Article

Vulnerability of blue foods to human-induced environmental change

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Global aquatic or 'blue' foods, essential to over 3.2 billion people, face challenges of maintaining supply in a changing environment while adhering to safety and sustainability standards. Despite the growing concerns over their environmental impacts, limited attention has been paid to how blue food production is influenced by anthropogenic environmental changes. Here we assess the vulnerability of global blue food systems to predominant environmental disturbances and predict the spatial impacts. Over 90% of global blue food production faces substantial risks from environmental change, with the major producers in Asia and the United States facing the greatest threats. Capture fisheries generally demonstrate higher vulnerability than aquaculture in marine environments, while the opposite is true in freshwater environments. While threats to production quantity are widespread across marine and inland systems, food safety risks are concentrated within a few countries. Identifying and supporting mitigation and adaptation measures in response to environmental stressors is particularly important in developing countries in Asia, Latin America and Africa where risks are high and national response capacities are low. These findings lay groundwork for future work to map environmental threats and opportunities, aiding strategic planning and policy development for resilient and sustainable blue food production under changing conditions.

Blue foods, defined as fish, shellfish, plants and algae from fishing and farming in marine and freshwater ecosystems, play an important role in food and nutrition security for billions of people while supporting livelihoods, economies and cultures around the world[1-6]. As a key source of animal proteins, essential fatty acids and critical micronutrients, blue foods make vital contributions to averting the triple burden of malnutrition, particularly in low-income and Small Island Developing States (SIDS)[3]. Central to scientific and policy discussions on the sustainability of food production has been how this production affects the environment and resource systems, from local to global scales[7-12]. Historically, blue foods have been heavily underrepresented in global food systems, models and assessments[1,4,13,14]. Such oversights can lead to policies that are based largely on terrestrial foods, missing the opportunity to include blue foods in efforts to build a more diverse and resilient food system. In a world facing increasingly frequent and severe disturbances, blue foods play an increasingly important role in avoiding human food crises that terrestrial systems alone may not be able to address. Overlooking blue foods in food policy discussions

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also increases the chances of negative and suboptimal environmental outcomes that could arise from ignoring the many links between terrestrial and aquatic systems[15].

Given the growing emphasis on the role of blue foods in the current and future transitions to sustainable food systems, inadequate attention has been paid to the vulnerability of blue food systems to environmental disturbances, with the possible exception of assessments focused on the current and projected impacts of climate change[16–19]. Blue food production is tightly coupled with environment and resource systems. Wild fish stocks targeted by capture fisheries depend on marine, coastal and inland freshwater ecosystems, while most aquaculture also relies on healthy aquatic and terrestrial environments to provide suitable farming environments as well as fish feed, seed (broodstocks and larvae) and other supporting functions to ensure survival and production[4,11,18,20–22]. These close ties to the environment suggest that blue food production may be particularly susceptible to human-induced environmental change, from changes in habitat, alterations to water quality and quantity, and pollution that affects growth, among other factors.

Blue foods are highly diverse, encompassing more than 540 species farmed or harvested in freshwater and over 2,190 species produced in marine systems[2–4]. This diversity provides both potential environmental liabilities and advantages. Notably, the specific effects of anthropogenic pressures on blue foods probably vary widely across species and systems, with unique sensitivities to different combinations of stressors and subsequent direct and indirect effects; the liability then is that key foods may be particularly vulnerable to anthropogenic pressures, but the advantage may lie in greater sustainability and resilience through portfolio effects[11,23].

Here we focus on how environmental disturbances, characterized by 17 anthropogenic stressors, are expected to affect the quantity (volume produced) and quality (food safety) of blue foods produced in the wild and through farming. Following a vulnerability assessment framework[24] that defines 'vulnerability' as a combination of sensitivity (that is, susceptibility to external stresses) and adaptive capacity (that is, the intrinsic ability to adjust to potential damage, to take advantage of opportunities, or to respond to consequences of environmental variability and external disturbance), and 'impact' as a function of vulnerability and exposure (that is, external stresses), we rely on expert elicitation, literature review and spatial analysis to investigate the spatial impacts of environmental change on global blue food production systems (Methods). We first use literature review and expert judgement to identify the most relevant and well-documented anthropogenic stressors and corresponding geospatial indicators. Next, we estimate exposure scores for each production system–stressor combination at the national level using a multifactor spatial analysis[25,26] and assess the vulnerability of blue foods to environmental change. Finally, we compute an impact index by country to map how environmental stresses impact the quantity and safety of blue food production systems. Our analysis fills a critical need to improve our understanding of the potential feedback between environmental change and blue food systems, and helps identify priority areas for research and action. In addition, we identify key opportunities and challenges for reducing impacts and mitigating risk to ensure the continued provision of blue foods in the future.

Exposure of blue foods to environmental stresses

Given their great diversity, blue foods may experience exposure to anthropogenic environmental stresses in different ways. We first used expert assessment workshops with paper co-authors to classify blue food production into groups according to the environment (marine or freshwater), production method (capture or aquaculture) and production system (for example, pond, cage), leading to 15 production archetypes (see 'Blue food system and archetype classification' in Methods). Seven of these were for capture fisheries, such as marine commercial

benthic and artisanal rivers, and eight were for aquaculture, such as cage finfish and pond crabs. Our goal in delineating these archetypes was to represent the predominant aquatic production systems and account for broad differences in their responses to stressors, including production links to specific biomes or habitats, the degree of production intensity and functional traits of the species produced.

We then performed a literature review using the Google Scholar keyword searching tool to identify the dominant anthropogenic stressors that have direct impacts on the quantity or the quality (safety) of blue foods at the production stage of the value chain (see 'Stressor identification' in Methods and Supplementary Data 1). Ten key stressors affecting the production quantity of blue foods were identified, including five climatic stressors (warming, acidification, sea level rise, severe weather events and altered precipitation) and five non-climatic stressors (hypoxia, eutrophication, diseases, invasion and parasites). In addition, seven stressors were identified as primary concerns for blue food safety, including three biological stressors (harmful algal bloom toxins, non-indigenous bacteria introduced by humans into aquatic systems and indigenous bacteria influenced by anthropogenic drivers such as climate change) and four chemical stressors (heavy metals, in this context referring to mercury; persistent organic pollutants (POPs); pesticides; and antibiotics). Stressors were also defined as either press (persistent and long-term, as with sea level rise (SLR)) or pulse (brief and short-term although potentially frequent, as with severe weather events)[27] (Supplementary Fig. 1). Harmful algal bloom (HAB) toxins are unique among this set in having a dual effect on both the quantity and quality of blue foods[28]. Other stressors not included here, such as different types of pathogens and a number of chemical pollutants, may be of localized importance but are not globally prevalent or have been identified as severely lacking evidence.

Once key archetypes and stressors were defined, a multifactor spatial analysis[25,26] was conducted to quantify the spatial exposure of blue food production to these stressors, including presence and intensity[29]. The exposure level for each stressor showed notable spatial variability. Some stressors exhibited localized concentrations of exposure intensity (for example, acidification, hypoxia, parasites and inland warming in Europe, and inland precipitation variability in Asia), while others were more dispersed (Fig. 1). Thailand was found to be highly exposed to pathogens associated with blue food production. Cyprus suffers from high exposure to antibiotics. Trinidad and Tobago has the highest exposure to mercury across freshwater and marine water bodies, mainly attributed to the widespread small-scale gold mining in Latin America[30]. Belgium and the Netherlands are particularly exposed to harmful parasites. Climate-linked stressors on the production quantity demonstrate high exposure intensity across a wide geographic range, particularly in the Northern Hemisphere, while non-climatic stressors show similarly high intensity across just a few countries (Supplementary Fig. 2). For food safety, most countries show moderate to high exposure to inland chemical stressors and low to moderate exposure to biological stressors and marine chemical stressors, with only a few countries in Southern Europe and Africa showing the highest intensity of exposure (Supplementary Fig. 2). Our indicator data for environmental stressors were derived from historical observations from different public recordings and may contain observational bias. Some of the unique exposure levels were, however, supported by the literature; for example, severe exposure to antibiotics in Cyprus primarily arises from the high consumption of anti-infective agents[31].

Vulnerability of blue foods

We assessed the likely vulnerability of each blue food archetype to each stressor using targeted literature reviews and drawing on expert assessment to score each stressor–archetype interaction as high, medium, low or none (see 'Vulnerability' in Methods and Supplementary Data 2). The purpose of the vulnerability assessment was not to describe how each archetype is currently functioning, but rather to focus on the
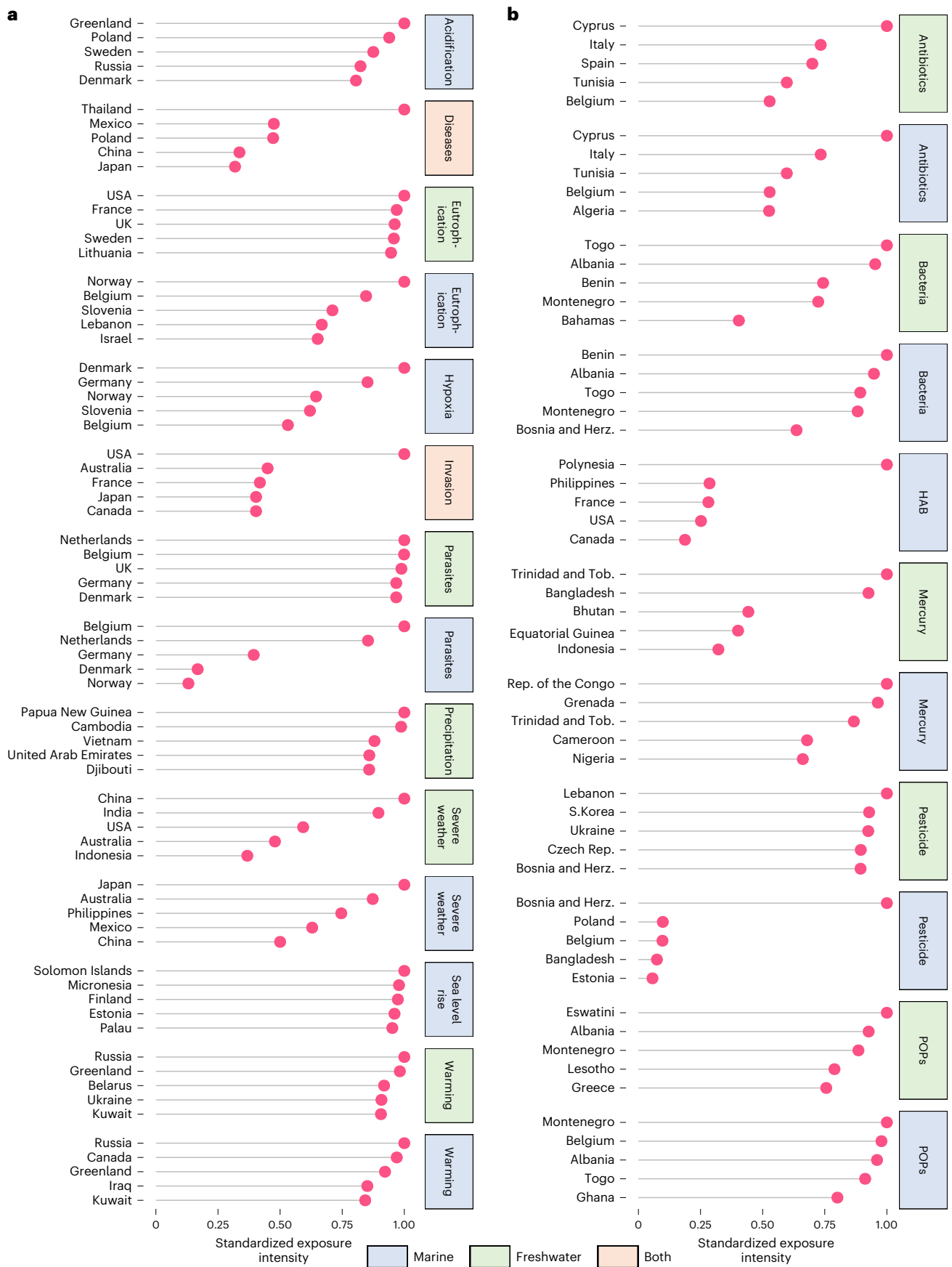
Fig. 1 | Top five countries with the highest exposure to anthropogenic stresses. a,b, Exposures are in terms of production quantity (**a**) and food safety (**b**). Scores were standardized and should only be compared within stressors.
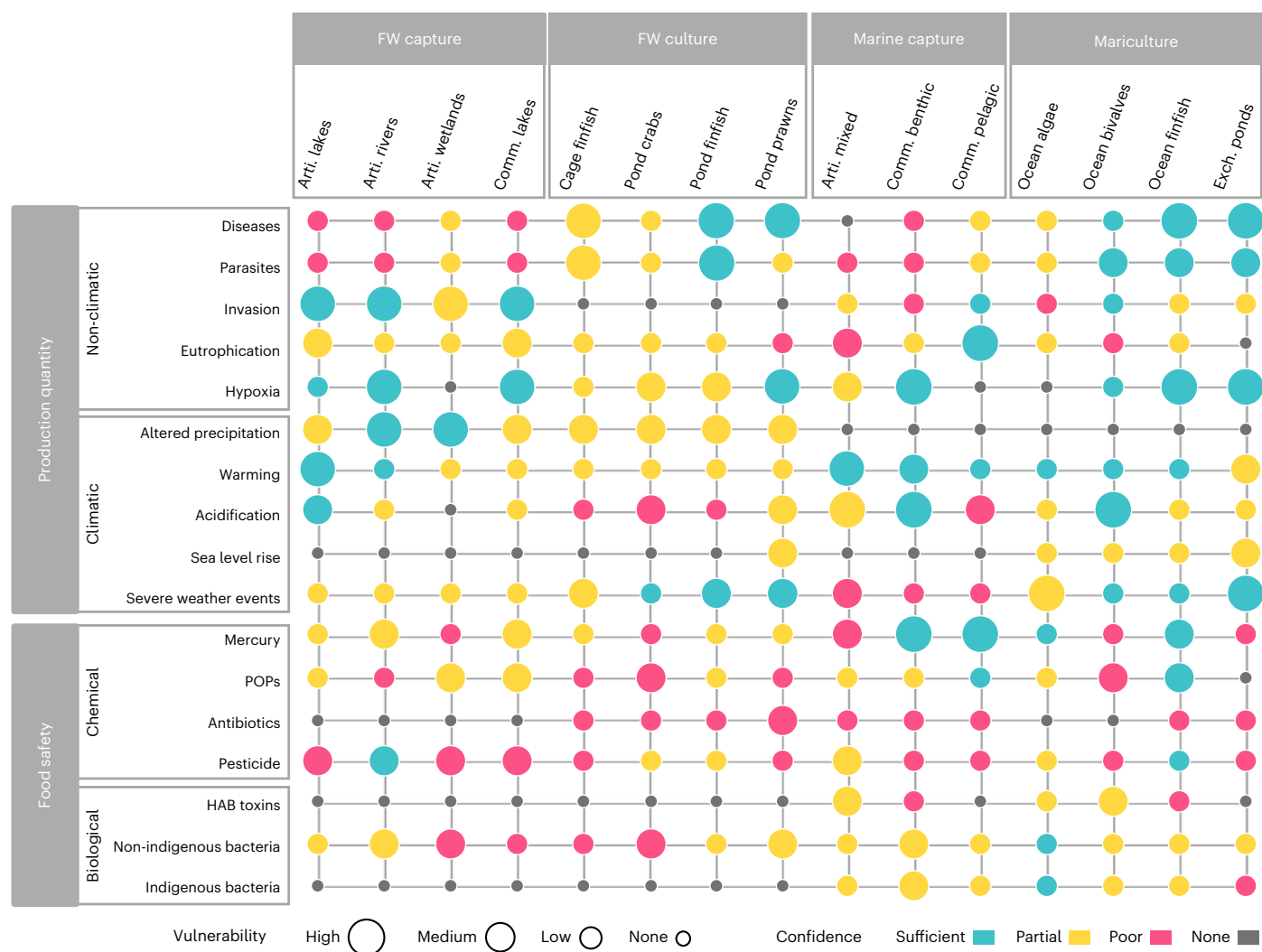
Fig. 2 | Vulnerability scores of 15 blue food archetypes to anthropogenic stressors affecting production quantity and food safety. Confidence scores are provided for each archetype–stressor assessment on the basis of the availability of evidence determined through the literature review and expert input. FW, freshwater; Arti., artisanal; Comm., commercial; Exch., exchange.

potential reduced functioning of each archetype under a given stress. Archetypes were vulnerable to different combinations of stressors and the extent of vulnerability varied (Fig. 2). Capture fisheries generally demonstrated higher vulnerability than aquaculture. Of all archetypes, marine fisheries, particularly artisanal mixed and commercial benthic fisheries, were the most vulnerable, mainly due to mercury, acidification and warming. Seaweed mariculture, which accounts for over 99.5% of global algae production, was the least vulnerable, demonstrating its outstanding potential for mitigation and adaptation to environmental disturbances.

In terms of production quantity, freshwater production was generally more vulnerable than marine production. Freshwater prawn ponds and marine exchange ponds appeared most vulnerable due to disease and hypoxia stresses. Freshwater fisheries were more susceptible to the introduction of invasive species and altered precipitation than others, which was consistent with the literature[32,33]. Indeed, altered precipitation was the only climatic stressor that primarily contributed to the vulnerability of the freshwater archetypes, with riverine and wetland fisheries being the most vulnerable. Across all stressors, hypoxia demonstrated the broadest impacts with associated effects of low water flows, increased water temperature and increased nutrient pollution. Artisanal fisheries were most vulnerable to surface water

warming, as frequently targeted fish communities in lakes and coral reefs are more sensitive to warming[34,35]. In general, marine fisheries were more vulnerable to climatic stresses particularly warming and acidification, while aquaculture was more vulnerable to non-climatic stresses such as diseases and hypoxia.

Vulnerability scores were generally lower across archetypes for food safety stressors than for production quantity. However, given the potential human health consequences of reduced food safety, even low-vulnerability blue food groups should be of concern in food system management[4]. Mercury contamination was the most pervasive stressor creating the highest vulnerabilities across archetypes. Impacts of mercury were exceptionally high for marine commercial benthic and pelagic fisheries, resulting in them being the most vulnerable archetypes in terms of food safety, partially due to the trophic levels targeted. The growing list of chemicals (for example, antibiotics) classed as persistent organic pollutants (compounds that persist in the environment, being resistant to degradation) and the prevalence of non-indigenous bacteria were of broad concern across the archetypes. Vulnerability to pesticide use was highest in freshwater and brackish systems. Anthropogenically linked increases in indigenous bacteria were largely a marine issue of lower concern than non-indigenous introductions, and benthic fisheries demonstrated the highest vulnerability.

Capture fisheries, particularly freshwater ones, showed higher vulnerability to food safety stressors than aquaculture. The confidence scores indicated a lower level of evidence related to food safety stressors at the level of archetypes than for production quantity, which was largely due to the reliance on monitoring efforts at the environment rather than the production system or species level.

This assessment took a holistic view of the vulnerability of blue food archetypes where relevant information was available, but trade-offs were necessary for data compilation on food safety stressors including pesticides, antibiotics and HAB toxins. Given that in many cases the specific food safety stressor–archetype interaction is a relatively niche piece of information to access, we needed to generalize from more specific foci for the vulnerability assessment. The characteristics of some food safety stressors (for example, mercury, POPs and bacteria) demonstrating substantial, fine-scale spatial and temporal fluctuations, potentially exceeding thresholds for human health, could not be sufficiently covered. Such details are utterly important when considering vulnerability. In these cases, it was necessary to generalize risk considerations. For example, mercury demonstrates global airborne deposition (delivery of substances by air) in aquatic environments but also notable point source (single identifiable source) inputs, which may impact vulnerability as well as exposure in very localized areas, such as in artisanal gold mining areas for freshwater systems[36].

Estimated impacts of anthropogenic stresses on blue foods

Variations in blue food exposure and vulnerability generated large spatial differences in estimated total impact (as a function of exposure and vulnerability and determined by spatial analysis; see 'Estimated impact' in Methods) and key sources of impact across environments and nations. Production quantity of aquaculture was predicted to be more severely impacted than capture fisheries in freshwater environments, while the opposite was true in marine environments (Fig. 3a). With at least one of the four production systems having standardized impact scores above 0.8, blue food production quantity in leading producing countries such as China, Norway and the United States was estimated to be most affected. Across these countries, high exposure to inland eutrophication, inland warming, altered precipitation and sea level rise was mostly common.

Whereas impacts on quantity were concentrated, impacts on food safety were sporadically distributed across the globe, with relatively consistent patterns between freshwater and marine production (Fig. 3b). Blue food safety in Albania and Montenegro was estimated to be most impacted at the production stage, as more than three of their four production systems had standardized impact scores above 0.8. Impacts of POPs, bacteria and inland pesticides were particularly acute in these two countries. Although a comparable distribution was found in production quantity impacts across continents, Oceania was markedly lower than other regions in terms of risks to food safety, as it has fewer potentially highly polluting industries in SIDS (Supplementary Fig. 3). A deeper dive into the impact profiles revealed that there was no clear relationship between the impacts on quantity and those on safety (Supplementary Fig. 4). Thus, the culmination of different threats and the realized impacts of stressors on blue foods require highly contextualized mitigation and adaptation strategies to ensure stable production under environmental change.

To identify particularly vulnerable groups of countries at risk from multiple forms of environmental change, we performed a cluster analysis of the overall impact for 222 countries and territories that reported blue food production over the past decade. We found four groups of countries characterized by high, medium-high, medium-low and low impacts (Fig. 4). The high and medium-high impact groups included many of the major blue food producing countries on our planet (for example, China, India, Vietnam, Norway and the United States). The medium-low impact group was dominated by landlocked countries,

while the low impact group was dominated by SIDS. Both freshwater production quantity and safety, particularly from aquaculture, were moderately to highly affected in all country clusters except SIDS, mainly attributed to warming, altered precipitation and eutrophication. Meanwhile, in SIDS, marine production quantity was most affected due to high exposure to sea level rise. Our results highlight the need to design effective management systems to enhance adaptation to climate change and to support climate-resilient fisheries and aquaculture for all countries. In addition, more stringent control of inland eutrophication will be priorities for all countries except SIDS.

To identify and prioritize adaptation and resilience-building strategies, particularly for countries with high estimated impacts, we assessed national response capacities reflecting their social, political and economic potential or ability to cope and adapt to environmental stresses (Supplementary Fig. 5). We then explored the relationship between estimated impacts on blue food production and national response capacity at the country level and prioritized outliers for mitigation (Fig. 5). Regarding production quantity, Denmark, Belarus and the United States appeared as mean-shift outliers with high response capacity but disproportionately large risks. In terms of food safety, Albania, Montenegro, and Bosnia and Herzegovina were identified as outliers due to extremely high impacts. Countries with the highest estimated impact but lowest national response capacity (that is, countries in the upper left corner of Fig. 5) may be priorities for impact mitigation and capacity building in terms of improved governance, economy and social development to enable more resilient blue food production. In terms of production quantity, high impact and low-capacity countries were found only in freshwater aquaculture. These countries, all of which are developing countries, including Uganda, Bangladesh, Eswatini, Honduras and Guatemala, were mostly affected by altered precipitation and parasites. Therefore, coping with impacts of climate change and specific harmful parasites in these countries should be prioritized to promote resilient aquaculture. With low national response capacities, Togo and Benin face high food safety threats for freshwater aquaculture and marine fisheries due to high exposure to inland pesticides, marine POPs and bacteria in both freshwater and marine water bodies. These acute impacts call for urgent and effective countermeasures to reduce and manage organic pollutants, control pesticide use and better screen for food safety at production sites.

Improving future blue food vulnerability estimates

Estimating the vulnerability of blue foods to anthropogenic stressors at the global scale necessarily faces data and methodological limitations. Global datasets for selected key stressors are limited, constraining our ability to assess exposure to certain stressors and most stressors at subnational resolution. Furthermore, most vulnerability assessments, including our study, remain primarily based on historical trends or snapshots, which may lead to inadequate conclusions about future risk[37,38]. Finally, data reported at different scales had to be resolved to the coarsest scale, resulting in some information reduction. For example, indicators for climatic stressors are often available at finer spatial resolution than for biological and chemical stressors; to address this, we aggregated high-resolution spatial data to calculate a national average over space for the geospatial mapping, limiting our ability to address subnational variation. Despite data limitations, the uncertainty analysis showed that our overall results were robust (Supplementary Fig. 6).

A critical gap influencing the assessment of food safety risks is accounting for the relationship between point source pollution, its distribution, and subsequent uptake and bioaccumulation in blue foods. Local-scale models exist for the distribution, accumulation and circulation of pollutants within ecosystems, but we lack regional or global scale high-resolution models that allow for the global assessment and comparisons done here. Building off the structure of existing datasets for chlorophyll, silicate, nutrients and sea surface temperature, such
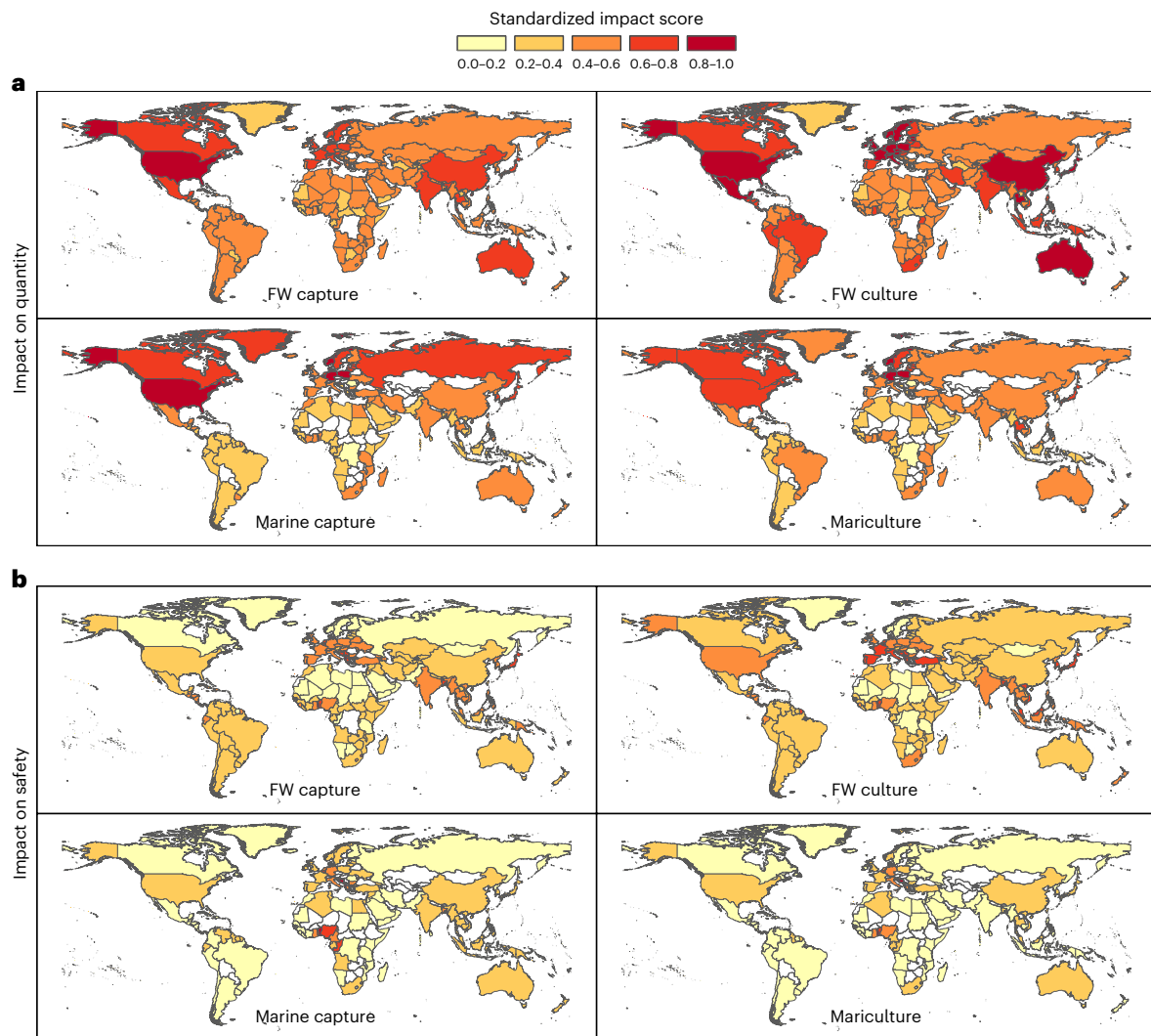
Fig. 3 | Estimated impacts of anthropogenic stresses on global blue food production. a, Impacts on quantity. **b**, Impacts on safety. Results were standardized and presented at the national level for each blue food production system. The four production systems included freshwater capture fisheries, freshwater aquaculture, marine capture fisheries and mariculture.

as Bio-ORACLE[39,40], to guide and standardize global data on pollutants would substantially advance analytical options. Additionally, we need continued research on the uptake, processing and storage of pollutants by aquatic organisms used for food throughout their life stages to better assess the vulnerabilities of blue foods and design mitigation strategies. A critical trade-off exists for organisms that are vulnerable to human health risks, such as stationary filter-feeding bivalves, but that may also provide key nutrition[3] through high nutrient density or accessibility to malnourished populations, and may be a sustainable alternative compared with production of other organisms[7]. In such cases, localized capacity for mitigation of such risks will be a key determining factor in their promotion. Combined, the above information will add to expanding understanding of sustainability and nutritional contributions for better planning of what species to harvest, avoid or mitigate, as well as developing strategies for when and where to harvest or cultivate them.

Additional challenges arise in accounting for the synergistic or cumulative impacts from multiple stressors that often vary among stressor combinations and across temporal and spatial scales[38,41]. These interactions remain poorly understood and need to be addressed in future vulnerability assessments, particularly at the regional or local level. Our results here represent conservative estimates of realized

impacts of stressors on blue foods. We assessed vulnerability only at the production stage; however, future work needs to improve understanding of post-production human health risk profiles through the value chain and the pathways by which they accumulate into organisms before human consumption.

Policy implications

Blue foods are an indispensable part of sustainable and equitable food systems and healthy diets[3,4], making it important to understand the extent to which anthropogenic environmental stressors may impede production of and access to adequate and safe seafood. This paper presents a comprehensive global analysis based on a composite vulnerability index to illustrate how pervasive anthropogenic stressors may affect the quantity and safety of fisheries and aquaculture production. Our analysis suggests that in marine environments, capture fisheries are generally more vulnerable than aquaculture, while the opposite is true in freshwater environments. Highly vulnerable production systems exist across all continents. Potential effects of environmental change on production quantity and safety differ in that production quantity faces high threats in both marine and freshwater systems across many locations, whereas food safety receives elevated impacts across a narrower geographical focus. In both cases, there is a need to address
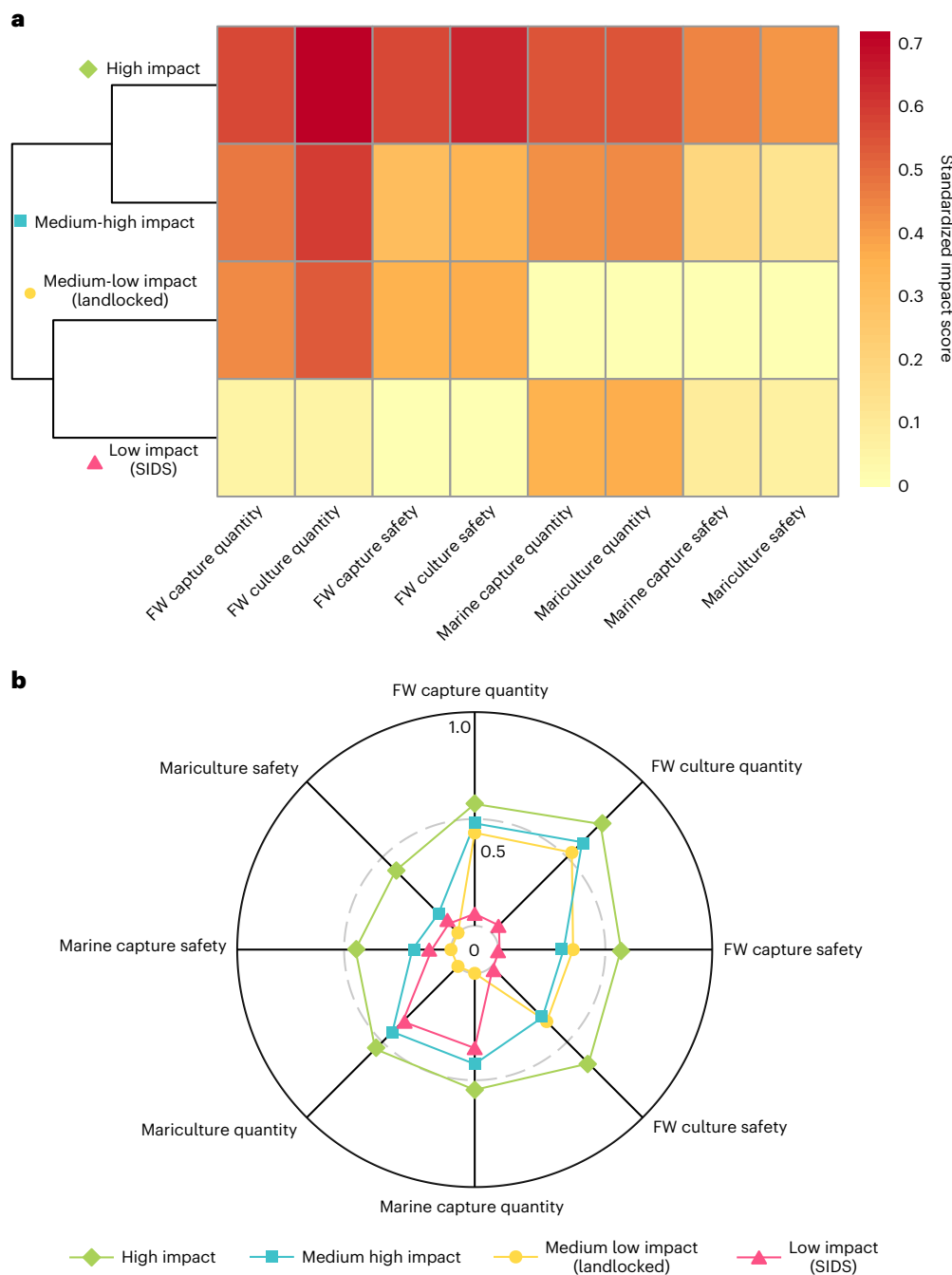
Fig. 4 | Cluster analysis based on the overall impact of all blue food systems for a total of 222 countries and territories. a,b, Heat map (**a**) and radar plot (**b**) of standardized impact scores of the four clusters obtained by *k*-means analysis. The four clusters are characterized by high impact (*n* = 33 countries), medium-high impact (*n* = 91 countries), medium-low impact (*n* = 39 countries) and low impact (*n* = 59 countries). The list of countries of the four clusters is provided in Supplementary Data 3.

stressors regionally, as stressors cross boundaries, and strengthen national response capacity where most necessary depending on the level of dependence on marine versus inland production.

Our analysis of blue food vulnerability at the national level can help us understand how each nation suffers from different combinations of stressors and its varying extent of vulnerability. Countries identified as highly vulnerable include the major blue food producers in Asia (for example, China, Japan, India and Vietnam) that account for over 45% of global landings and 85% of global aquaculture production, and thus require priority adaptation and mitigation actions to reduce vulnerability and exposure to hazards. Particular attention should

be paid to developing countries in Asia (for example, Bangladesh), Africa (for example, Togo) and Latin America (for example, Honduras) where risks are high and national response capacities are low. These countries are more likely to suffer from environmental disturbances and should prioritize both impact mitigation and capacity building in terms of improved governance, economy and social development to enable more resilient blue food production. In these countries, diversification of production (for example, expanding aquaculture in regions where it is still nascent and has low estimated impact) will be necessary unless sufficient mitigation and adaptation strategies are implemented.
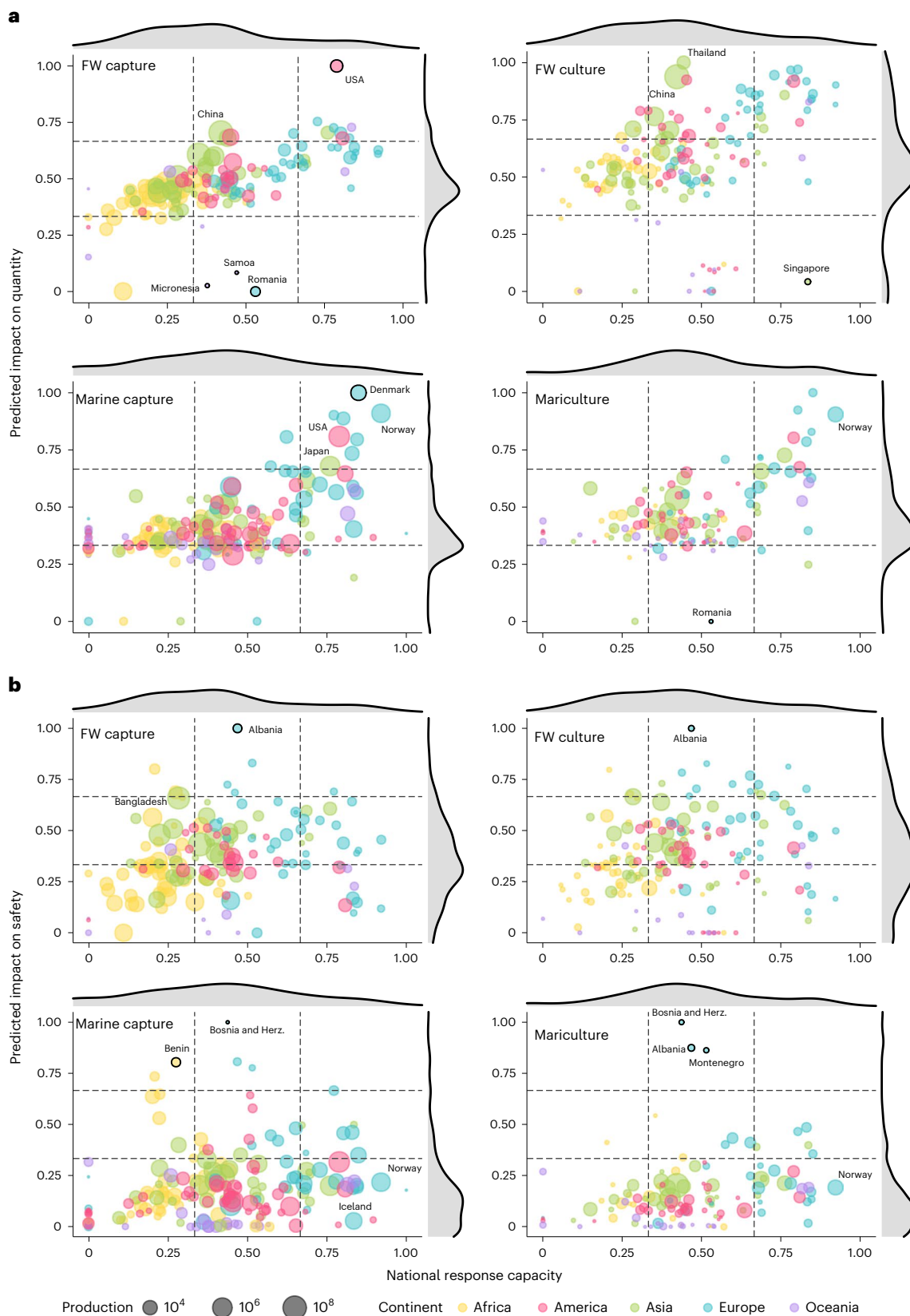
Fig. 5 | Relationship between the estimated impact and national response capacity of each blue food nation. a, Quantity. **b**, Safety. Circle size indicates the average blue food production (metric tons) of each nation for the past 10 yr. Circles with solid line borders and corresponding country names in bold indicate mean-shift outliers (extreme observations furthest from the mean value of the neighbourhood) based on Bonferroni outlier tests (*P* < 0.05, two-sided;

see 'Bonferroni outlier test' in Methods). Dashed lines indicate the one-third division lines of the maximum values of the horizontal and vertical axes. Grey shadings along the axes indicate density curves (the total area under the density curve represents probability). Most country names have been hidden to improve readability, and a detailed list of country rankings for each production system is provided in Supplementary Data 4.

Our findings provide key insights needed for decision-makers to formulate strategic actions in their jurisdictions, particularly with respect to specific vulnerabilities of blue foods disaggregated by region and production archetype. For example, the prevalent shrimp aquaculture in Thailand faces substantial climate and disease risks, and requires not only technological innovation in farming but also risk-sharing strategies such as price contracts and insurance[42]. These results also highlight the need for transboundary collaboration in mitigating stressors, particularly for food safety, given that risks can be transmitted through interconnected ecosystems (across national boundaries) and ultimately via the supply chain in a highly globalized food system that 'redistributes' our impact results to ultimate locations where blue foods are consumed. Such transboundary issues highlight the importance of international policy in maintaining sustainable blue food production under anthropogenic environmental change.

Across all blue food archetypes, greater stakeholder engagement in efforts to understand, monitor and mitigate pressures on different food types will be essential to bring higher-resolution information to bear on our understanding of vulnerability and exposure. Greater stakeholder engagement will also be important in efforts to design effective management actions and enhance local adaptation responses. Particularly for artisanal fisheries archetypes and heavily marine fisheries-dependent countries such as SIDS that often have limited data but require urgent actions to cope with climate change[43,44], incorporation of local and indigenous knowledge will be critical inputs for strategic planning and policy development. Indeed, this information is paramount for the one-third to one-half of the world that lies within indigenous lands and territorial waters[45].

Despite progress in developing adaptation strategies in blue food systems to climate change[19], substantial challenges remain in developing similar strategies for the complete set of stressors associated with anthropogenic environmental change. Our work provides an important foundation to guide future blue food research to develop such strategies and assess national-scale impacts to help inform context-specific mitigation strategies. Translating this global work into regionally and locally appropriate actions remains a key next step.

Methods

Ethics declaration

This study was granted exemption by the Ethics Committee of Xiamen University. We certify that the study was performed in accordance with the Declaration of Helsinki and later amendments. Informed consent was obtained from all the participants (that is, all co-authors in this study) before the study.

Expert assessment protocol

This study is part of Blue Food Assessment (www.bluefood.earth), an international joint initiative that brings together more than 100 scientists from over 25 institutions spanning the globe. At the preparation stage, a highly interdisciplinary group of over 20 experts was recruited by the lead authors of this paper as co-authors, taking full account of the diversity of age, gender, cultural background and specialization. All co-authors are familiar with blue foods and each has expertise in at least one area related to fisheries, aquaculture, seafood safety, climate change, environmental health or risk assessment. Following the standard 4-step principle ('investigate–discuss–estimate–aggregate') of expert elicitation[46,47] (see flowchart in Supplementary Fig. 7), the overall aim was to establish an unstructured expert assessment protocol to assist in study design and data selection and acquisition. Specific objectives were to: (1) gather expert opinions on blue food system and archetype classification, (2) select prevalent environmental stressors and associated indicators and (3) determine vulnerability scores and uncertainty. It should be noted that in the latter two assessment processes, an integrated approach of scoping literature review and expert assessment was used. Three expert assessments were conducted via interactive workshops and online document sharing. During the assessment, experts were first asked to answer the pre-designed questions independently. Facilitators then synthesized initial responses and returned anonymous results to all experts for discussion, allowing them to give a second round of feedback accordingly. Then the mode of the second round of responses was aggregated and shared with all experts for final review and approval. The last step was repeated until none of the experts disagreed, thus reaching a consensus. Full details of the protocol are provided in the Supplementary Information.

Blue food system and archetype classification

To represent the diversity of blue food systems and capture how each system will be affected by environmental stressors, we ran a first expert assessment and asked experts to individually answer one question: "What are the main blue food systems and archetypes?" We initially classified production into freshwater and marine systems, inclusive of both capture fisheries and aquaculture. Archetypes were then developed through a series of workshops with the co-author team, alongside discussions on the scope of the paper. Following such discussions, it was agreed that categorization should aim to represent dominant global production systems and, in particular, to categorize these systems by aspects that affect their vulnerability to stressors. The defining characteristics of such systems are linked broadly to the habitats or environments utilized and the species targeted or cultured. Further discussion refined these aspects to be broadly dominated by operation type and target environment for fisheries, and operation type and taxa produced for aquaculture. A resulting initial long list of 28 production types was then refined for feasibility to the final 15 archetypes, with the aim to best capture differences with respect to how stressors may impact production.

The 15 archetypes are: freshwater capture fisheries (artisanal lakes, artisanal rivers, artisanal wetlands and commercial lakes); freshwater aquaculture (cage finfish, pond crabs, pond finfish and pond prawns); marine capture fisheries (artisanal mixed, commercial benthic and commercial pelagic); and mariculture (ocean algae, ocean bivalves, ocean finfish and exchange ponds). We acknowledge that there are probably important differences in potential vulnerability of individual species within these broad archetypes, and suggest that future research could usefully focus on understanding the diverse responses within groupings.

Stressor identification

A scoping review was conducted to identify the key anthropogenic stressors that have a direct impact on blue food production systems (Supplementary Fig. 8a). Stressors impacting blue food production 'quantity' (volume produced) and 'quality' (food safety as it pertains to human health) were addressed separately.

The most prevalent stressors impacting blue food production quantity were first identified by screening published studies using the Google Scholar keyword searching tool. We used the search string (system name) AND (target name) AND (environment name) AND (extension 1 name) AND (extension 2 name), with detailed information provided in Supplementary Data 1. Each archetype corresponded to an individual searching process. The first 500 items of each search process (7,500 items in total for the 15 archetypes), sorted by relevance, were screened in titles, abstracts and keywords, yielding 508 useful articles within the search criteria. We acknowledge the limitations of keyword searching, which may not capture all relevant research, so a further assessment of identified stressors was done by the author team to check and verify the reasonableness of the stressors screened from the literature and finally select the stressors on which all experts reach consensus. In addition, stressors impacting blue food quality (that is, specific pollutants) were subject to an independent feasibility review to assess the appropriate levels of evidence, drawing on the results of a systematic review[48].

After the above literature review was completed, we conducted a second expert assessment with the co-author team. All experts were first given the screening results from the literature and then asked two questions: "Which of the stressors are reasonable to be retained in this research?" and "What are the indicators available for each stressor?". On the basis of the literature and expert assessment, we identified a total of 17 well-documented key stressors impacting production quantity and food safety of blue foods. Considering geospatial data availability, we further selected a globally available set of 28 indicators to represent and quantify those stressors (see Supplementary Table 1 for data sources, time span and resolution of all indicators). The indicators used to characterize each stressor affecting the production quantity of marine and inland blue food systems were slightly different. Sea surface temperature, pH and sea level rise were used as indicators of climate stressors for marine systems, while altered precipitation and air temperature were used for inland systems. The incidence of floods, typhoons and droughts was used as indicators of severe weather events. Hypoxia and eutrophication observations were used only for marine systems, while nitrate and phosphorus usage were indicators of eutrophication for inland systems. Records of disease outbreaks and the number of invasive species found in each country, as well as the spatially recorded occurrence of lice, leeches and protozoans as indicators of parasites, were obtained from public databases. Estimated mercury releases, pesticide risks and antibiotic usage, as well as monitored concentration of polychlorinated biphenyls (PCBs), hexachlorocyclohexanes (HCHs) and dichloro-diphenyl-trichloroethane (DDT), were used to reflect chemical stressors on food safety. The occurrence of HABs was used to represent HAB toxins. The occurrence density of *Listeria*, *Salmonella*, *Vibrio* and *Yersinia* was used to represent the major aquatic foodborne bacteria.

Countries included

Countries and territories with records of blue food production in the most recent decade (between 2010 and 2019) were included in the study ($N = 222$; 141 with both freshwater and marine production; 41 with marine production only; and 40 with freshwater production only). Current blue food production data in the FAO database (https://www.fao.org/fishery/en/topic/166235) are not differentiated by archetype, so we focused our spatial analysis on the four high-level production systems (freshwater capture fisheries, freshwater aquaculture, marine capture fisheries and mariculture). In addition, production from brackish water was considered to be marine.

Exposure

We conducted a multifactor spatial analysis[25,26] to assess the exposure of blue food production to environmental stresses by combining multiple indicators into a composite measure for each stressor. We assessed exposure where the fishing activities happen within the national boundaries of each nation and then aggregated that up to national-level statistics. This study excluded fishing in areas beyond national jurisdictions because our focus on national-level results was intended to aid in policy and management decisions within jurisdictions. Historical observation records (Supplementary Table 1) were used to reflect the intensity of each indicator. Histograms for many of the indicators revealed skewness in their distributions (as detailed in Supplementary Table 2), so these skewed indicators were first transformed (for example, logarithmic or square root transformation, see transform methods and effects in Supplementary Table 2) to support subsequent analysis, which requires mean and variance as meaningful summaries of the data. Outliers represent natural variations in this study, so they were left for subsequent analysis. To make the variables measured at different scales and units comparable for spatial analysis, we used the min-max normalization method (formula: $x' = (x - min) / (max - min)$, where x' is the rescaled value, x is the original value, max is the maximum value of x and min is the minimum value of x) to rescale the value

of each feature to a dimensionless range between 0 and 1. Different types of data were initially compiled at the national level as follows: (1) for geospatial data displayed in grids, data were aggregated to national geographic boundaries (territorial land for inland systems and EEZ for marine systems) to calculate national averages using the 'extract' function in the 'terra' package in R; (2) for observation records with spatial coordinates, data were converted into geospatial data using the 'Kernel Density' geoprocessing tool (with default parameters) in ArcGIS 10 and further calculated to obtain national averages; (3) for observation records without spatial coordinates (for example, invasive species and disease occurrence), data were counted and aggregated by country. In the complex blue food systems, there is no good way to determine the weight of each indicator for each stressor, as it may vary from region to region. On the basis of our expert discussions, we decided to assign the simplest equal weight to each indicator within each stressor to overcome the data limitation problem.

The exposure (E) of the blue food system (j) in a country (i) in response to a stressor (s) was calculated as a mean across indicators:

$$E_{i,j,s} = \sum_{k=1}^{n} X_{i,j,k} \times \frac{1}{N_s},\qquad(1)$$

where $X_{i,j,k}$ is the normalized value of indicator k to which system j is exposed in the country i, and N_s is the number of indicators that are used to create the composite measure for stressor s.

Vulnerability

The vulnerability of blue foods to environmental change was assessed as a combination of sensitivity (that is, the degree to which a system is affected by environmental variability or change) and adaptive capacity (that is, inherent ability to not only recover from but also adapt to environmental change) using an integrated approach of scoping review (Supplementary Fig. 8b) and expert assessment. Review keyword planning and search string development were conducted in consultation with the co-author group. We used the search string (stressor name) AND (system name) AND (target name) AND (environment name) AND (extension 1 name) AND (extension 2 name), with detailed information provided in Supplementary Data 1. The included literature was limited to publication (excluding books) after 2000 as a suitable cut-off both for the inclusion of modern aquaculture systems and the inclusion of increased rates of research related to many stressors. Each archetype–stressor combination corresponded to a separate search process using Google Scholar, comprising a total of 255 processes (15 archetypes multiplied by 17 stressors). The first 200 results of each searching process, sorted by relevance and screened in titles, abstracts and keywords, yielded a total of 51,000 literature results. Full-text screening then determined inclusion in vulnerability assessments following the criteria: (1) articles investigated an impact on production quantity or quality (decrease or increase) explicitly linked to the relevant stressor; (2) articles demonstrated impact on a production system or production scenario (for example, specific farm, specific fishery) explicitly relevant to the archetype; (3) the impact on production was quantified at the scale of the study, and in the case of food quality, an explicit link to a human health impact was made (although this might not have been quantified); (4) articles did not contain important methodological flaws under the reviewers' assessment; and (5) articles were published after the year 2000.

Due to data limitations, the vulnerability scoring was necessarily a partially subjective process, so we conducted a third expert assessment, with the co-authors divided into six groups and performing semi-quantitative and qualitative syntheses of the information related to archetypes, ranging from species to system level. Each expert group was responsible for a different subset of archetype–stressor combinations. Each expert in the same group was asked to give an individual score for each archetype–stressor assessment. Individual scores were

subsequently synthesized and shared with the entire co-author team to allow for feedback until a consensus was reached.

On the basis of the literature screening results, vulnerability levels were qualitatively defined by co-authors as: (1) high: system performance or safety severely impacted; (2) medium: system performance or safety moderately impacted, or a moderate subsection of the system was impacted; (3) low: low impact on performance at the system level, or a minor subsection of the system was impacted; (4) none: no impact. The vulnerability of a high-level blue food production system to a specific stressor was determined as the mode value of archetype vulnerability levels in that system (Supplementary Table 3). The final results were placed in a pre-coded Excel template. Key supporting literature for each assessment is provided in Supplementary Data 2.

Meanwhile, co-authors also discussed and quantified the uncertainty for each vulnerability score for each archetype–stressor assessment to communicate the level of our 'confidence' in the validity of the result[49,50]. Our confidence scores were identified as appropriate by experts and qualitatively defined as: (1) sufficient: a sufficient amount of evidence existed for this assessment to be made, such as a relevant review. Impacts were communicated in the primary policy narratives and the papers were largely up to date (<10 yr); (2) partial: a robust level of evidence existed, but with gaps in knowledge or some difficulty in aligning evidence directly with the archetype categorization. The papers were relatively up to date (<20 yr); (3) poor: largely theoretical evidence or poor empirical research that may only loosely align with the archetype categorization and few recent papers. (4) None: no evidence was found.

Alternatively, if finer-scale data become available, additional insights for adaptive strategies can be gained using a more in-depth analysis of vulnerability of archetypes to environmental stresses. As illustrated in our case study (Supplementary Fig. 9), we demonstrated how to assess the expected consequence of anthropogenic pressures on the production quantity of each blue food archetype in two related ways (exposure and vulnerability). Both were measured as a combination of the vulnerability of each archetype to a stressor, the production amount of that archetype and the stressor intensity to which it is exposed.

Estimated impact

The estimated impact or pressure of environmental change on blue food production was considered as a function of exposure and vulnerability[24]. We calculated the estimated impact ($PI_{i,j}$) as the vulnerability-weighted sum of stressors for each stressor–system combination, where the rescaled stressor intensity values were multiplied by the system's categorical vulnerability score ($V_{s,j}$, 3.0 for high, 2.0 for medium, 1.0 for low, 0 for none; see Supplementary Table 2) to the stressor.

$$PI_{i,j} = \sum_{1}^{s} E_{i,j,s} \times V_{s,j}, \qquad (2)$$

where $V_{s,j}$ is the categorical vulnerability score of system j to stressor s, and $E_{i,j,s}$ is the exposure of system j in country i to stressor s.

To facilitate mapping, the estimated impact scores were first rescaled using min-max normalization, such that each country had a value from 0 to 1 for each system, and then categorized into quintiles and mapped at the national level in R.

Uncertainty analysis

As our results were highly dependent on data availability and the quality of reported data, we further included an uncertainty analysis to show how the expected outcomes of environmental change vary when jittering the stress indicators. National exposure to each stress indicator is the sum of uncertain terms[51,52]. On the basis of the indicator information listed in Supplementary Table 2, we first calculated the mean

(close to the expected value) and standard deviation (reflecting the dispersion of the mean) of each indicator across all countries. Then we randomly simulated each indicator 1,000 times and recalculated the estimated total impact scores using the 'rnorm' function in R to obtain the mean and standard deviation of the recalculated impact scores for each country.

Cluster analysis

To identify global patterns and find meaningful groupings of countries that shared similar impact or pressure profiles, a cluster analysis was performed on the basis of the outputs of the impact assessment. We used the conventional k-means algorithm[53] due to its simplicity and inexpensiveness. The algorithm was employed to partition countries into k distinct clusters such that each country belonged to the cluster with the 'closest' mean, where closeness was measured by the Euclidean distance. Eight variables, including the estimated impact scores for both quantity and safety for all production systems, were used to calculate the Euclidean distances between clusters. We computed k-means clustering with the 'kmeans' function in R by varying k from 2 to 15 clusters. For each k, we calculated the total within-cluster sum of squares (WSS) and plotted the curve of the WSS (Supplementary Fig. 10) to choose the best classification and determine the appropriate groupings. All results were obtained with the algorithm using the naïve method and default parameter settings. After determining the appropriate number of clusters, we used the 'pheatmap' package in R to create a heat map for visualization. Radar plots were used to show the differences in the estimated impact on country clusters. This analysis allows decision-makers to tailor mitigation efforts for each cluster to achieve greater effectiveness. Means and standard deviations of standardized impact scores for each country cluster are listed in Supplementary Table 4.

National response capacity

We assessed the capacity (encompassing the three dimensions of human and economic development and governance) of each blue food nation to respond and implement effective adaptation strategies to cope with environmental stresses. Following ref. 54, we used the Human Development Index (HDI) to represent human development, the Gross Domestic Product (GDP) per capita to describe economic status and the World Governance Index (WGI) to indicate governance effectiveness. These indicators are generalized socio-economic metrics and are publicly available and continuously updated (see Supplementary Table 5 and Fig. 11 for more details). All of the metrics were subjected to min-max normalization that rescaled the data to values between 0 and 1, and the average of these rescaled metrics was then used to denote the response capacity score of each nation[54].

Bonferroni outlier test

The relationship between estimated impacts and national response capacity at the country level was explored on the basis of a generalized linear model. We also aimed to test all observations simultaneously to identify country outliers, so we used the Bonferroni outlier test to protect from type I error[55]. We used the 'outlierTest' function in the 'car' package in R to perform the test. Countries with Bonferroni $P < 0.05$ were considered mean-shift outliers that had extreme observations furthest from the mean value of the neighbourhood (Supplementary Table 6).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Source data were all retrieved from publicly accessible databases as presented in Supplementary Tables 1 and 5. Additional data are available in the Supplementary Data file.

Code availability

The analysis code used to produce the results of this study is available at https://github.com/bluefoodvulnerability/bluefoodvulnerability.git.

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Author contributions

L.C., B.S.H. and M. Troell designed and conceptualized the research idea. Scoping review was performed by L.C., B.S.H., M. Troell, R.S., C. Zeng, Z.J., Y.L., C. Zou, C.L., S.L., X.L., W.W.L.C., R.S.C., F.D., S.G., J.A.G., D.G.-S., J.I.K., F.M., R.L.N., H.J.P., E.R.S., U.R.S. and M. Tigchelaar. Data acquisition was done by L.C., M. Troell, R.S., C. Zeng, Z.J., Y.L., C. Zou, C.L., S.L. and X.L. Data compilation, spatial analysis and data interpretation were conducted by L.C., C. Zeng, Z.J. and Y.L. The original paper was drafted by L.C., B.S.H., M. Troell, R.S. and Z.J., and edited and revised by L.C., B.S.H., M. Troell, R.S., C. Zeng, Z.J., Y.L., C. Zou, C.L., S.L., X.L., W.W.L.C., R.S.C., F.D., S.G., J.A.G., D.G.-S., J.I.K., F.M., R.L.N., H.J.P., E.R.S., U.R.S. and M. Tigchelaar.

Competing interests

The authors declare no competing interests.

Additional information

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Software and code

Policy information about availability of computer code

Data collection	No software was used for data collection.
Data analysis	All data analysis steps are described in Methods. Briefly, when compiling data of environmental stressors at the national level, the extract function in terra package (version 1.6-7) in R (version 4.1.1) was used for geospatial data displayed in grids, and the Kernel Density tool in ArcGIS (version 10.2.2) was used for observation records with spatial coordinates. The rnorm function in R (version 4.1.1) was used to obtain the mean and standard deviation of the recalculated impact scores in uncertainty analysis. The kmeans function in R (version 4.1.1) was used to compute k-means clustering. The pheatmap package (version 1.0.12) in R (version 4.1.1) was used for visualization of cluster analysis. The outlierTest function in car package (version 3.1-1) in R (version 4.1.1) was used for Bonferroni outlier test. The essential custom code developed for this study is available in Github at: https://github.com/bluefoodvulnerability/bluefoodvulnerability.git.

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Source data were all retrieved from publicly accessible databases as presented in Table S1 and Table S5. Additional data are available in the Supplementary Data file. Publicly accessible databases include the following:

[1] FAO. FishStatJ. URL https://www.fao.org/fishery/en/topic/166235.
[2] University of East Anglia. CRU datasets. URL https://crudata.uea.ac.uk.
[3] NOAA. NCEI metadata. URL https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0206289.
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[6] NCAR. IBtrACS: Tropical cyclone best track data. URL https://climatedataguide.ucar.edu/climate-data/ibtracs-tropical-cyclone-best-track-data.
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Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Vulnerability analysis of blue foods under the stress of anthropogenic environmental change
Research sample	This study involves existing datasets. See above for the publicly available data sources.
Sampling strategy	N/A
Data collection	Publicly available data were used in the study and web links were provided as above.
Timing and spatial scale	Global scale.
Data exclusions	N/A
Reproducibility	All results are reproducible via the code provided.
Randomization	N/A
Blinding	N/A

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☐	☒ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Human research participants

Policy information about <u>studies involving human research participants</u>

Population characteristics	This study enlists the expertise of its co-authors, all of whom are human participants, to evaluate the environmental pressures on blue food production. The participant pool is diverse and not defined by characteristics such as race, ethnicity, national or social origin, sex, or gender identity.
Recruitment	At the preparation stage, a highly interdisciplinary group of over 20 experts was recruited by the lead authors of this paper as coauthors. All coauthors are familiar with blue foods and each has expertise in at least one area related to fisheries, aquaculture, seafood safety, climate change, environmental health, or risk assessment.
Ethics oversight	This study was granted exemption by the Ethics Committee of Xiamen University. We certify that the study was performed in accordance with the Declaration of Helsinki and later amendments. Informed consent was obtained from all the participants (i.e., all co-authors in this study) prior to the study.

Note that full information on the approval of the study protocol must also be provided in the manuscript.