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Vulnerability and adaptation of US shellfisheries to ocean acidification

This section details the data compiled in this synthesis. Each indicator is described below and listed in Supplementary Fig. 1.

1. Natural System Indicators

To evaluate threat of exposure to shelled mollusks from ocean acidification, we mapped four factors that influence aragonite saturation state in the coastal zone: (1) projected aragonite saturation in adjacent open-ocean resulting from expected global CO_2 emissions; (2) upwelling; (3) anthropogenic eutrophication; and (4) low Ω_{Ar} river water.

1.1.Global Change from Atmospheric CO_2 Concentration

To estimate future aragonite saturation conditions from global CO_2 emissions, we used climatologies of the average output from an ensemble of six global climate models[1] under the RCP 8.5 emissions and land-use scenario, which represents the current trajectory of growth in population, income, and international emissions policy development [2]. Relative exposure to globally CO_2-driven OA was defined by the date that mean annual surface conditions are projected to drop below an estimated conservative chronic threshold (Ω_{Ar} = 1.5) for several species of larval bivalves. Risk is higher in regions reaching this threshold sooner (Supplementary Fig. 2).

The mean saturation state of 1.5 was chosen to represent a conservative, but realistic, threshold below which water may be chronically stressful to larvae of commercially harvested shelled-mollusk species in the U.S. The larval life history stage is the point of interest in this study because larval mollusks are most susceptible to slow growth, delayed metamorphosis, and decreased survival caused by ocean acidification. Larval survival strongly influences population size in mollusks[3]. Numerous studies show mounting evidence for developmental and growth effects in larval bivalves at omega aragonite thresholds above 1.0[4]. Acute and chronic responses to aragonite saturation states between 1.2 and 2.0 for larvae of Pacific oysters, Olympia oysters, Eastern oysters, and California and Mediterranean mussels have been documented[5-9]. Far from a comprehensive review, enough studies suggest that the larvae of some commercially and ecologically important species will be impacted at aragonite saturation states well above 1.

The use of a hypothetical 'averaged' threshold was a practical solution to evaluating large-scale patterns of shelled mollusk exposure across the U.S. While this threshold does not indicate all shelled mollusks will be affected, published experimental work noted above, and production data from a commercial hatchery[7] indicate some species will be affected at this point. In fact commercial hatcheries in the Pacific Northwest are currently chemically buffering waters to an aragonite saturation state of approximately 4 as their optimal value to maximize growth for several cultivated species. Although individual organisms in the wild do not experience mean, 'average' conditions, a shift in the average baseline to a critical threshold implies an increased probability of extreme events and suboptimal conditions (or at least half of the time conditions will be below the threshold).

Alternative criteria for evaluating the potential for disruption of biological processes (larval calcification) from anthropogenic OA exist. These include time to exceed the historic range of Ω_{Ar} (Supplementary Fig. 3), among others. The absolute threshold was the preferred gauge primarily because empirical evidence exists for chronic and acute thresholds, even for bivalve populations living in naturally high CO_2 conditions. Still, we evaluated the spatial patterns of relative risk for each scenario to examine the robustness of our assumptions, as described in the main text of Ekstrom et al. in the section 'Robustness of analysis'.

1.2 Amplifiers of Local Acidification: eutrophication, upwelling, river water

Through the input of CO_2 from respiration, eutrophication can nonlinearly exacerbate ocean acidification[10]. We evaluated relative exposure from eutrophication with a dataset scoring the degree to which U.S. estuaries exhibit eutrophic conditions[11] (Supplementary Fig. 4). Upwelling along coasts can bring high carbon-dioxide water to the surface, accelerating the appearance of ocean acidification seasonally[12,13]. The significance of upwelling evaluation developed by Hoekstra and colleagues[14] was used to estimate the importance and likelihood of upwelling for sections of the U.S. coast (Supplementary Fig. 5).

River water discharged into the coastal zone can provide intermittent floods of corrosive , low Ω_{Ar} water, moving Ω_{Ar} closer to thresholds for shellfish[15]. We estimated relative risk from river discharge with a measure that combined annual mean discharge volume (cubic feet) with mean aragonite saturation state of river water from USGS data (above the region of tidal influence). River pH, alkalinity (or acid neutralizing capacity), calcium concentration, and discharge flux at the farthest downstream USGS monitoring stations were obtained for the list of U.S. rivers studied in [16] (R. Striegl and P. Raymond, pers. comm.) from the USGS National Water Information System (NWIS)[17]. Because data were not always collected at the same times, even for different parameters at the same station, we averaged each river's time series of pH, alkalinity, temperature, and calcium, then used these approximate average values to calculate an approximate carbonate ion concentration with CO2SYS [18] using freshwater constants.

Approximate mean saturation state of aragonite was then calculated from the product of [Ca^{2+}] and [CO_3^{2-}] divided by the freshwater solubility product at average temperature. 126 sample sites reported both discharge volume and aragonite saturation and were used in the analysis. Discharge volume and saturation state for each station were log-transformed and re-scaled (0-1). An index of relative ocean acidification threat from river discharge was created by multiplying the transformed, normalized discharge by the inverse of the transformed, re-scaled saturation state (Supplementary Fig. 6). This way, we sought to capture rivers with high discharge and low saturation state as presenting the highest threat of amplifying acidification in coastal zones.

1.3 Exposure to Hazard

The goal of the exposure component of a vulnerability assessment is to inventory the elements that could be exposed to the hazard[19]. In this case, shellfish are directly exposed to the changing chemistry of the oceans. Without comprehensive spatial information on the distribution of shelled mollusks and their larval ‘footprints’, we map the exposure components by coastal marine bioregions around the US, delineated by the National Estuarine Research and Reserve System (NERRS) based on their “biological and geographic characteristics”[20]. These discrete areas line the coastline and extend to the oceanward boundaries of the U.S. EEZ (Supplementary Fig. 7).

We did not combine scores of all the exposure indicators into a single aggregate index for two reasons. First, temporal and spatial scales differ across the indicators, making true quantitative aggregation impossible. The year of global projected OA is a future threat based on how soon changes in aragonite saturation state will occur in adjacent oceans to the nearshore, while local amplifiers of ocean acidification capture present stressors that can magnify global change. Second, available data are not adequate to calculate how projected global OA and local amplifiers of acidification interact. In terms of combining these indicators, some studies suggest effects may be additive[10,12,21-23]. However, it is likely that these interactions will vary seasonally and regionally[24], therefore, combining exposure indicators could mask important effects or make possible management options less clear. We therefore generated a single map displaying the intersection of all the exposure indicators in each bioregion showing how shellfishes' exposure to hazards differs geographically (Fig. 2 of main text and Supplementary Table 1).

We created logical rules for each indicator of OA exposure as what level of each poses a high threat and attributed them to bioregions (see main text Table 1). The score of the global driver, based atmospheric CO_2 projections, is reported based by the date that annual mean surface waters are projected to reach our chosen threshold (sooner contributing to higher exposure, later contributing to relatively lower exposure, Supplementary Table 1, main text Fig. 2). Local amplifiers of ocean acidification are reported based on presence of potentially harmful conditions. Every bioregion that contained at least one estuary scored 'highly eutrophic' in the dataset used[25] was flagged for eutrophication and the number of highly eutrophic estuaries is reported, along with the total number evaluated per bioregion (main text Fig. 2). As with estuaries, the number of high scoring rivers and total evaluated per bioregion are reported in Fig. 2 (of main text) and Supplementary Table 1.The bioregions receiving discharge from the top 20% highest-scoring rivers (high discharge, low saturation state) were marked for having rivers that may contribute to acidification along the coast. The bioregions with very high or highly significant upwelling zones were flagged for having upwelling that may contribute to acidification in coastal waters.

2. Social System Indicators

Social vulnerability here represents the social dimension of ocean acidification. It addresses the question: ‘who has the propensity to be harmed by loss of shellfish?’ A total of nine indicators were evaluated to calculate social vulnerability: three indicators combined to represent sensitivity and five indicators combined to represent threat-specific adaptive capacity.

2.1. Sensitivity

Three datasets were used to indicate the susceptibility of people to shellfish loss (Table 2). We include shellfish that come from wild harvest and also commercial aquaculture operations. In some parts of the country, shellfish harvesting and aquaculture are important contributors to state and regional economic activity. In other parts of the country, the economic contribution of shellfish may be locally important even when the scale of the overall industry is small compared to other regional and statewide economic activities. It is important to note that these measures do not point to a probability of where individual operations may be harmed, but rather indicate more of a combined potential economic loss.

To capture the importance of shelled-mollusk fisheries to each geographic scale (local, regional, state), we focused our analysis on as small a geographic unit as possible given constraints from confidentiality laws. Following indicators of harvest engagement in commercial fisheries developed and employed in Jepson and Colburn[26], we assessed the annual fisherman-reported dollar value of landed shelled mollusks, the number of commercial fisherman jobs reliant on shelled mollusks, and the proportion of the area’s fishery that relies on shelled mollusks. We obtained these datasets from regional fishery databases or state sources, which database managers aggregated into applicable county clusters. The Atlantic Coastal Cooperative Statistics Program (ACCSP) provided datasets for the east coast, the Gulf State Marine Fisheries

Commission for Gulf of Mexico states, and the Pacific Fisheries Information Network (PACFIN) for California, Oregon, and Washington. The States of Alaska and Hawaii provided data individually. County clusters were developed by the authors in close collaboration with the data providers to avoid confidentiality constraints but at the same time provide the highest resolution possible of the shellfish landed. Shellfish were grouped together as a single taxonomic group rather than compiled by individual species because of confidentiality constraints.

The dollar value of landed shellfish was characterized by the median value across 10 years[1] (2003-2012), smoothing fluctuations over time which is typical in any fishery. These numbers included value of shelled mollusks reported by aquaculture facilities to each associated state's departments of fish and wildlife. The number of commercial fishing jobs was estimated using the five-year median number of licenses or permits for fishing shelled mollusks, reflecting the time span over which these data are most consistent and available. Aquaculture facilities were reported as a single license, thus making the total number of licenses permitted a minimum value for jobs.

Lastly, to gauge the direct economic importance of shelled mollusks to a community relative to other fisheries, we calculated the ratio of the ten year median (2003-2012) of shelled mollusk revenues to total commercial fish revenues (in dollars).

Sensitivity Subindex

We combined the three sensitivity indicators into a single subindex that could be mapped. Following the World Risk Report[27] method of aggregation, each indicator was re-scaled (0-1) and then the subindex was calculated for each county cluster by averaging the three re-scaled

[1] We calculated the median over five years for the State of Texas landed value because prior to 2008, the data was considered inconsistent and unreported (pers. comm. Gulf State Marine Fisheries Commission staff).

indicators (Supplementary Fig. 8). In cases where an indicator was missing for a specific county cluster, the average indicator value across all county clusters was used to represent the missing indicator data.

2.2 Adaptive Capacity

Adaptive capacity is commonly evaluated based on a set of indicators that relate either generally to the people's ability to deal with any disaster or community disturbance[28,29] or to a set of indicators that relate specifically to defined disaster or disturbance (see distinction in [30]). We evaluated both types of indicators, but based on the data scale challenges for establishing relevant spatial boundaries for the generic indicators, we chose to gauge adaptive capacity using a threat-specific, rather than generic, indicators for the hazard of ocean acidification specifically, and the people likely to be affected. Other studies looking at social vulnerability to ocean acidification have assessed adaptive capacity with general characteristics that relate to people's ability to deal with any disaster. While general adaptive capacity measures (e.g., per capita income, age, education, health status, food security, employment) are useful for looking at a combination of multiple hazards [27,31], they often do not accurately represent fishing communities at risk from a single hazard because large coastal populations (even in relatively small multi-county clusters) frequently overshadow and mask the issues relevant to fishing communities [26]. Because our study focused on commercial impacts via shelled mollusks, we developed a set of indicators that relates to the loss of this sector. The indicators we developed broadly cover three types of adaptive capacity: access to relevant science; employment alternatives; and political action capacity (main text Table 3, Supplementary Fig. 9).

Indicators that represent the ability of shellfish harvesters and aquaculture managers to access and use relevant scientific knowledge in adapting to OA are based on the number of marine university laboratories and recent state Sea Grant budgets. Collaborations between several academic laboratories and the aquaculture industry in the Pacific Northwest helped oyster hatcheries protect themselves from exposure to harmful coastal waters through the development of early warning systems[32]. Other potentially useful scientific knowledge emerging from research laboratories in the future could include improving our understanding of impacts to commercially valuable species, establishing coastal monitoring systems, or identifying (or developing) OA-resilient strains of shellfish.

To represent the influence of potential access of scientific assistance that fishing communities have, we developed indicators based on number of university marine labs and Sea Grant budgets. To create an indicator of potential marine lab influence for each county cluster, we combined two calculations using the counts of university marine labs. These metrics represent the statewide benefit marine labs can provide and the more localized impact that marine labs can have for communities within proximity to the lab. First, the count of all university marine labs per state was normalized (divided) by the state's length of shoreline. The re-scaled score (0-1) for each state was attributed to the relevant county clusters. Second, we scored each county cluster by the number of university marine labs present and re-scaled this scoring 0-1. The two scores for each county cluster were averaged to create a single marine lab indicator. This end score incorporates the high local influence that marine labs have, but also recognizes the potential contribution of marine labs beyond their immediate areas, especially within the university's home state.

In addition, Sea Grant extensions play an important role as boundary organizations that distribute scientific research findings to local stakeholders[33]. Sea Grant extensions also engage with the fishing communities to identify fisheries-related research needs that academic research can investigate. In this way, Sea Grant extensions also can increase the salience of science produced for fishing communities faced with the threat or onset ocean acidification. We gauge the outreach potential of state Sea Grant programs to connect with fishers and aquaculture managers normalizing the Sea Grant budgets for each state by the length of shoreline. Specifically, this includes the total annual budgets for each state divided by the state's length of shoreline (miles, includes bays, inlets and islands)[34]. The normalized re-scaled score (0-1) for each state was attributed to the relevant county clusters.

For employment alternatives, we focused within sector and measured the diversity of shelled mollusk fisheries in the region. We used this to indicate the ability of a fisherman or aquaculturist to target species that may be more tolerant ocean acidification without undergoing a major equipment or occupational shift. We used the Shannon Weiner Index to calculate the diversity of shellfish fisheries by landed value. Data for this indicator used the landed value of each shellfish fishery by type: hard clams, oysters, soft clams, geoducks, and mussels.

We looked at political action to indicate awareness of politicians and other decision-makers, and thus potential assistance or other resources that could be useful to communities. To gauge political action, we scored states based on whether a climate adaption plan exists and whether any legislation has been passed specifically addressing ocean acidification.

Most of the adaptive capacity indicators were based on state-level data, and then each was attributed to associated county clusters so that adaptive capacity could be viewed alongside (and ultimately combined with) sensitivity to assess social vulnerability (Table 3 main text, Supplementary Fig. 9).

Adaptive Capacity Subindex

The variables representing adaptive capacity (described in Table 3 main text, mapped in Supplementary Fig. 9) were combined with the same method applied to sensitivity indicators. The re-scaled score (0-1) of each indicator was averaged for each county cluster. A low score (closer to zero) represents a high adaptive capacity because this is the direction the component contributes to social vulnerability, meaning that low adaptive capacity is what increases social vulnerability.

In addition to evaluating the threat-specific adaptive capacity indicators, we tested a set of generic adaptive capacity indicators to understand how this would change the maps of total adaptive capacity and social vulnerability. The measures we used to represent indicators of generic adaptive capacity were as follows: per capita income, education (percent of population over 25 years old with less than high school degree), unemployment prevalence (percent of population over 16 unemployed), and elderly (percent of population over 65 years old). Previous disasters have shown that populations of people with these characteristics (low income, low education, high unemployment, high elderly) often have a more difficult time when exposed to a hazardous event[31,35], thus these are commonly used to represent adaptive capacity in social vulnerability assessments. These generic indicators could be useful at the fishing community level, however, due to confidentially constraints we did not have sufficient information nationwide about the boundaries of shellfish fishing communities. Such boundaries are necessary to generate the adaptive capacity reflecting these fishing communities. For demonstration and discussion purposes, we did evaluate four measures of generic adaptive capacity at the county level.

Results of the generic adaptive capacity index differed largely for some places from those of the threat-specific adaptive capacity (Supplementary Fig. 10); therefore, so did the social vulnerability index when calculating it with the generic adaptive capacity rather than the threat-specific adaptive capacity. Overall, the areas scoring as lowest threat-specific adaptive capacity concentrated in the Gulf of Mexico. The spatial pattern of adaptive capacity changes dramatically with generic adaptive capacity indicators, with the lowest adaptive capacity appearing in other coastal regions, including one county cluster on the west coast (Oregon). Notably, several coastal areas around the country measured with much lower generic than threat-specific adaptive capacity. These included county clusters in the Pacific Northwest (Southern Oregon), Florida, Maryland, and Virginia. On the other hand, there were a few county clusters (in Louisiana) that measured as lower adaptive capacity with the generic indicators when compared to the threat-specific indicators.

2.3 Social Vulnerability

To calculate vulnerability (SV), the overall scores of S and AC were summed. We summed rather than multiplied these scores to avoid either of them from unintentionally weighting the final SV score[36,37]. Areas of highest concern have highest SV, where sensitivity is high and adaptive capacity is low, which both contribute to increasing the risk of harm to people due to the loss of shellfish from ocean acidification, thus higher social vulnerability. Six of the top 10 rank as high social vulnerability using either the generic or the threat-specific indicators of adaptive capacity. These include county clusters in Massachusetts (the highest using either type of AC), New Jersey, North Carolina, Virginia, Florida, and Louisiana (Supplementary Fig. 11). Using the generic adaptive capacity, several county clusters show high social vulnerability that did not in using the threat-specific adaptive capacity indicators: Washington and northern Oregon, Eastern Maine, and Maryland.

Winsorizing

To deal with major outliers in the data for sensitivity (e.g. top 10% of county clusters have landings that range from $250mil to $23million), we trimmed the data to get a more normal distribution. Our process is described below.

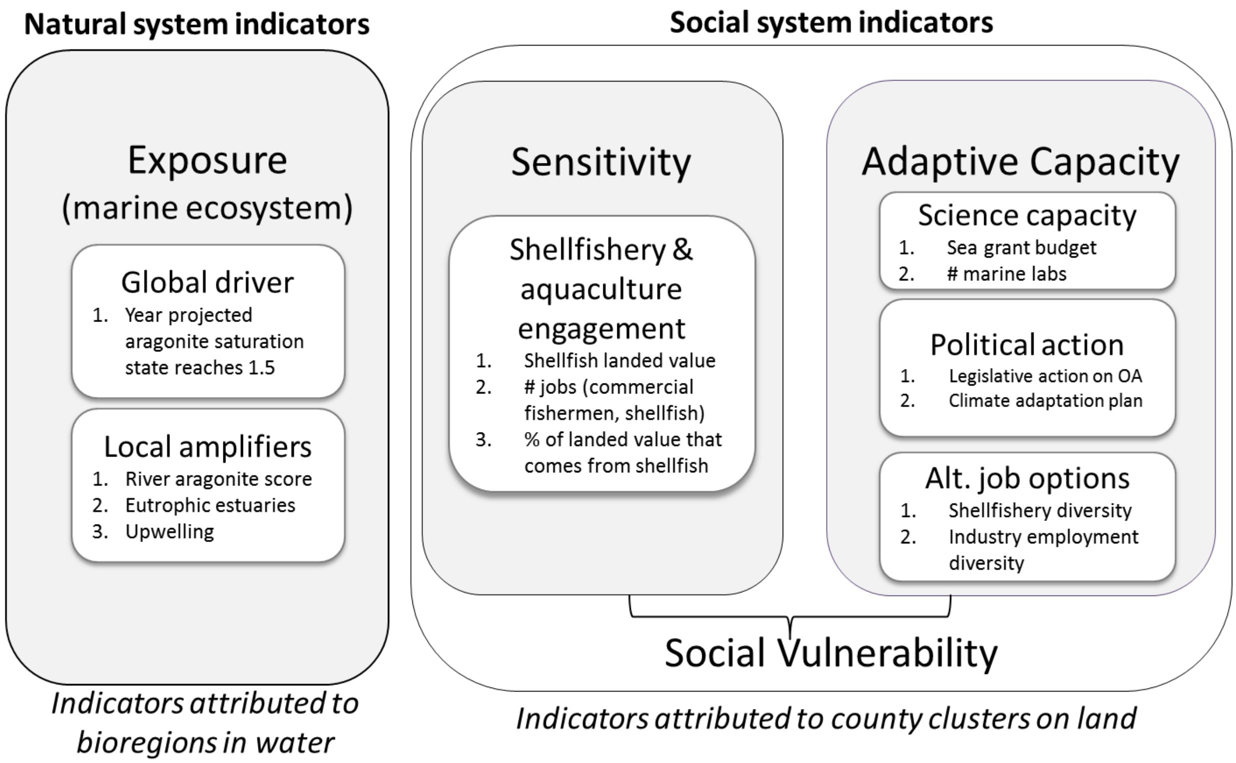
Winzorization: The MedUSD landings data ranged from 0-24,742,677. Given the uneven distribution of the data, re-scaling without adjustment would create very low values for all but one of the county clusters (the highest - MA-S). To adjust the re-scaled scores for the very large values so that they do not diminish the importance of the rest of the county cluster’s landed values, we trimmed or *winsorized* the top 10% of the values. This shifted the distribution of data, removing high outliers (Supplementary Fig. 12).

B. Supplementary Table

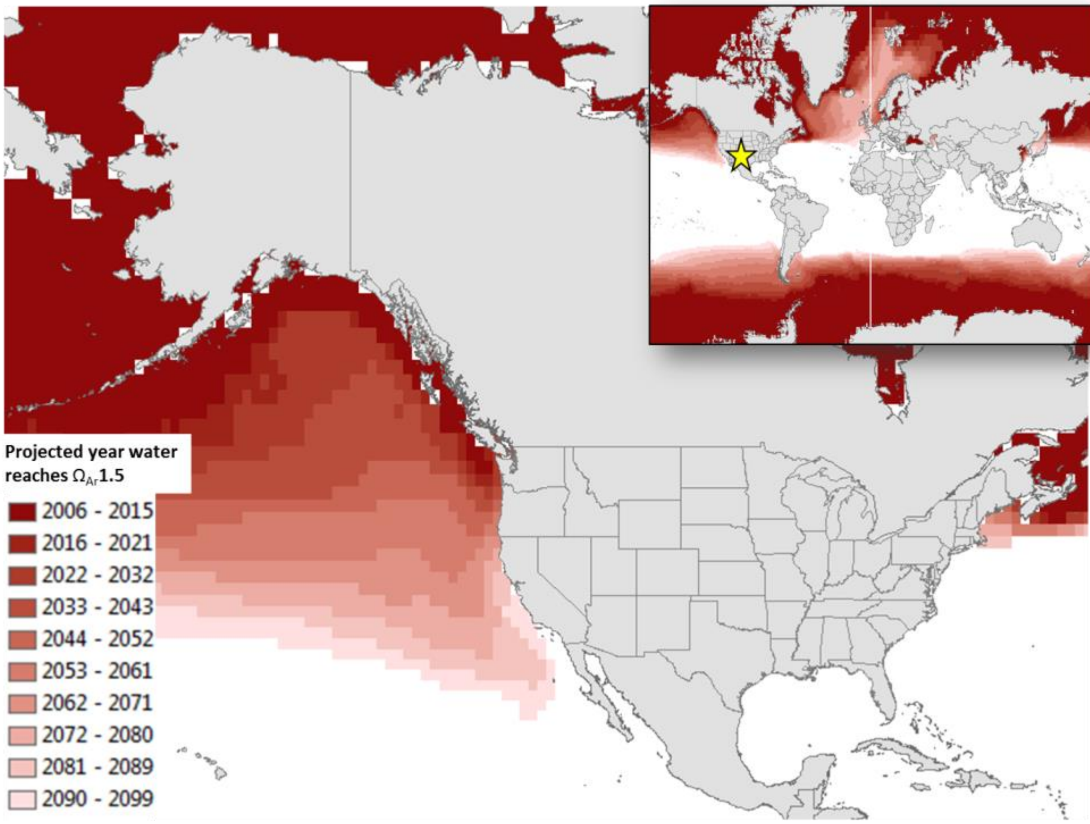
Supplementary Table 1. Global and local exposure indicator scores for each bioregion. See Supplementary Fig. 6 for location of bioregions by ID.

Location			**Global**	**Local**				
	Bioregion ID	Region description	Ω_{Ar} 1.5 year	No. Estuaries Scored as high eutrophic	No. Estuaries evaluated in nation-wide dataset	No. Rivers scoring in top quintile	No. Estuaries evaluated in nationwide dataset	Upwelling influence (presence of high)
East coast	1	E Maine coast	2050	0	1	*nd*	0	
	2	Gulf of Maine	2052	0	11	3	4	
	3	Long Island to Cape Cod	2085	2	8	2	7	
	4	Mid-Atlantic	>2099	3	6	0	5	
	5 (bay)	Chesapeake Bay	*nd*	5	8	0	8	*na*
	6	South-Mid Atlantic	>2099	1	5	4	8	
	7	S Atlantic	>2099	1	10	4	7	
	8	NE Florida	>2099	*nd*	0	0	2	
Gulf of Mexico	9	SE Florida	>2099	0	3	0	2	
	10	W Florida	>2099	0	6	0	10	
	11	NW Florida	>2099	1	5	2	12	
	12	Mid Gulf of Mexico	>2099	1	11	7	9	
	13	Texas coast	>2099	0	4	0	10	
Contiguous west coast	14	S California	2081	0	2	0	5	high
	15	C California	2060	0	2	0	4	high
	16 (bay)	San Francisco	*nd*	0	2	0	3	*na*
	17	N California and Oregon	2027	0	6	0	9	high
	18	Washington	2028	0	2	1	6	high
	19 (bay)	Puget Sound	*nd*	1	7	2	9	*na*
Alaska	24	Southeast Alaska	2006	*nd*	0	*nd*	0	high
	25	Southwest Alaska	2006	*nd*	0	*nd*	0	high
	26	Northern and western Alaska	2006	*nd*	0	*nd*	0	
Hawaiian Islands	27	Hawaii	>2099	*nd*	0	*nd*	0	

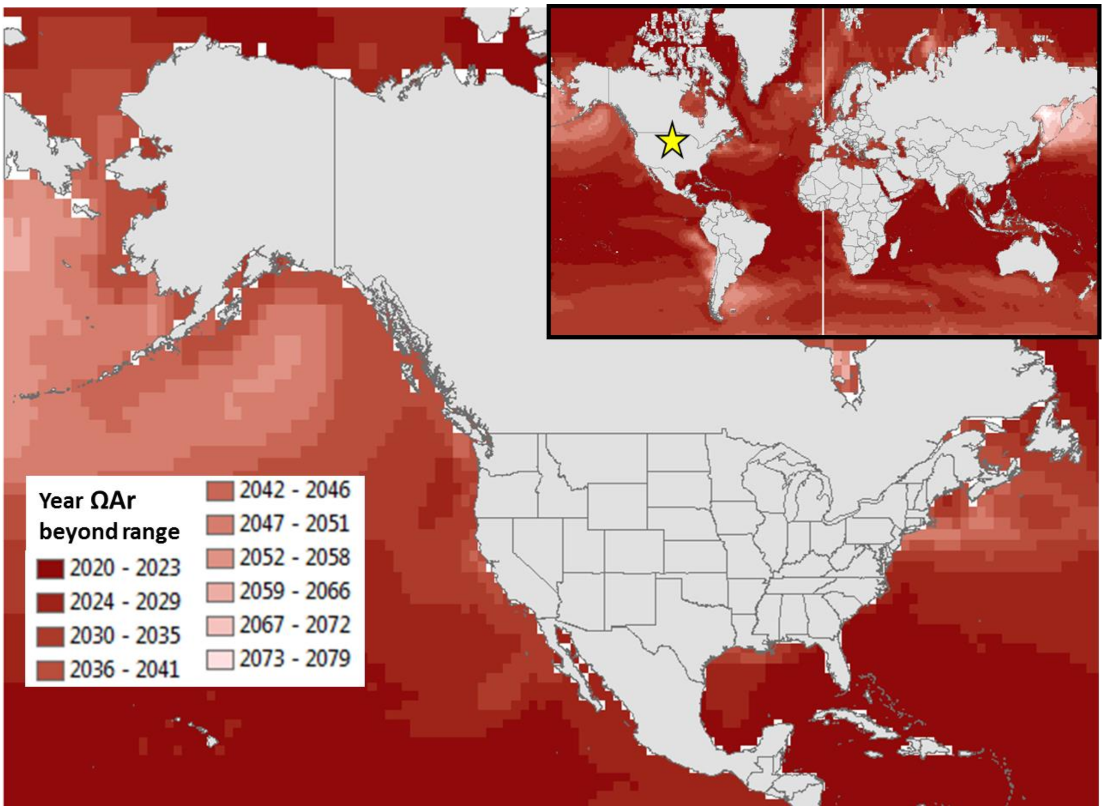
C. Supplementary Figures



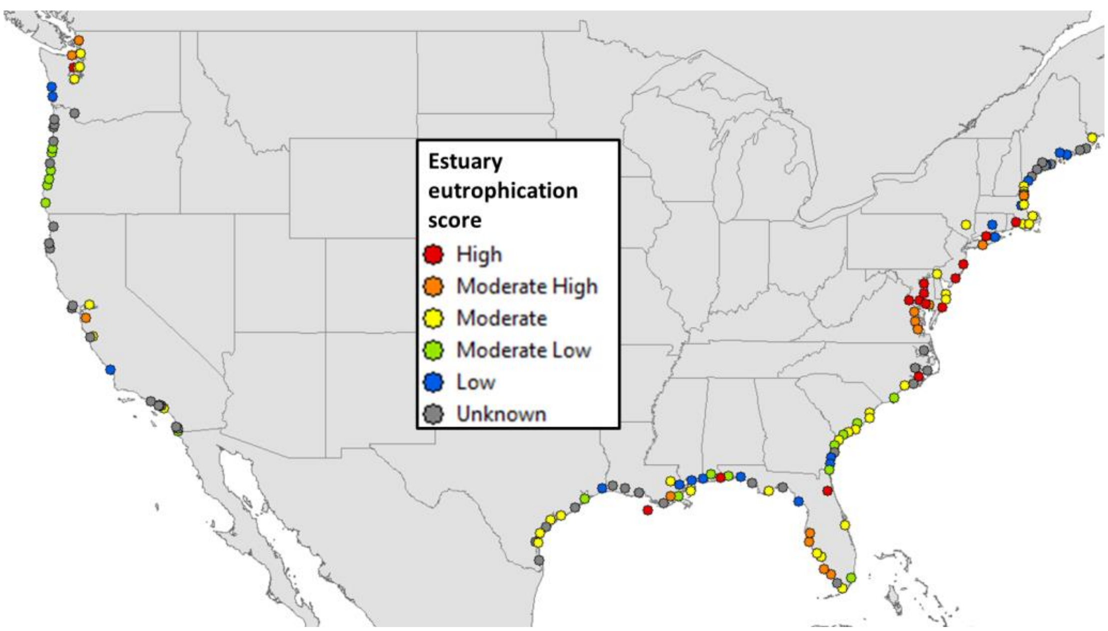
Supplementary Figure 1. Indicators used to calculate each component of vulnerability (also see Fig. 1 for framework in main text).



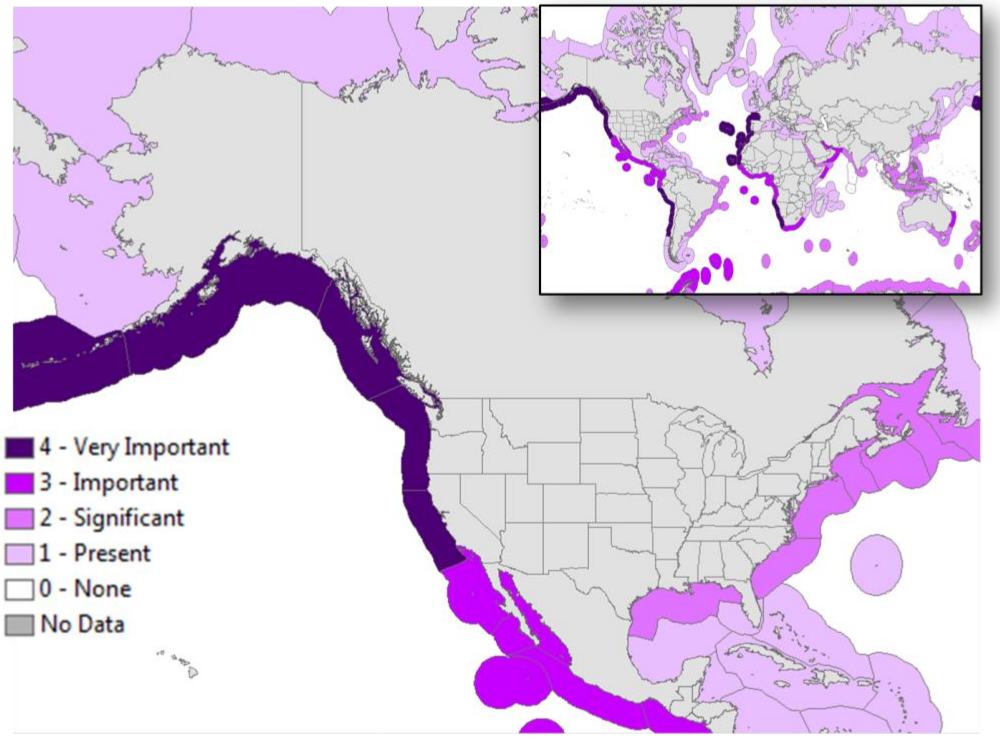
Supplementary Figure 2. Projected year at which sea surface water reaches Ωar 1.5, the threshold that this study uses to indicate when water becomes chronically stressful for shelled mollusks. Source: Ruben van Hooidonk using GHG emission scenario RCP 8.5[1].



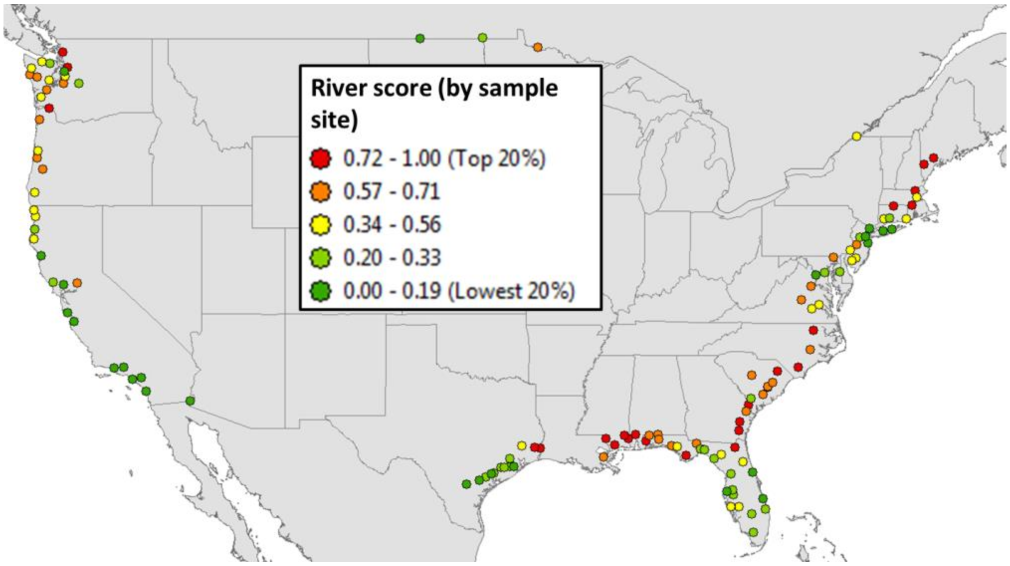
Supplementary Figure 3. Year at which the annual mean surface water is projected to go out of historical range in aragonite saturation state. Source: Ruben van Hooidonk using GHG emission scenario RCP 8.5[1].



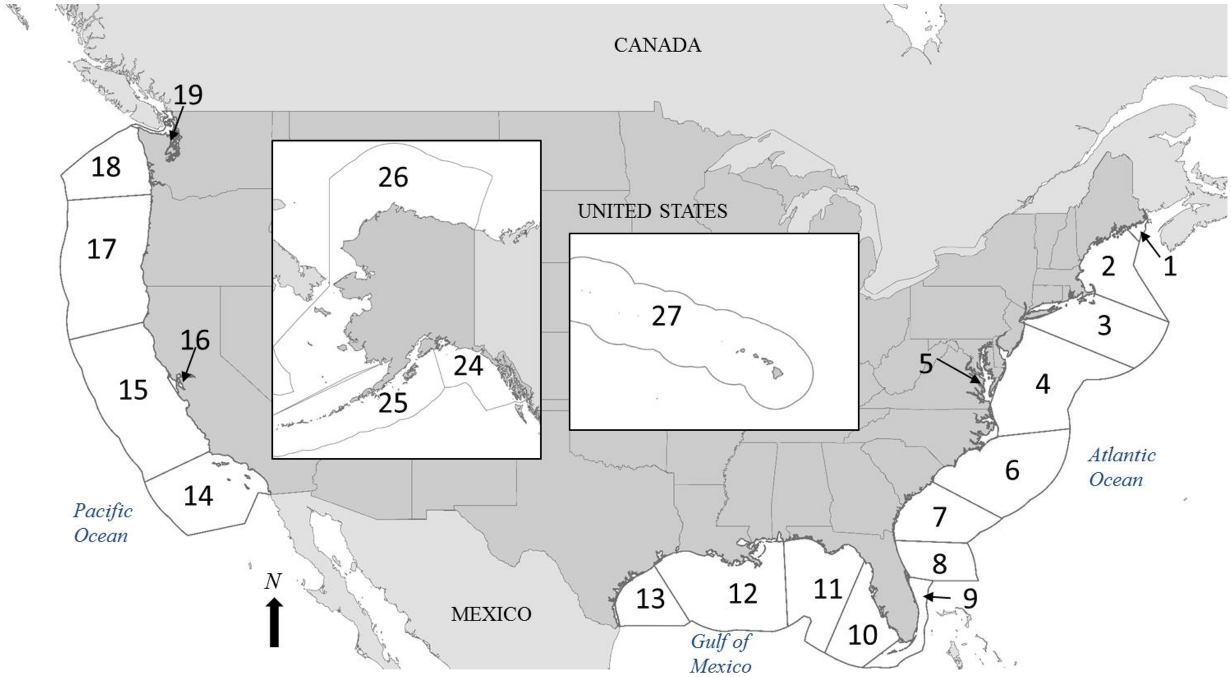
Supplementary Figure 4. Eutrophication scores of estuaries in the US. Source: Susan Bricker shared data reported in [11].



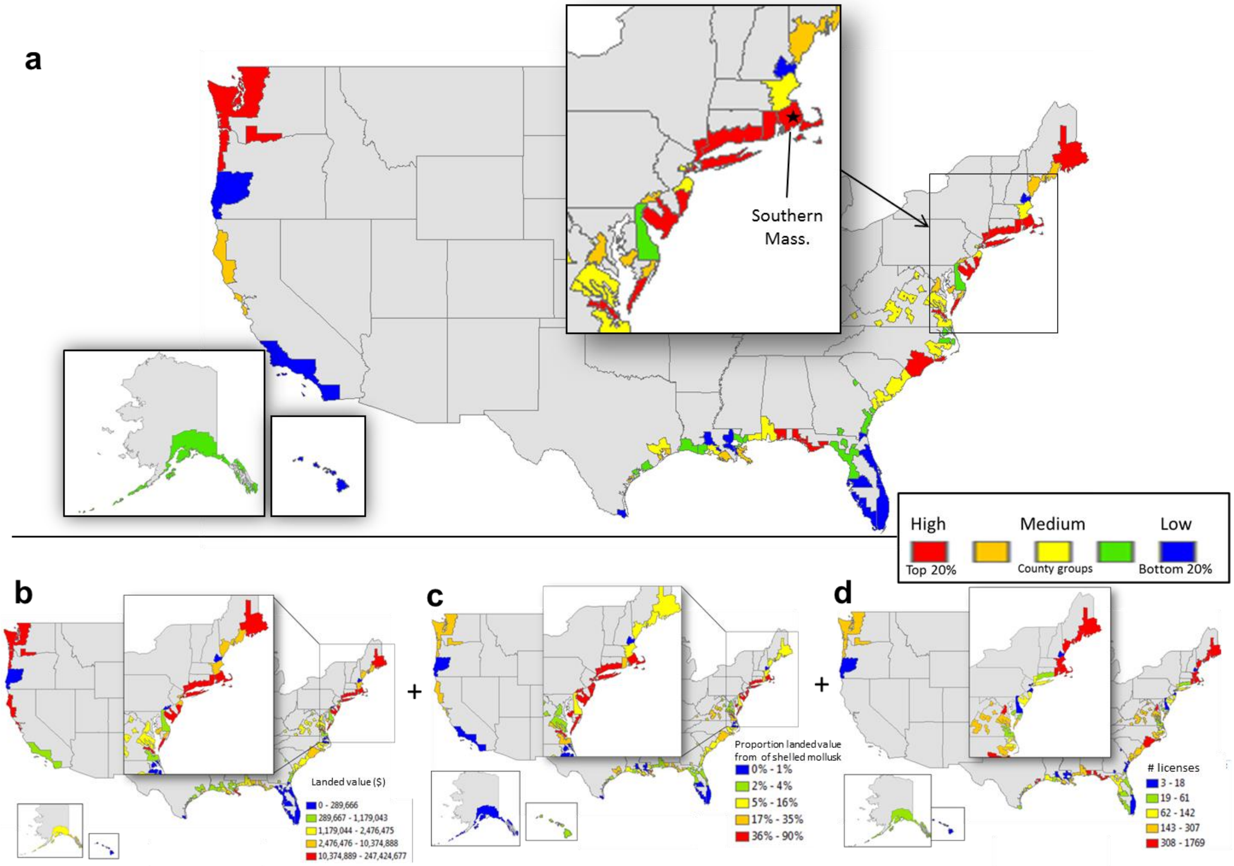
Supplementary Figure 5. Upwelling significance globally in ecoregions as defined by a synthesis from The Nature Conservancy. Source: [14].



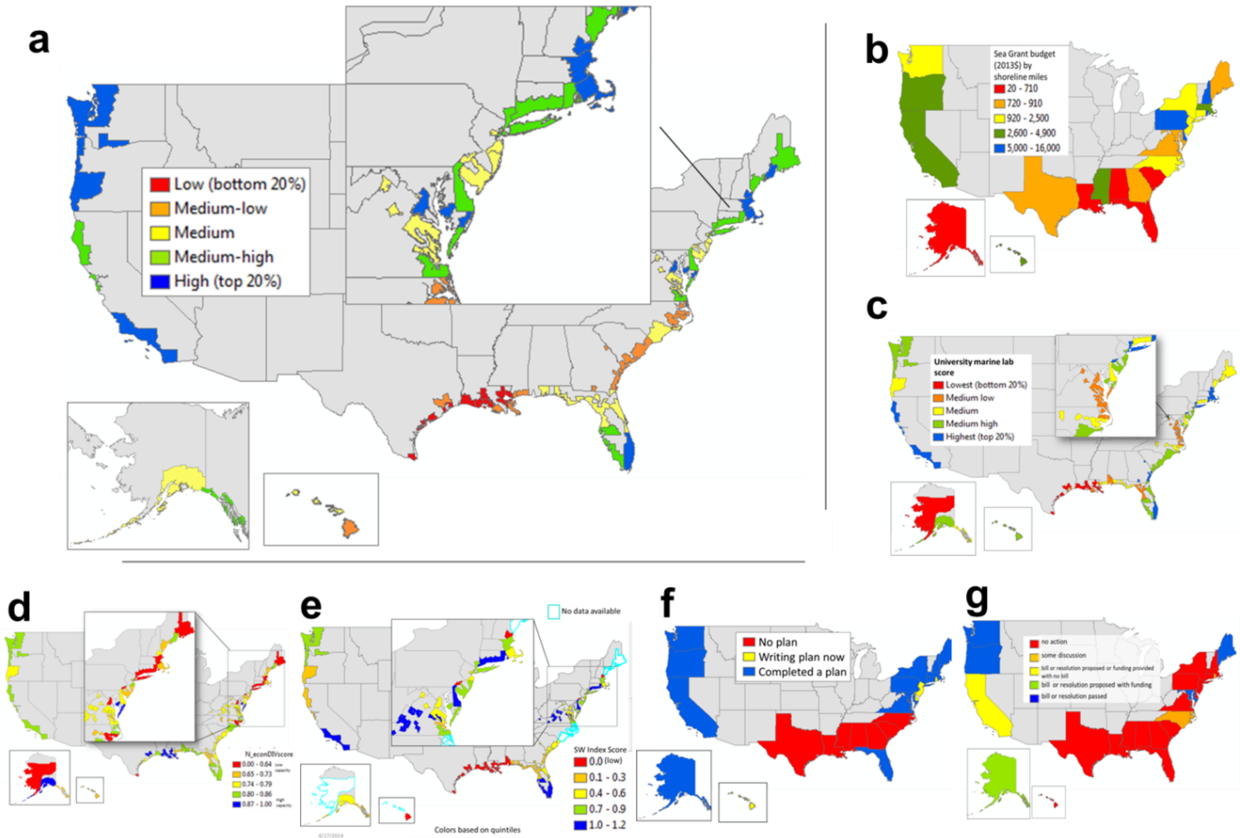
Supplementary Figure 6. Relative scoring of river input aragonite contribution to coastal waters. Authors generated score by combining annual discharge with aragonite saturation state derived from sampled data. The top 20% represent those rivers that may present the highest threat of amplifying acidification. Source of raw data: [17].



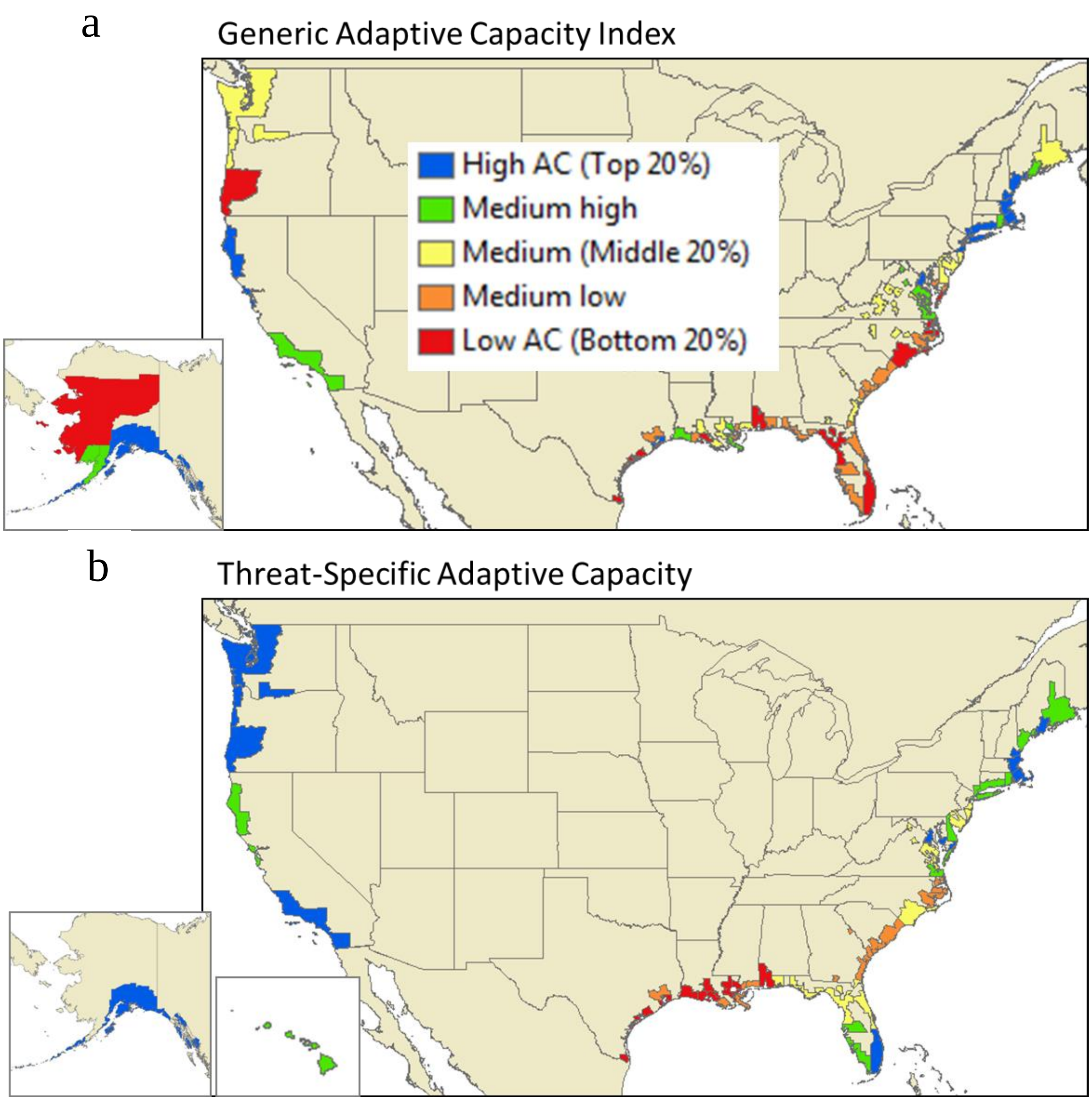
Supplementary Figure 7. Coastal marine bioregions in the United States Exclusive Economic Zone. Redrawn from the National Estuary Research Reserve System website [20]. Numbering scheme consistent with NERRS and used in reporting results in Supplementary Table 1.



Supplementary Figure 8. Sensitivity (economic dependency) of US coastal communities to changes in mollusk fisheries. a) Overall sensitivity score; b) landed shelled mollusk value; c) percent of shelled mollusk to all fish harvested, and d) number of commercial shelled mollusk fishing jobs. Star in inset of panel indicates the county cluster with the highest overall sensitivity. Colors based on quintiles.

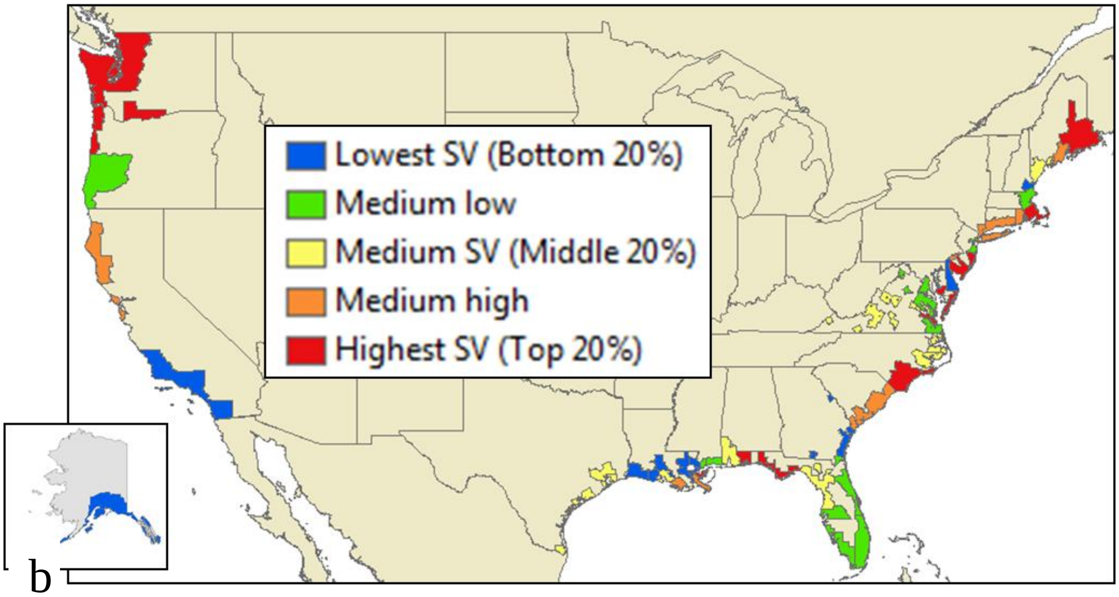


Supplementary Figure 9. Overall threat-specific adaptive capacity is higher along west and Northeast coasts. (b) State Sea Grant budgets (2013) normalized by shoreline length, (c) university marine lab score (see main text Table 3) based on university marine lab count statewide divided by shoreline miles and lab count in each county cluster, (d) economic industry diversity, (e) shellfish fishery diversity, (f) state climate change adaptation plan status, (g) and state legislative status on ocean acidification (as of April 2014).



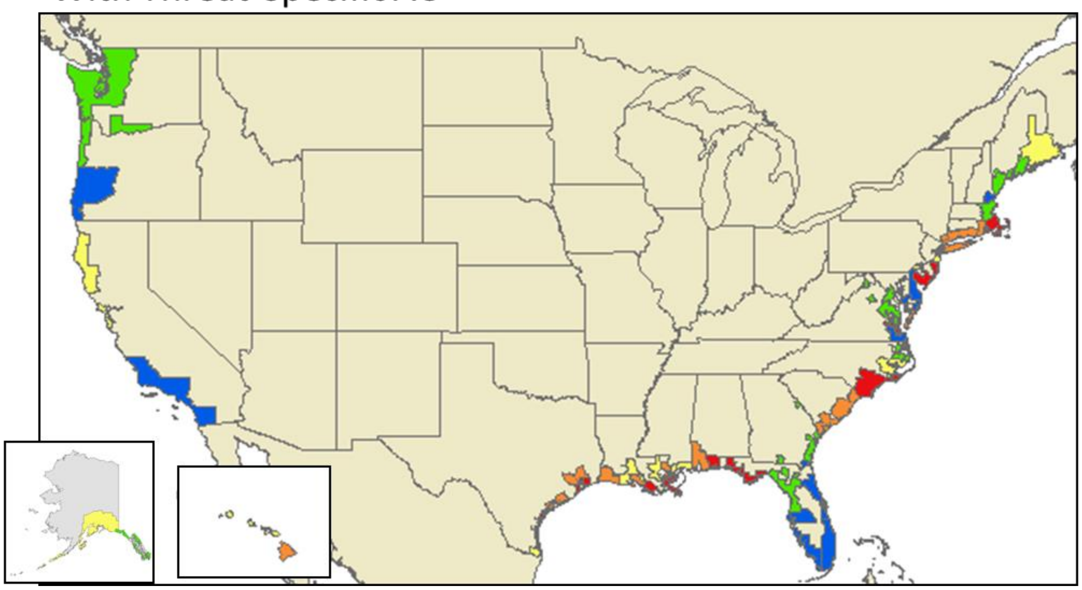
Supplementary Figure 10. Adaptive capacity indices constructed from (a) a set of general indicators (education, unemployment, age, and income) and (b) a set of threat-specific indicators.

a With Generic AC



b

With Threat-Specific AC



Supplementary Figure 11. Maps of social vulnerability scores constructed with different indicators of adaptive capacity: (a) generic adaptive capacity indicators and (b) threat-specific adaptive capacity indicators.

Original data

Trimmed data

CtyGrpID	MedUSD	Winz_medUSD	norm_medUSD
MA-S	247,424,677	23,650,564	1.00
NJ-S	116,991,069	23,650,564	1.00
WNO	103,136,415	23,650,564	1.00
VA-M	66,663,650	23,650,564	1.00
NY-A	23,650,564	23,650,564	1.00
CT-A	17,238,256	17,238,256	0.73
RI-A	14,348,285	14,348,285	0.61
VA-E	14,020,101	14,020,101	0.59
CA-NC	13,440,483	13,440,483	0.57
LA-PLQ	12,593,576	12,593,576	0.53

Highest 10% of dataset

Lowest value of the top 10%

Supplementary Figure 12. Sample of landed value dataset and how we trimmed (winsorized) the top 10% to be equal

D. Supplementary References

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