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Vulnerability and adaptation of US shellfisheries to ocean acidification

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Ocean acidification is a global, long-term problem whose ultimate solution requires carbon dioxide reduction at a scope and scale that will take decades to accomplish successfully. Until that is achieved, feasible and locally relevant adaptation and mitigation measures are needed. To help to prioritize societal responses to ocean acidification, we present a spatially explicit, multidisciplinary vulnerability analysis of coastal human communities in the United States. We focus our analysis on shelled mollusc harvests, which are likely to be harmed by ocean acidification. Our results highlight US regions most vulnerable to ocean acidification (and why), important knowledge and information gaps, and opportunities to adapt through local actions. The research illustrates the benefits of integrating natural and social sciences to identify actions and other opportunities while policy, stakeholders and scientists are still in relatively early stages of developing research plans and responses to ocean acidification.

The ocean has absorbed about 25% of anthropogenic atmospheric CO_2 emissions, progressively increasing dissolved CO_2, and lowering seawater pH and carbonate ion levels[1]. On top of this progressive global change in oceanic carbon conditions, local factors such as eutrophication[2,3], upwelling of CO_2-enriched waters[4] and river discharge[5] temporarily increase anthropogenic ocean acidification (OA)[6] in coastal waters[7–9]. Ocean acidification could primarily affect human communities by changing marine resource availability[1]. Studies have shown that, in general, shelled molluscs are particularly sensitive to these changes in marine chemistry[10–12]. Shelled molluscs comprise some of the most lucrative and sustainable fisheries in the United States[13]. Ocean acidification has already cost the oyster industry in the US Pacific Northwest nearly US$110 million, and directly or indirectly jeopardized about 3,200 jobs[13]. The emergence of real, economically measurable human impacts from OA has sparked a search for regional responses that can be implemented immediately, while we work towards the ultimate global solution: a reduction of atmospheric CO_2 emissions. Yet there is little understanding about which locations and people will be impacted by OA, to what degree, and why, and what can be done to reduce the risks.

Here, we present the first local-level vulnerability assessment for ocean acidification for an entire nation, adapting a well-established framework and focusing on shelled mollusc harvests in the United States; for other evaluations of OA social vulnerability, see refs 14–16. We explored three key dimensions — exposure, sensitivity and adaptive capacity (Fig. 1 and Supplementary Fig. S1) — to assess the spatial distribution of vulnerable people and places to OA. The underlying assumption guiding this assessment is that addressing existing vulnerability can reduce future vulnerability to OA, sometimes called 'human-security vulnerability'[15].

Exposure of marine ecosystems encompasses acidification driven by global atmospheric CO_2 and amplified by local factors in coastal waters. We divided the coastal waters around the United States into existing National Estuary Research Reserve System bioregions[17] (Supplementary Fig. S7), and for each bioregion, examined: (1) projected changes to ocean chemistry based on a reduction in aragonite saturation state (Ω_{Ar}) (Supplementary Fig. S2), and (2) the prevalence of key local amplifiers of OA, including upwelling, eutrophication and input of river water with low-aragonite saturation state, for each bioregion (Table 1 and Supplementary Figs S4–S6). Aragonite saturation state (Ω_{Ar}) is a measure of the thermodynamic stability of this mineral form of calcium carbonate that is used by bivalve larvae and other molluscs, which is also commonly used to track OA[1]. Declining Ω_{Ar} makes it more difficult and energetically costly for larval bivalves to build shells even before Ω_{Ar} becomes corrosive, and Ω_{Ar} seems to be the important variable for the most sensitive early stage of

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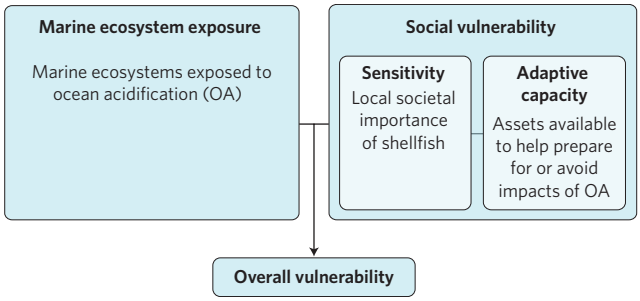

Figure 1 | Conceptual framework structuring the analysis of vulnerability to ocean acidification. Vulnerability analyses can focus on three key dimensions (exposure, sensitivity and adaptive capacity): (1) the extent and degree to which assets are exposed to the hazard of concern; (2) the sensitivity of people to the exposure; and (3) the adaptive capacity of people to prepare for and mitigate the exposure's impacts. These three dimensions together provide a relative view of a place's overall vulnerability. Adapted conceptual model components from refs 16,52–55.

bivalve larvae[18]. We evaluated relative exposure to anthropogenic OA as the projected year when the mean annual surface seawater will exceed an empirically informed absolute Ω_{Ar} threshold for several species of bivalve larvae. This indicator of disruption to the biological processes of calcification and development in larval molluscs was favoured over alternatives (for example time until the historic range of Ω_{Ar} is exceeded) because the biological mechanism was clear[19] and empirical evidence exists[20]. For comparison purposes, the Supplementary Information includes the time until the historic range of Ω_{Ar} is exceeded (Supplementary Fig. S3), but below we document the outcomes based on the Ω_{Ar} threshold projections and local amplifiers of OA.

Sensitivity of social systems was evaluated at the scale of 'clusters of coastal counties' around the United States, using three indicators of community dependence on shellfish, adapted from the National Marine Fisheries Service's fishing community vulnerability and resilience index[21]: (1) the 10-year median landed value of shellfish (including both wild and aquaculture harvests); (2) the 10-year median proportional contribution of shellfish to total value of commercial landings; and (3) the 5-year median number of licences (representing jobs) supported by shelled mollusc fishing (Supplementary Information). Sensitivity indicators were re-scaled and combined into a single index (Table 2, Supplementary Information and Supplementary Fig. S8).

Adaptive capacity of social systems to cope with and adapt to OA is represented by three classes of indicators: status of state government climate and OA policies, local employment alternatives and availability of science (Table 3). We examined a total of six indicators representing adaptive capacity that are derived largely from the broader economic and policy landscape, yet are directly relevant for dealing with the threat of OA (Supplementary Fig. S9). This is a deliberate departure from studies conducted at broader and finer geographic scales that use general demographic indicators (see Supplementary Information). We assessed 'potential government support for adaptation' through measures of: (1) the status of state legislative action on OA and (2) the status of state climate adaptation planning. These indicators reflect social organization and assets at the state jurisdictional level that could be used by communities to adapt to, cope with, or avoid the impacts of lost shellfish harvests. We examined aspects of employment alternatives through: (3) the diversity of shelled mollusc harvests, suggesting potential alternative shellfish that could be harvested and (4) the diversity of non-shellfish-related employment industries. These reflect the likelihood of job alternatives for shellfish harvesters and those in the aquaculture industry. Finally, we captured 'access to and availability of science' through (5) a score for marine laboratories developed to take into account the high local influence that such laboratories can have as well as the potential contribution beyond their immediate vicinity. For each county cluster, a metric based on the number of university marine laboratories (on-campus and satellite laboratories) in that county

Table 1 | Indicators of drivers and amplifiers of ocean acidification, and the criterion for each used in this study.

Factors causing and amplifying OA (reducing Ω_{Ar})	Indicator	Scoring scale	Criterion for ranking the risk factor as 'high'
Rising atmospheric CO_2 reduces Ω_{Ar} causing chronic stress to shelled mollusc larvae	Projected year that surface water will reach Ω_{Ar} = 1.5 (ref. 27)	Continuous scale from current year to 2099	Ω_{Ar} = 1.5 threshold reached by 2050
Eutrophication increases pCO_2 locally via respiration, leading to reduced Ω_{Ar}	Degree of eutrophication[56]	Eutrophication scored on a five-point scale: low to high	Presence of a high-scoring eutrophic estuary in bioregion
River water can reduce Ω_{Ar} locally in coastal waters	Combined metric of river's aragonite saturation state and annual discharge volume	Rivers scored on a five-point scale: low to high	Presence of high scoring river (for low aragonite saturation and high discharge volume) in bioregion
Significant seasonal upwelling delivers water rich in CO_2 to shallow waters, leading to reduced Ω_{Ar}	Degree of upwelling[58]	Coastal zones scored on a five-point scale: low to high	Presence of high upwelling zone in bioregion

Table 2 | Indicators representing 'sensitivity' (people's dependency) on organisms expected to be affected by ocean acidification (in this study, shelled molluscs).

Indicator or measure	Source	Raw format	Processing for subindex
Landed value (median of 10 years)	Regional fisheries databases (ACCSP, GulfBase, PacFIN), and States of Alaska and Hawaii	US dollars, annual	Calculated median for years 2003–2012 Winsorized the top 10%
Percentage of total fisheries revenues that are from shelled molluscs (median of 10 years)		For each year: shelled molluscs value/total commercial landed value	Divided landed value of shellfish by landed value of all fish Winsorized the top 10%
Number of licences as proxy for jobs (median over 5 years)		Number of commercial licences, annual	Winsorized the top 10%

All indicators are in units of county clusters.

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Table 3 | Threat-specific indicators used to assess capacity of fishing communities to deal with impacts of ocean acidification.

Group	Indicator	Source	Raw format	Processing for subindex
Access to scientific knowledge	Budget of Sea Grant programmes	National Sea Grant	State-level total funds of budget (state and federal contributions combined, 2013)	• Normalized by state's shoreline length re-scaled (0–1) • Attributed scores to each county cluster
	Number of university marine laboratories	Direct count from registries and Internet	Latitude/longitude location of laboratories	• Combined score of laboratories per state/shoreline length and labs per county cluster
Employment alternatives	Shelled mollusc diversity	Regional fisheries databases (ACCSP, GulfBase, PacFIN), and States of Alaska and Hawaii	Ratio of landing revenues for each taxon by county cluster	• Calculated Shannon Weiner Diversity Index
	Economic diversity	ACS Census	Proportion of county population employed in each industry	• Calculated Shannon Weiner Diversity Index for county clusters
Political action	Legislative action for OA	Keyword searches on legislature websites and follow-up calls	Established five-point scale for state's legislative progress on OA	• Re-scaled 0–1 • Attributed score to county clusters
	Climate adaptation planning	Georgetown Law School Climate Center website	Status of climate adaptation plan for state	• Re-scaled 0–1 • Attributed score to country clusters

See Supplementary Information for discussion and presentation of alternative indicators and measures.

cluster was averaged with a metric based on the total number of university marine laboratories in that state (see Supplementary Information for more information) and (6) Sea Grant state budgets normalized by shoreline length. These indicators represent the availability of local scientific capacity, the potential for trouble-shooting assistance, and the possibility of access to a range of tools and data products, such as available early warning information. We attributed each county cluster (as used in Sensitivity) to each variable score of the six indicators. We then combined into a single index by averaging re-scaled (0–1) overall component scores for sensitivity and adaptive capacity (Supplementary Information Fig. S9). Coincidence of high marine ecosystem exposure to OA with high sensitivity and low adaptive capacity of social systems reveals the areas at highest overall vulnerability to OA.

Places vulnerable to ocean acidification

Our results show that 16 out of 23 bioregions around the United States are exposed to rapid OA (reaching Ω_{Ar} 1.5 by 2050) or at least one amplifier (Fig. 2 and Supplementary Table S1); 10 regions are exposed to two or more threats of acidification (note that Alaska and Hawaii are missing local amplifier data; Fig. 2). The marine ecosystems and shelled molluscs around the Pacific Northwest and Southern Alaska are expected to be exposed soonest to rising global OA, followed by the north-central West Coast and the Gulf of Maine in the northeast United States. Communities highly reliant on shelled molluscs in these bioregions are at risk from OA either now or in the coming decades. In addition, pockets of marine ecosystems along the East and Gulf Coasts will experience acidification earlier than global projections indicate, owing to the presence of local amplifiers such as coastal eutrophication and discharge of low-Ω_{Ar} river water (see Supplementary Figs S4–S6 and Supplementary Table S1).The inclusion of local amplifiers reveals more coastline segments around the United States that are exposed to acidification risk than when basing exposure solely on global models.

Combining sensitivity and adaptive capacity reveals that the most socially vulnerable communities are spread along the US East Coast and Gulf of Mexico (Fig. 2), yet the sources of high social vulnerability are very different between these two regions (see Supplementary Information for breakdown separated by sensitivity and adaptive capacity, Figs S8 and S9). Specifically, the East Coast is dominated by high levels of sensitivity, or economic dependence, from strong use of shellfish resources. For example, southern Massachusetts measures as having the highest sensitivity. This county cluster ranks in the top four for all three sensitivity indicators (Supplementary Fig. S8), meaning that this area has the highest mollusc harvest revenues of any coastal area in the United States, second highest number of licences and fourth highest proportion of seafood revenues coming from molluscs. In contrast, the Gulf of Mexico region is socially vulnerable from low adaptive capacity, owing to social factors such as low political engagement in OA and climate change, low diversity of shellfish fishery harvest and relatively low science accessibility (Supplementary Fig. S9).

Importantly, our visually combined overall vulnerability analysis reveals that a number of socially vulnerable communities lie adjacent to water bodies that are exposed to a high rate of OA or at least one local amplifier, indicating that these places could be at high overall vulnerability to OA (Fig. 2). The areas that are exposed to OA (including local amplifiers) and where high and medium–high social vulnerability is present include southern Massachusetts, Rhode Island, Connecticut, New Jersey and portions around the Chesapeake Bay, the Carolinas, and areas across the Gulf of Mexico (Fig. 2b–d). Interestingly, global ocean models that project the advance of OA, primarily as a result of atmospheric CO_2, do not reveal these areas as exposed to global OA until after 2099, based on our study's Ω_{Ar} threshold (Table 1). The marine ecosystem exposure in the areas located along the Atlantic coast and the Gulf of Mexico is from low-Ω_{Ar} conditions caused primarily by the addition of river water and eutrophication, local factors that have only more recently been considered major amplifiers of nearshore acidification[6,7]. These coastal processes are likely to tip coastal oceans past organism thresholds as atmospheric CO_2 uptake continues in the future (see ref. 22). Although the Pacific Northwest, northern California and Maine exhibit only medium and medium–low social vulnerability (Fig. 2a,b), these areas are particularly economically sensitive and lie adjacent to marine ecosystems highly exposed to global OA[23,24] (sensitivity, Supplementary Fig. S8). This profile of relatively high dependency and high exposure in these three regions has already activated significant research and local action/engagement among local scientists, government and shellfish growers (see for example refs 25,26). This engagement has driven up adaptive capacity (based on our study's indicators) in these areas, which reduces their social vulnerability relative to other regions across the United States. In comparison, the lower level of OA-related action in other regions such as the Gulf of Mexico (Fig. 2d), Massachusetts (Fig. 2b) and

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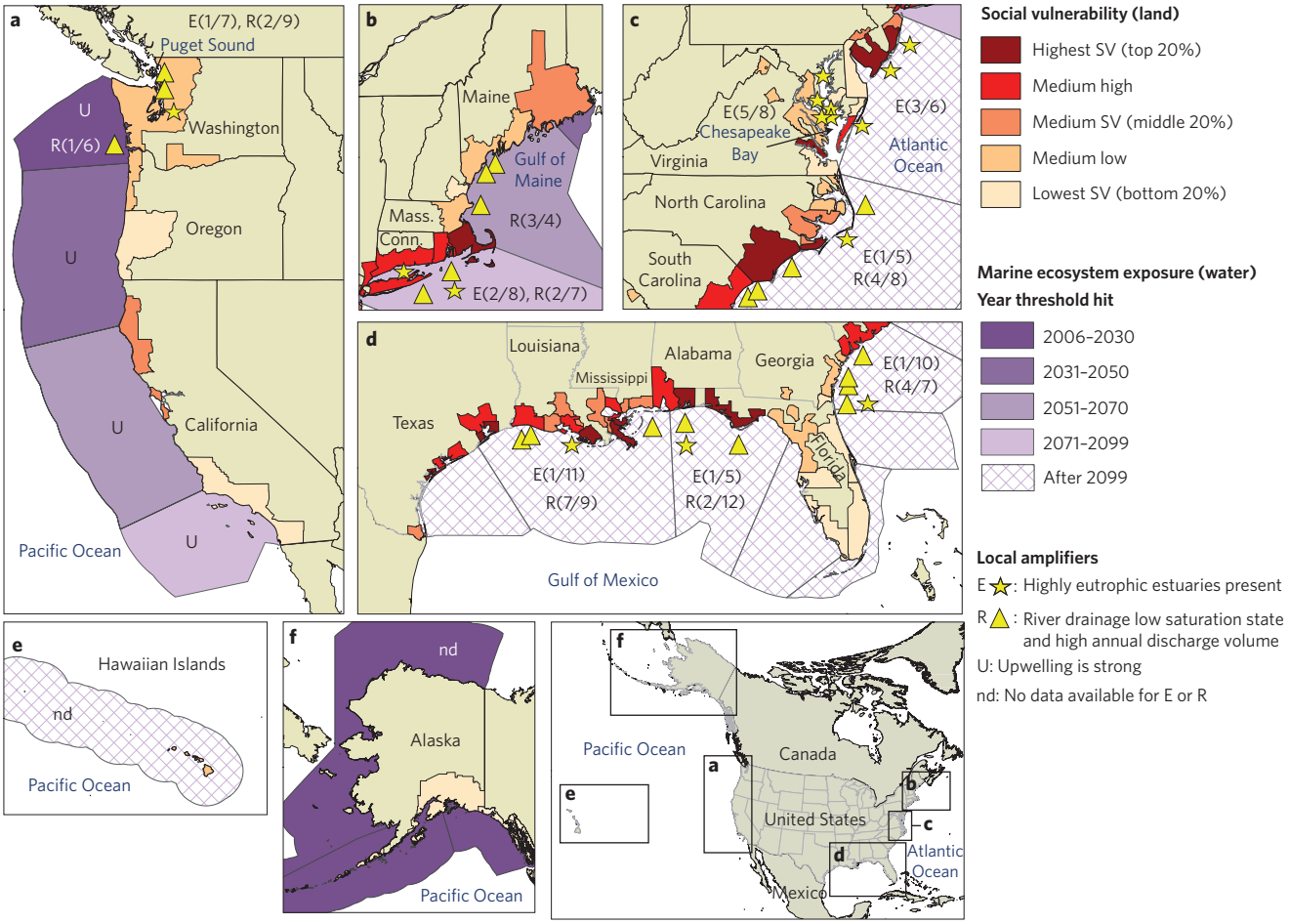

Figure 2 | Overall vulnerability of places to ocean acidification. a–f, Scores of relative social vulnerability are shown on land (by coastal county cluster) and the type and degree of severity of OA and local amplifiers to which coastal marine bioregions are exposed, mapped by ocean bioregion: contiguous US West Coast (**a**), Northeast (**b**), Chesapeake Bay (**c**), the Gulf of Mexico and the coast of Florida and Georgia (**d**), the Hawaii Islands (**e**), and Alaska (**f**). Social vulnerability (red tones) is represented with darker colours where it is relatively high. Exposure (purple tones) is indicated by the year at which sublethal thresholds for bivalve larvae are predicted to be reached, based on climate model projections using the RCP8.5 CO_2 emission scenario[27]. Exposure to this global OA pressure is higher in regions reaching this threshold sooner. Additionally, the presence and degree of exposure to local amplifiers of OA are indicated for each bioregion: E(*x*/*y*) marks bioregions in which highly eutrophic estuaries are documented, *x* is the number of estuaries scored as high, and *y* is the total number evaluated in each bioregion[56], locations of highly eutrophic estuaries are marked with a star; R(*x*/*y*) marks bioregions in which river water draining into the bioregion scored in the top quintile of an index designed to identify rivers with a very low saturation state and high annual discharge volume (calculated by authors from US Geological Survey data[57]), *x* is the number of rivers scoring in the top quintile of those evaluated, and *y* is the total number evaluated in this study. Approximate locations of river outflows of those rivers scoring in the top quintile are marked with a yellow triangle, and U marks bioregions where upwelling is very strong in at least part of the bioregion[58].

Mid-Atlantic (Figs 2c,d) with high overall vulnerability profiles might be partly because their marine ecosystem exposure is dominated by the presence of local OA amplifiers rather than global OA (Supplementary Fig. S2 and Supplementary Table S1). At the same time, some of these areas (for example Maryland) do have strong advocates for addressing water quality which could provide an opportunity to address locally driven acidification as awareness of the issue grows.

Robustness of analysis

To examine the robustness of these spatial patterns of vulnerability, we varied the index aggregation methodology and the selection of indicators. To test the difference in index aggregation methods for social vulnerability, we compared the output of adding and multiplying sensitivity and adaptive capacity indices and found little difference; the same set of county clusters made up the top 10 most socially vulnerable places using either aggregation method.

To explore the effect of indicator selection on adaptive capacity (and thus social vulnerability), we compared a set of commonly used generic indicators for adaptive capacity relating to income, poverty, education and age with the set of threat-specific indicators developed for this study (see Table 3 and Supplementary Figs S10 and S11). Using the generic capacity measures to calculate social vulnerability, we found that six of the same county clusters measured within the top 10 highest socially vulnerable places in the United States as those found using the threat-specific capacity indicators (see Supplementary Information for analysis and maps). This is considerable overlap given that the two sets of variables indicate entirely different notions of adaptive capacity. Because the sensitivity indicators were developed and vetted by fisheries social science researchers[21] and alternative potentially appropriate data were not available nationwide, we did not have a useful comparison for this element from which to draw.

To explore the criterion for Ω_{Ar}, we examined one alternative for disruption of biological processes with respect to rising

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atmospheric CO_2: the time until average surface waters move outside the present range of Ω_{Ar} (that is, exceeding a historic envelope)[27]. The map generated by this 'historic envelope' approach shows that southern areas experience potential OA exposure earlier, which is nearly an inverse pattern to our chosen criterion of a chemical threshold when calcification and development of larval molluscs may be disrupted (Supplementary Fig. S3). This difference in patterns is because natural variability is much smaller in southern regions, although evidence of greater sensitivity in populations of bivalves that live in tropical and subtropical waters is lacking. This discrepancy underscores the need for targeted research integrating a physiological, ecological and evolutionary perspective on the potential and limitations of strong local biological adaptation to different carbonate regimes for commercially valuable shelled mollusc populations.

Overall, we found that variable selection has stronger effects than aggregation methods, which provides high confidence in our aggregation methods for social vulnerability. The differences found in variable selection identify research needs relating to what factors underlie vulnerability on the ground that are relevant to OA; this conversation has only just begun.

Opportunities to reduce vulnerability to ocean acidification

Social–environmental syntheses, including vulnerability analyses, can help to identify opportunities for actionable solutions to address the potential impacts of ocean acidification. Our analysis reveals where and why the overall vulnerability from OA varies among the many coastal areas of the United States, and thus identifies opportunities to reduce harm.

One way to tackle OA is by reducing marine ecosystem exposure to it. Several portions of the east coast are highly exposed to OA from high levels of eutrophication (Fig. 2b–d). In addition to releasing extra dissolved CO_2 and enhancing acidification, eutrophication can also decrease seawater's ability to buffer further acidification[3]. People in these regions are uniquely positioned to reduce exposure to OA through regional actions by curtailing eutrophication (as compared, for example, with regions exposed to upwelling). Although a significant challenge, reducing nutrient loading to the coastal zone in these areas could provide multiple benefits, making it a no-regrets option. Reducing eutrophication can decrease hypoxia and harmful algal blooms, in addition to reducing risk from fossil-fuel-derived OA at the local and regional level. Policy instruments to reduce eutrophication exist in the United States[28] and can be leveraged to facilitate efforts to reduce OA[8].

Another important way to combat the effects of OA will be by reducing social vulnerability. In regions where high sensitivity (one component of social vulnerability) arises from the structure of the fishing industry, an entirely different approach to adaptation may be more appropriate than those geared to reduce marine ecosystem exposure. For example, where fishery harvest portfolios are dominated by a single species, such as in the Gulf of Mexico where mollusc production is limited to the eastern oyster (*Crassostrea virginica*), diversification of the species harvested might be a beneficial strategy.

A further way to reduce social vulnerability may be by increasing adaptive capacity of people and regions. Access and availability to science already has helped shellfish aquaculturists in the Pacific Northwest to identify and avoid some of the consequences of OA[20]. Working with local scientists, hatcheries have implemented several strategies to adapt and mitigate OA effects on bivalve seed production. Through local industry–research partnerships in the Pacific Northwest, implementation of real-time monitoring of saturation state, chemical buffering of water, changes in timing of seasonal seed production and use of selectively bred lines of oyster broodstock, this collaboration has prevented collapse of the regional oyster industry.

In every case, when developing a broader array of adaptation strategies, it is critical to work directly with the coastal communities in each region so they can develop context-appropriate and feasible adaptation options. Targeted projects to develop local adaptation plans may even require developing further regionally relevant indicators of adaptive capacity and community resilience that this nationwide study does not capture. In fact, zooming in to assess particular regions at a higher resolution would enable regional stakeholders to provide input into a possible different set of variables that defines vulnerability in their particular region based on local values and social or economic context.

Barriers to and path forward for addressing OA

This study offers the first nationwide vulnerability assessment of the spatial distribution of local vulnerability from OA focusing on a valuable marine resource. But it is just a first step to understanding where and how humans and marine resources are at highest risk to OA and its local amplifiers. Another key finding of this assessment is that significant gaps in the scientific understanding of coastal ocean carbonate dynamics, organismal response and people's dependence on impacted organisms limit our ability to develop a full suite of options to prepare for, mitigate and adapt to the threats posed by OA. These gaps can be considered in a structured way using the framework (Fig. 3). The types of gaps identified — as commonly classified in information science and other disciplines[29,30] — range from data inaccessibility to knowledge deficiencies.

Marine ecosystem exposure. Key gaps remain in understanding how global and local processes interact to drive nearshore OA, and how this will affect marine organisms and ecological systems. Recent studies suggest that the biogeochemical interaction between global OA and local amplifiers is additive[3,22,31]; however, most ocean models used to project future OA cannot adequately resolve these processes, which are also increasingly affected by human activity[7,32]. Even though direct measurements incorporate an ever-growing global network of monitoring instruments, they are often located offshore and remain too sparse in space and time to resolve the dynamics of seawater chemistry near shore, where most shellfish live. Historically, OA monitoring has focused on offshore regions, where long-term, high-accuracy and precise measurements enabled detection and attribution of the rising atmospheric CO_2 acidification signal. But many commercially and nutritionally important organisms live in the coastal zone where they experience the combined effects of multiple processes that alter the carbonate chemistry[7]. This results in greatly variable 'carbonate weather' for a given location[33]. Characterizing this variation, including modelling how rising atmospheric CO_2 will increase the frequency, duration and severity of extreme events, would provide a fuller picture of how OA is unfolding within the dynamic coastal waters.

To improve our understanding of which marine ecosystems and organisms are most susceptible to ocean acidification, additional information on the Ω_{Ar} thresholds below which reproduction and survival are disrupted is needed. In the US context, the concentration of value in a limited number of shellfish species means that the identification of biologically susceptible and resistant species and populations is both prudent and feasible. Based on total landed value from 2003 to 2012, approximately 95% of shelled-mollusc revenues in the United States come from only 10 species (and 80% from five). These species include sea scallop (52.9%), eastern oyster (11.3%), Pacific geoduck (5.8%), Pacific oyster (5.2%) and six species of clam (that range from 5% to 2.6% of total value)[34]. There is some evidence of local biological adaptation of other marine taxa to varying carbonate chemistry regimes[35–37]. This potential genetic variation, if present, could

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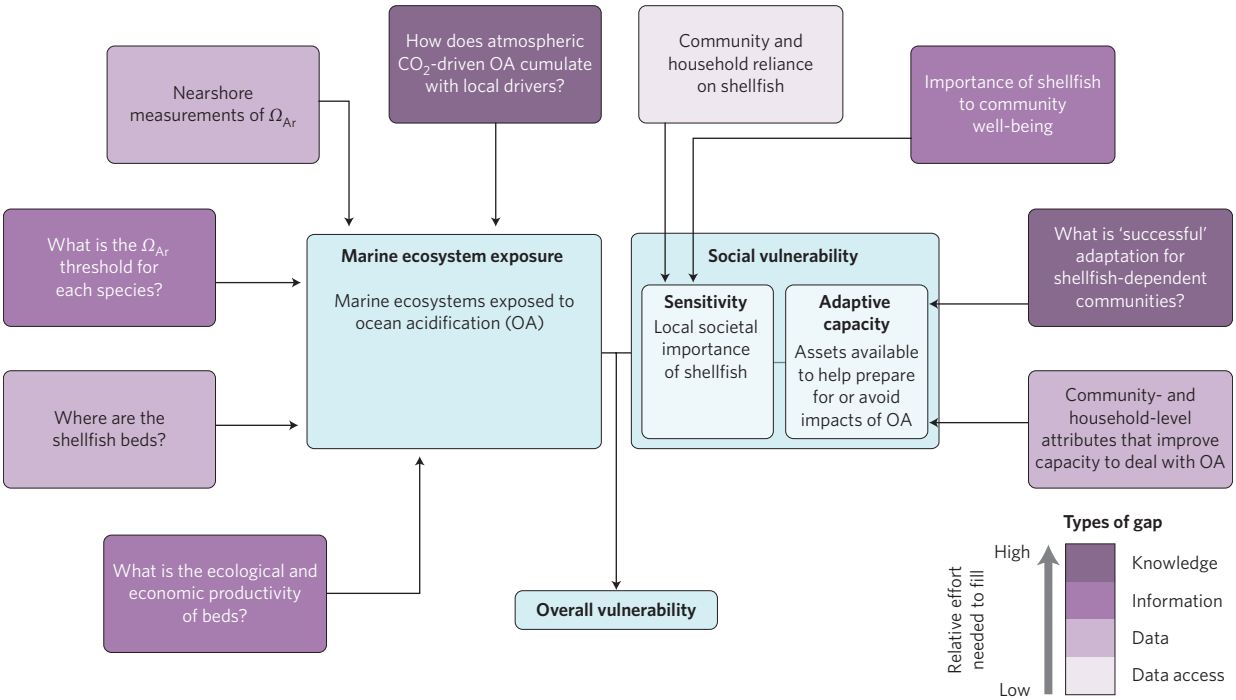

Figure 3 | Sample of gaps in knowledge related to OA vulnerability, organized around components of the framework. Different types of gaps are classified by the level of effort that is required to fill them (gaining knowledge is the most challenging, whereas data access tends to be the most straightforward).

be documented to aid in the development of resistant strains of cultured or other organisms.

Social vulnerability. Our study also revealed large gaps in information about mollusc-dependent communities to inform measures of social vulnerability. We do not have high-resolution nationwide data on the full cultural and societal significance of shelled molluscs. Even data on the contributions of shellfish to human nutrition, shoreline protection, and water filtration were inadequate nationwide. Incorporation of these other ecosystem services provided by molluscs could alter the social vulnerability landscape. For the commercial fisheries data that we did obtain, confidentiality constraints forced us to aggregate our analysis into county clusters, preventing county-specific or port-level analyses of social vulnerability that might have revealed more spatial heterogeneity. We also lack social science data that describe use at species-, human community-, port- or household levels. We lack data on the value chain that links threatened organisms to harvesters, processors and end-users. Finally, empirically tested adaptive capacity measures could contribute to a more rigorous evaluation of social vulnerability. This includes data on scientific spending and infrastructure directly relevant to end-users, as well as social and demographic data that are reflective of end-users (for this study, fishing and aquaculture communities) and not the general population (for example generic indicators quantifying education and income).

Beyond helping in prioritizing and developing adaptation strategies, social science is also useful to inform and guide planning for social adaptation and mitigation. As with climate change adaptation, preparing for and adapting to the impacts of OA is a social process[1,38,39]. Implementation does not occur automatically once strategies are developed, but instead must often overcome a suite of institutional (including legal), political, psychological and other types of barriers[40]. As learned from climate change initiatives, the 'softer side' of adaptation (such as coordination among stakeholders, industry and scientists) is the first step towards preparing for a threat like OA[41]. Despite its fundamental importance, this type of effort is often overlooked and remains underfunded. Social science can also help practitioners even in early stages of adaptation figure out how to engage public and policy-makers effectively in OA issues[42–44]. Farther along in adaptation processes, social science can inform the development of strategies by accounting for social values[45,46] and existing property rights in use and norms[47,48] and even helping to work out what type of information is salient for and trusted by decision-makers[49,50]. Although important for reducing social vulnerability to OA, investment in social science on this issue has been minimal thus far. A budget assessment conducted by the Interagency Working Group on Ocean Acidification reported that federal research in fiscal year 2011 allocated US$270,000 of Federal funds for social science research related to OA, which represents 0.9% of the entire OA spending for that year's budget[51].

Conclusions

As with other global environmental changes, acidification of the oceans is a complex and seemingly overwhelming problem. Here we have focused only on OA (and nearshore amplifiers) as the threat to coastal species. Although other stressors also threaten coastal ecosystems, our single-threat assessment allows us to tease out where OA in isolation could hit people and organisms the hardest, which can inform research agendas and decision-making geared specifically to address OA. A vulnerability framework helps to structure our thinking about the ways in which ocean acidification will affect ecosystems and people. The framework also helps to identify and organize the opportunities and challenges in dealing with these problems. But this study is the beginning; adaptation to OA and other global environmental change is an iterative process that requires both top-down and bottom-up processes. Our analysis of OA as it relates to US shelled mollusc fisheries makes clear just how much the pieces of the OA puzzle vary around the country. Marine ecosystem exposure, economic dependence and social capacity to adapt create a mosaic of vulnerability nationwide. An even more diverse set of strategies may be needed to help shellfish-dependent coastal communities adapt to OA. Rather

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than create and apply a nationwide solution, decision-makers and other stakeholders will have to work with fishing and aquaculture communities to develop tailored locally and socially relevant strategies. Meaningful adaptation to OA will require planning and action at all levels, including regional and local levels, which can be supported with resources, monitoring, coordination and guidance at the national level.

Over the past decade, scientists' understanding of ocean acidification has matured, awareness has risen and political action has grown. The next step is to develop targeted efforts tailored to reducing social and ecological vulnerabilities and addressing local needs. Tools like this framework can offer a holistic view of the problem and shed light on where in the social–ecological system to begin searching for locally appropriate solutions.

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Author contributions

All authors provided input into data analysis and research design, and participated in at least one SESYNC workshop; J.A.E. led the drafting of the text with main contributions from L.S., S.R.C., L.H.P., G.G.W. and J.E.C.; R.v.H. contributed projections of ocean acidification; L.H.P. contributed shelled mollusc diversity scores; J.A.E., L.S., S.R.C., J.R., L.H.P. and C.D. collected the data; J.A.E. carried out data analysis and mapping.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to J.A.E.

Competing financial interests

The authors declare no competing financial interests.

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