Shifting habitats expose fishing communities to risk under climate change

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Introductory paragraph

Climate change is expected to profoundly impact the distribution, abundance, and diversity of marine species globally (1, 2). These ecological impacts of climate change will affect human communities dependent on fisheries for livelihoods and wellbeing (3). While methods for assessing the vulnerability of species to climate change are rapidly developing (4) and socio-ecological vulnerability assessments for fisheries are becoming available (5), there has been less work to understand how the ecological impacts of climate change will differentially affect fishing communities. We developed a linked socio-ecological approach to assess the exposure of fishing communities to risk from climate change that draws on nearly two decades of data on fishing community practices and five decades of surveys on marine fish and the physical environment. Using a case study of New England and Mid-Atlantic (USA) fishing communities, we found that community-level differences in fishing practices, together with spatial differences in projected habitat suitability for species, led to a wide range of exposures to risk among fishing communities even within the same region. By integrating climate, ecological, and socio-economic data at a scale relevant to fishing communities, this analysis identifies where strategies for adapting to the ecological impacts of climate change will be most needed.

Introduction

Climate change is altering the distribution, abundance, and diversity of marine species globally (1, 2, 6). On a local scale, conditions will become more favorable for some species and less favorable for others, which will ultimately alter the mix of species available for harvest in any given coastal ecosystem. Despite widespread acknowledgement that climate change is a key challenge for sustainable fisheries and communities (7, 8), we have limited understanding of the relative exposure of fishing communities to climate change risk. Such information is critical for creating adaptation policies, prioritizing research and management efforts, and for reducing community exposure to risk on the ground (7).

Ecological risk or vulnerability assessments identify which species or populations may be most at risk from climate change or other stressors. For fisheries, these assessments are usually aimed at the species or stock level (e.g. 4). However, a fishing community's exposure to risk depends not only on which species or stocks they target, but where in the ocean they target them and how much flexibility they have to adapt to new conditions. Social-ecological risk assessments can link ecological risk to community vulnerability (3, 5), but methods to do so at the appropriate scale for adaptation planning have not been well-developed.

While fish species may shift in response to climate change (6), fishers are often limited in where they can fish based on local ecological knowledge (LEK), vessel size or gear type, geographic distance, spatial management or conservation measures, and in some cases, customary territories (9). Peer groups of vessels from the same port and using the same gear type are often subject to a common set of spatial constraints (e.g. shared LEK, vessel mobility) and, as a result, typically exhibit distinct and relatively enduring spatial patterns of ocean use (10, 11). The "communities-at-sea" concept (11) recognizes that shared patterns of ocean use indicate shared spatial constraints as well as resident community processes and practices that shape both community identity as well as the capacity to adapt and respond to environmental change (12). The community-at-sea concept was developed based on communities in the Northeast region of the USA (NEUS), but could be applied more generally to identify groups of fishers likely to face similar challenges and opportunities under climate change.

To develop and test socio-ecological methods for assessing the exposure of fishing communities to risk under climate change, we integrated climate, ecological, and socio-economic data from the NEUS at the scale of communities-at-sea. First, we quantified the spatial patterns of projected changes in habitat suitability for individual species under climate change. We then linked these projected ecological changes to information on fishing community practices to assess how exposed fishing communities were to risk based on their harvest portfolios and spatial use of the ocean. We discuss these results in light of adaptation possibilities and barriers. Providing local-scale information on the projected changes to species habitat, and the exposure of coastal communities to these changes, is an important step towards creating climate adaptation plans and prioritizing adaptation actions and investments.

Results

Species distribution models fit to more than 40 years of scientific survey data indicated that temperature was a significant predictor of species occurrence in space and time based on out-of-sample predictive skill (Table S1). For the majority of species (24 of 33), habitat was projected to improve in some regions of the NEUS shelf, but deteriorate in others by 2040-2050 (Figure 1B). For instance, monkfish habitat was expected to expand in the Gulf of Maine (GOM) but become less suitable throughout the Mid-Atlantic Bight (Figures 1C, 1D). Only two species were expected to have improved habitat throughout the region, while seven were expected to have generally decreased habitat suitability (Figure 1B). Atlantic cod was one of the species expected to experience entirely negative impacts, and temperatures even in the coldest areas were expected to exceed the thermal optimum for cod by 2050. In fact, rapid warming in the last decade has already contributed to the collapse of GOM cod (13). In general, the northern part of the study region was expected to have more “winners” (species gaining habitat suitability), while the Mid-Atlantic Bight and Georges Bank had more “losers” (species losing suitability). However, we only included species that were historically common in the trawl survey, thus missing species that may expand into the Mid-Atlantic in a warmer future.

Fishing communities varied drastically in the size and location of their servicesheds, or customary fishing grounds (see Methods; Figure S1, Table S2). Of the four vessel/gear types examined here, communities of large bottom trawlers (>65ft) had the largest servicesheds (mean 40,000 km^2), extending often to the continental shelf break. Communities of small trawlers typically utilized much smaller areas (mean 4300 km^2) closer to port. Beyond gear type, even nearby communities showed little overlap in their spatial use of the marine environment in some cases (Figure S2). These geographic differences translated into different exposures of fishing communities to the ecological impacts of climate change, even when targeting the same species (e.g. among gillnetters harvesting monkfish in MA; Figure 2).

Ultimately, fishing community exposure to risk (defined as projected changes in resource availability due to changes in habitat) depended on both their spatial use of the ocean and the portfolio of species caught. Revenue-weighted risk scores showed that a majority (64 of 85) of communities were exposed to increased risk by midcentury (Figure 3), suggesting declines in future fishing opportunities based on current practices. Exposure varied by state and vessel/gear type ($p<0.01$; Figure S3). Communities of small trawlers in Maine were most exposed because of their historical dependence on species expected to lose habitat suitability in the future (e.g., Atlantic cod and witch flounder).

However, we also found small-scale differences. For instance, communities-at-sea for small groundfishing vessels in Sandwich and Chatham, MA, were only 45 km apart but had different risk profiles due to their differing catches and servicesheds (Figure S4). The Sandwich community depended on winter flounder (67% of revenue), cod (8%) and yellowtail flounder (5%). Chatham's community had a more diverse revenue portfolio, with the greatest contributions from witch flounder (24%), cod (21%), and winter flounder (10%). Sandwich was expected to be less exposed to risk and have increased opportunities under climate change, whereas nearby Chatham was projected to be exposed to increasing risk. Notably, all but three out of 85 communities in this study have historically targeted at least one species that was projected to gain habitat within their serviceshed under climate change (Figure 3).

Discussion

By combining biophysical projection models with community-level data on fishing practices, we show that the exposure of fishing communities to climate risk depends not only on biophysical changes in the ocean, but also on how those changes intersect with community practices. Communities differ substantially in the species they target and where they target them, resulting in different risk profiles for communities even in close proximity. These findings echo community impacts that have been documented when areas of the ocean have been closed to fishing (14), but in this case, the impacts were driven by a changing environment. Our species-level results were broadly consistent with previous projections of climate change impacts in the region (4, 15; Table S3, Figure S5, S6, Supplementary Discussion). However, by considering variation in habitat alongside differing community practices, we captured variation relevant at the scale of communities. This emphasizes the importance of considering heterogeneity in both community practices and ecological responses when evaluating exposure to risk.

Our analysis indicated which communities-at-sea were most exposed to risk and most likely to need to adapt to a changing environment. Adaptation at the community level will likely require either shifting where vessels fish to follow their target species (16) or rebalancing the species caught towards winners rather than losers. In both cases, the speed at which a community may adapt will be determined by a range of factors. Evidence suggests that the overwhelming determinant of where fishers fish is their historical pattern of fishing (10). This context suggests that fishers will be slow to adapt to distributional shifts, preferring traditional fishing grounds over new, less familiar locations. Information sharing through social networks can lead to faster adaptation (14, 17), but while fishers in the NEUS have strong social capital in general, information sharing has been declining (18). Practical and regulatory considerations also shape how easily communities can follow their target species through space. Small vessels are limited in how far they can travel from port (16), and all vessels face travel costs. Shoreside infrastructure requirements and regulations dictating where species may be landed further hinder the ability of communities to move fishing grounds (19). Differences among communities in their responses to ongoing shifts in fish distributions have already been observed, including in the NEUS (16, 20) and Alaska (21) and likely reflect community-specific constraints to adaptation.

We have assessed the exposure of communities to risk based on their recent catch and revenue portfolios. However, one of the most important ways that communities can adapt to a changing ocean environment is by shifting their species portfolio. There is evidence that this is already happening, including the blueline tilefish fishery that emerged north of Cape Hatteras, NC in the early 2000s (22); new fisheries for squid, John dory, red mullet and sea bass that have emerged in the United Kingdom (23); and squid fisheries in the Gulf of Maine that developed during the particularly hot 2012 summer (24). However, there are also constraints to switching to new species, including limited entry in many fisheries or the high cost of permits or quota shares (25). Catch diversification can buffer fishers and communities against ocean change (16, 25, 26), but market forces can also incentivize specialization (27). Additional research is needed to understand how regulatory, economic, social, and other incentives shape adaptive capacity in fishing communities.

The type of community risk profiles we developed may be useful for climate adaptation in practice. Long-term projections for a community can help guide strategic decisions by individual fishers, processors, or other business-owners about investment and divestment in permits, quota, boats, gear, or in the time gaining or maintaining the local ecological knowledge to fish for particular species (8). Risk profiles could help guide strategic decisions by a port or municipality about infrastructure investment, community cooperatives, or the role of fishing in the local economy, especially when considered alongside indicators of social vulnerability (5). For a fisheries manager, understanding how fishing opportunities will change for communities can be important for charting out adaptation pathways and removing barriers along those pathways (28).

Notwithstanding the potential utility of our projections, several caveats should be noted. Temperature structures the physiology of marine species (29), but the species distribution models that we used detected correlations (not causation) and did not consider parameters such as pH or oxygen. The models implicitly assumed that species distributions were in equilibrium with their environment; that species interactions, phenology, disease, and acclimation will stay the same in the future; and that evolution will not be important. We explored parametric uncertainty (Figure S7), but future work should also explore structural uncertainty and sensitivity to the climate model. Coarse-scale GCMs, for example, may underestimate future warming on the NEUS shelf (30).

Conclusions

Our work highlights the importance of matching ecological and social scales in climate vulnerability assessments. We suggest that, in order to assess vulnerability at scales relevant to fishing communities, finer scale information on ecological processes as well as community practices is needed. Habitat heterogeneity and its interaction with species preferences results in spatial variation in impacts to species. Overlaid on these are enduring and unique patterns of ocean use by fishing communities that result in differential exposure of communities to climate change risk. Integrated, data-driven socio-ecological approaches can advance adaptation planning in communities dependent upon climate-sensitive resources.

Methods

Characterizing thermal habitat suitability for species

Bottom trawl data from the NOAA Northeast Fisheries Science Center (NEFSC) fall (1963-2014) surveys were used to characterize the realized thermal niches of species. At each survey station, fish of each species were counted and weighed, and surface and bottom temperature measurements were taken (details in (31)). Correction factors were applied to standardize catch rates for changes in vessel and gear type. A total of 33 species were selected based on their near continuous presence in the survey as well as relative importance to commercial fisheries. For 4 species, data from 1972 onwards were used because observations were irregular prior to that year.

GAMs were used to estimate the realized thermal niches of species. We restricted k (number of knots) to 4 or 6 for each of our covariates to ensure biologically meaningful responses. Our response variable was probability of occurrence in a trawl haul, and we used a binomial response with logit transform:

$$p(occur_{y,j}) \sim logit^{-1}\,(s(ST_{y,j})+s(BT_{y,j})+s(meanbiomass_{y})+s(rugosity_{j}))$$

where $ST_{y,j}$ and $BT_{y,j}$ are sea surface temperature and bottom temperature measured at each haul location *j* in year *y*, and $meanbiomass_y$ is the average annual catch across all hauls to account for interannual changes in abundance due to, e.g., fishing. $Rugosity_j$ is a measure of benthic habitat roughness, measured as the Terrain Ruggedness Index (32), using the GEBCO 2014 30-arcsecond bathymetry data (downloaded 4 Feb 2015 from http://www.gebco.net/). The resulting estimated smooth functions describing the relationship between probability of occurrence and temperature can be interpreted as realized thermal niches. Temperature may also be a proxy for other ecological conditions, such as prey availability. We did not include other habitat variables such as oxygen concentration or pH because of a lack of long-term spatial data for those variables.

For each species, the change in predicted probability of occurrence under future (2040-2050) projected climate conditions was compared to historical (1963-2005) conditions for each cell within a 0.25°x0.25° spatial grid. Because the modeled probability of occurrence included a component of catchability, values for each species were scaled by dividing by the maximum observed or predicted probability of occurrence across the study area. Positive values for a grid square indicated a projected increase in probability of occurrence, whereas negative values indicated a projected decrease in probability of occurrence. Throughout the study we refer to habitat suitability rather than probability of occurrence to specifically focus on climate-driven changes in habitat, as actual species occurrence depends on additional factors such as harvest policies.

Model performance and uncertainty

To test whether including temperature provided predictive information about species presence-absence, predictive error was quantified for the full models and models without temperature covariates. Models were fit to a training dataset consisting of the first 80% of samples (1963 - 2004), and model predictions for the test dataset (2005 - 2014) were compared with observations. The mean absolute error (MAE) was calculated as:

$$MAE = \frac{1}{n}\sum_{i}^{n} |(f_i - y_i)|$$

where f_i are predictions from the model and y_i are observed data. Note that the split of data into testing and training datasets was only used to assess model performance, and models fit to all available data were used for the rest of the study in order to best describe the realized thermal niches.

To assess the impact of uncertainty in model parameters on our results, we drew 1000 samples from the posterior distributions for the estimated GAM coefficients and then calculated predictions of historical and future probabilities of occurrence. For each cell on the projection grid, the 5th and 95th percentiles of calculated risk (change in scaled probability of occurrence) across the 1000 simulations were taken as prediction intervals.

Climate projections

Future temperatures were calculated by adding projected changes in surface and bottom temperatures to surface and bottom temperature climatologies (delta method; 33, 34). Climatologies were calculated from the surface and bottom temperature records in the NEFSC fall bottom trawl surveys 1963-2005. Records were averaged within 0.25x0.25° grids within each decade, then averaged across decades to reduce the impact of changes in the number of data points available in each decade (see (34)).

Projected changes in surface and bottom temperatures were calculated from a set of 13 global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (see Table S4) under Representative Concentration Pathway (RCP) 8.5, which represents a "business-as-usual" scenario. These models were used in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Changes were calculated as the difference between the base historical period (1963-2005) and each future year (2006-2100), averaged across the months of the climatology (September-December). Changes in temperature in each future year were additionally corrected for climate model drift, as assessed in the climate model's control simulation (no increase in greenhouse gases) by regressing temperature against year. The climate models were evaluated on a 1x1° grid, as is standard for these models. Models not on a 1x1° grid were interpolated to that scale before analysis. Changes in temperature from each model were then matched to the appropriate grid and depth of the surface and bottom temperatures in the climatology. Any grid cells in the climatology that were not directly overlapped by a grid in a climate model were interpolated with inverse distance weighting. For this study, we focused on projected conditions during the period 2040-2050 to reflect conditions approximately one human generation into the future.

Characterizing communities-at-sea and their servicesheds

Communities-at-sea are peer-groups of vessels which share a gear type and are associated with a particular port (e.g., vessels from New Bedford, MA that use gillnets). For vessels using trawl gear, small and large trawlers are considered separate communities according to vessel length (<> 65 feet). We used Vessel Trip Report (VTR) data for commercial fishing trips from 1996 to 2014, as reported by vessel captains , to determine the at-sea "servicesheds" or customary fishing grounds of communities. We use “serviceshed” to describe the area from which a community has historically received ecosystem services (35), specifically fish in this case. A trip was classified as belonging to a community if it shared the community's gear type and landing port, and either the vessel either declared that port as its principal port or landed in that port at least 50% of its trips that year (see (12, 16)).

Once aggregated into communities, trips were then weighted by a variable (“fisherdays”) indicating labor time expended on each trip: trip length (in days) multiplied by the number of crew on board (see (12)). Fisherdays indicate how important an area at sea is to a community in terms of how much time they invest in that location.

Given reported trip locations and fisherdays, we then created raster maps using a kernel density method. The resultant maps distribute fisherdays using different size kernels depending upon the fishery/gear-type/length. Nearshore fishing was processed using a smaller kernel (7.5 - 10 km) than offshore fishing (10 - 15 km). We used the area defined by a 90% volume contour (i.e., an area which encompasses 90% of fisherdays) to define the customary fishing grounds or servicesheds for a community. While fishing locations are reported with some error on VTRs (36), interviews with fishers indicated that aggregate maps of servicesheds were reasonably accurate (11; Supplementary Methods). For this analysis we focused on communities using gear that targets species also captured well in the NEFSC trawl survey (large trawlers, small trawlers, gillnet, and longline). Furthermore, we only analyzed communities present in the dataset for at least 8 years. These filters resulted in a subset of 98 communities for which we assessed exposure to climate change risk.

While the VTR program is designed to document all fishing trips by federally permitted vessels since 1994, the dataset is not complete: earlier years suffer from clear under-reporting, some Mid-Atlantic states did not collect VTR in early years, vessels without federal permits (e.g., those fishing exclusively in state waters) do not file VTRs, and some vessels with federal permits are occasionally exempt when fishing in state waters. Communities with fewer than 3 vessels were omitted to maintain confidentiality.

Landings and prices

To compare the relative historical importance of particular species to a community-at-sea, landings data were compiled from vessel trip reports and summed over the available years of data for each community. Price information was extracted from NOAA Fisheries, Fisheries Statistics Division (https://www.st.nmfs.noaa.gov/st1/commercial/landings/annual_landings.html). We used the average price per lb by species, adjusted for inflation (real 2014 prices in US$), over the period for which we had community-level data. State-level prices were used when available, and otherwise regional prices were used.

Fishing community exposure to risk

We assessed a community's exposure to risk based on their historical dependence on species and spatial fishing patterns. A community was more exposed to risk if the species from which it historically earned the most revenue were projected to lose habitat in the locations where the community has traditionally fished. Specifically, risk exposure scores for communities were calculated as:

$$Risk_c = \sum_{s=1}^{33} S_{s,c} * pRev_{s,c},$$

where $S_{s,c}$ is the mean projected change in habitat suitability for species *s* across the serviceshed of community *c*, and $pRev_{s,c}$ is the proportion of historical revenues from fishing that the community has derived from species *s*. Because some communities harvested species not included in our study (e.g. whelk), but which may represent significant sources of income, we only computed risk for a community if at least 70% of their historical revenues were accounted for by species in this study, resulting in scores for 85 communities. Note that by focusing on species well-sampled by the trawl survey, risk exposure scores did not include potential emergent fisheries for species expanding into the study area from the south. Positive risk exposure scores indicated expanding opportunities for communities based on their historical fishing revenue portfolios and projected changes to species habitat at sea, while negative values indicated shrinking opportunities and increased exposure to negative impacts of climate change. This approach considers the exposure of a community to risk based on their historical practices, thus highlighting when and where adaptation may be necessary, It does not attempt to predict how a community might alter their fishing grounds or catch portfolios in the future. Risk based on catch proportions was highly correlated (r = 0.94) with risk based on revenues (Figure S8).]

Acknowledgments

We thank NOAA-NEFSC for making data available from bottom trawl surveys and vessel trip reports, particularly Mike Fogarty, Julie Olson, and Sean Lucey. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. Thomas Frölicher helped with processing of the CMIP5 data. Funding for this project was provided by the Gordon and Betty Moore Foundation and by National Science Foundation #OCE-1426891. E. Fuller and T. Young were supported by NSF (GRFP & GEO-1211972, and GRFP DGE: 0937373, respectively).

Author contributions

LAR, RG, and MLP designed research; KStM provided data and the framework for characterizing communities-at-sea and their servicesheds; LAR, TY, EF, and MLP conducted analyses; all authors contributed to conceptual development; LAR and MLP wrote the manuscript with input from all authors.

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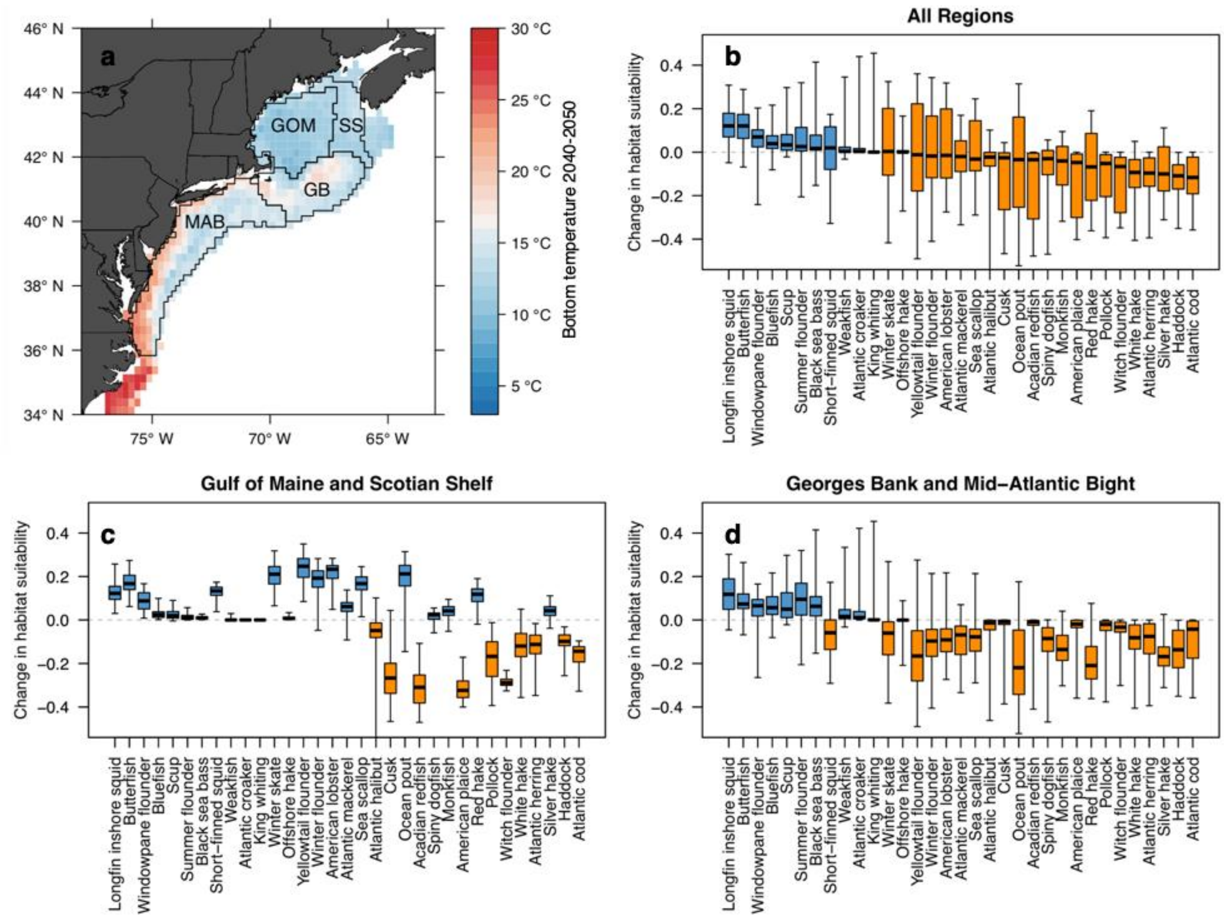

Figure 1: Projected changes in the thermal environment and species-specific habitat suitability on the NEUS shelf. a) Mean projected future (2040-2050) bottom temperatures, calculated for the months of Sep. – Nov. to correspond to historical survey timing. The Gulf of Maine (GOM), Scotian Shelf (SS), Georges Bank (GB) and Mid-Atlantic Bight (MAB) are indicated. The distributions (summarizing across space) of projected changes in habitat suitability for 33 species are shown for (b) the entire shelf, (c) GOM and SS, and (d) GB and MAB. Positive values indicate an increase in suitability in 2040-2050 over 1963-2005. Colors indicate whether the median is above (blue) or below (orange) zero.

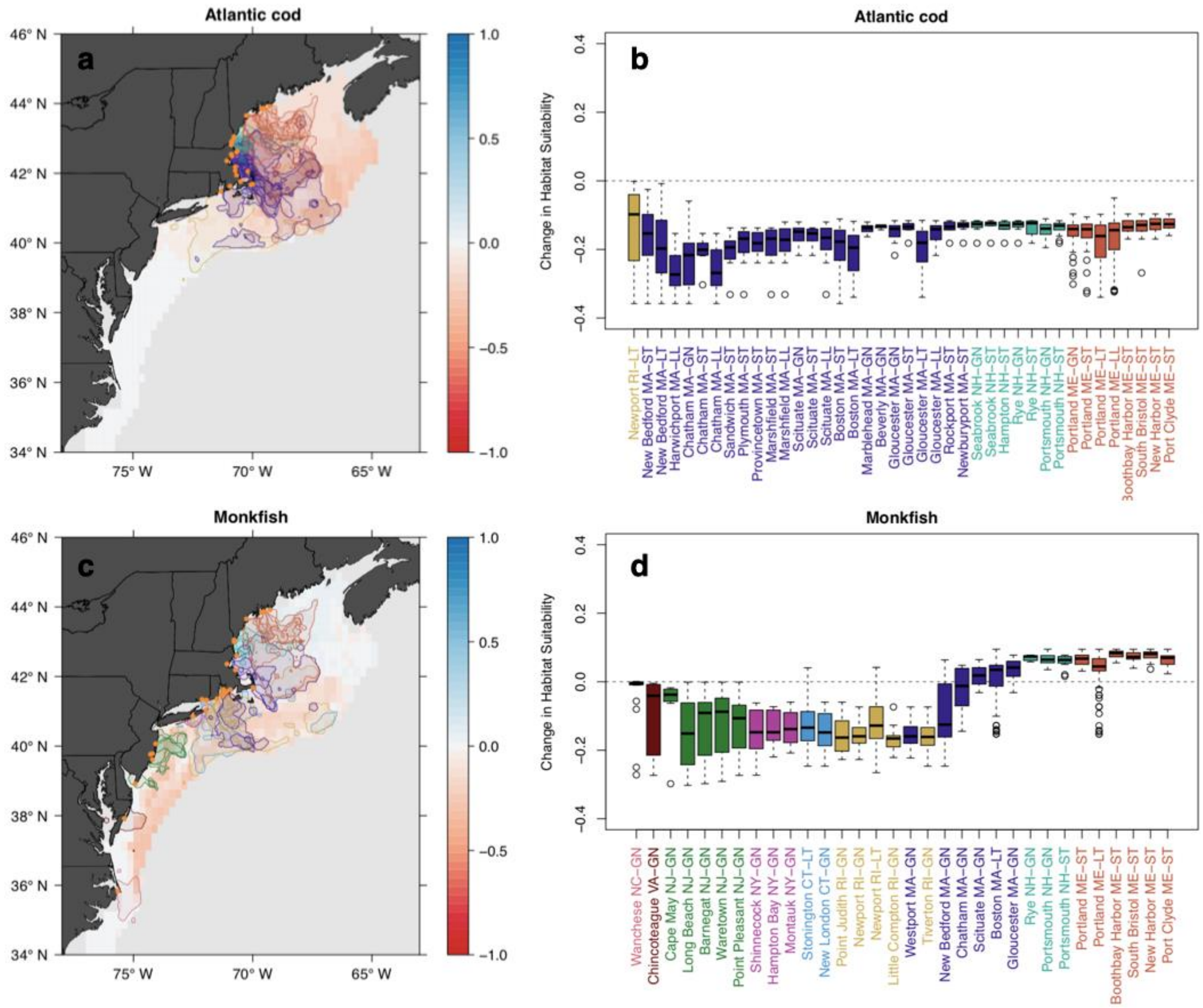

Figure 2: Predicted changes in habitat suitability by mid-century (2040-2050) for Monkfish (a) and Atlantic cod (c). Blue colors indicate improved habitat suitability, while red indicates reduced habitat suitability. Overlaid are outlines of servicesheds for communities-at-sea for which the species makes up at least 5% of revenues, colored by state to match panels c and d. Ports for individual communities are indicated by orange circles. Boxplots (b, d) summarize predicted changes in habitat suitability for the species within the serviceshed for each community. Boxplots are colored by state and arranged from south to north on the x-axis. Vessel/gear type is indicated in the label for each community by ST (small trawl), LT (large trawl), GN (gillnet), LL (longline).

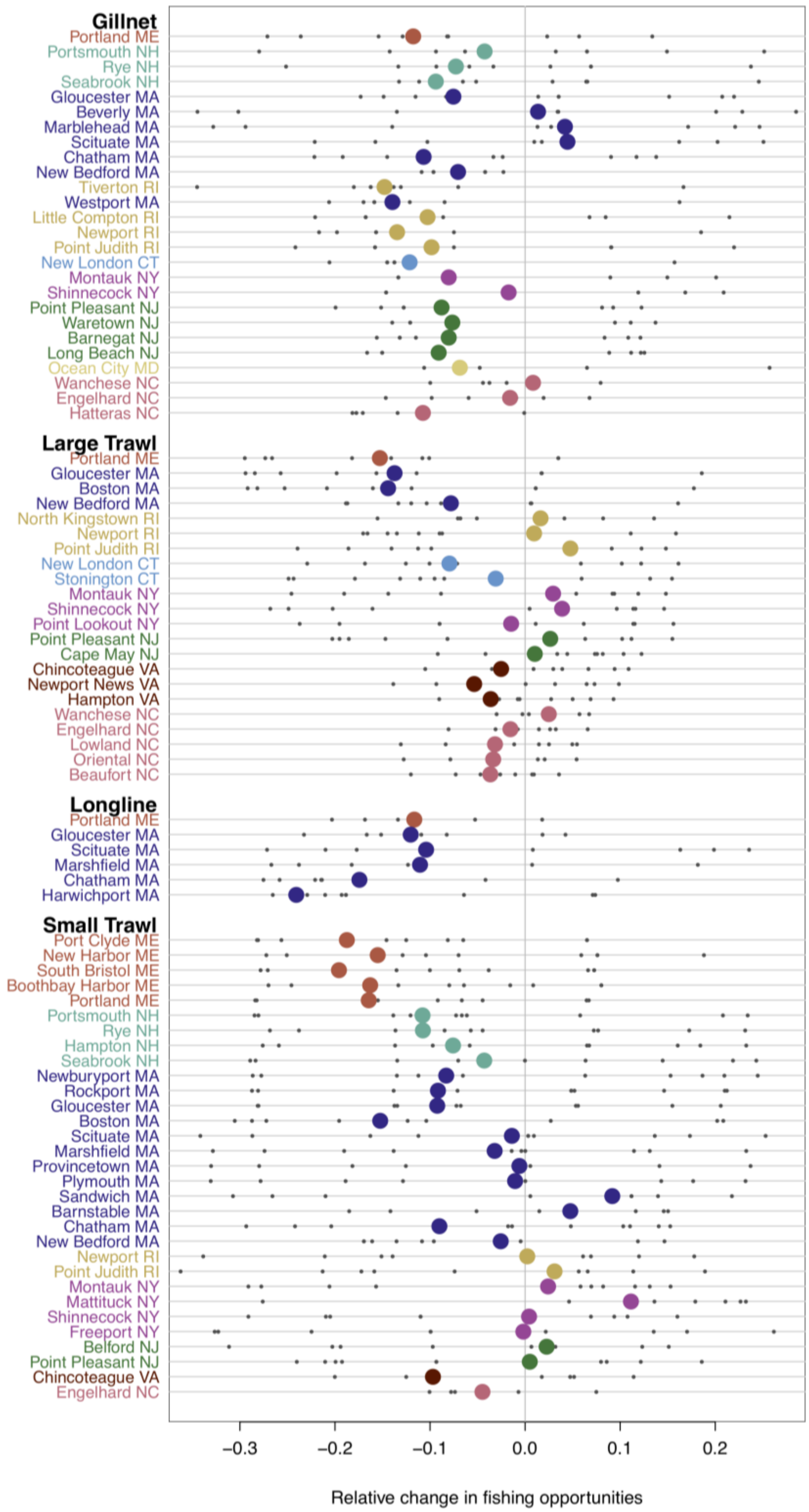

Figure 3: Exposure of communities-at-sea to risk from climate change impacts on harvested species (colored circles). Positive values indicate expanding opportunities for communities based on their historical fishing revenue portfolios and projected changes to species habitat at sea, while negative values indicate shrinking opportunities and increased exposure to risk. Within each gear type, ports are ordered by latitude and colored by state. Smaller black dots indicate change in habitat suitability for individual species that contribute to the community risk score (i.e. those that have historically made up at least 5% of the revenues for a community).