risk, while color corresponds to latitude.
(EPS)

**S1 Table. Linkage between individual ports and IO-PAC port groups.** The port groupings were developed by the PFMC for biennial groundfish harvest specifications. Aggregating individual ports into port groups is necessary to provide a feasible set of geographic areas for a coastwide climate risk analysis. Analysis at the individual port-level would violate confidentiality requirements, because there are often fewer than three buyers in any one port.
(DOCX)

**S2 Table. Percent reduction in hauls to achieve a clean dataset.** Percent reduction in hauls to achieve a clean dataset by reason for years 2011–2019, based on processing steps detailed here: https://zenodo.org/record/7916821.
(DOCX)

**S3 Table. Statistical results.** Summary of statistical results of regressions of (a-c) exposure, (d) sensitivity, (e-f) adaptive capacity, and (g-h) risk indices relative to latitude of each fleet.
(DOCX)

**S1 Text. Methods related to Fig 1.** Methods Related to Fig 1.
(DOCX)

**S2 Text. Exposure: Spatial considerations for thermal displacement.** Description of fishery closure areas and untrawlable habitat that influenced calculations of horizontal and vertical thermal displacement.
(DOCX)

**S3 Text. Leave one out cross validation analyses for regressions.**
(DOCX)

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