



Compound climate risks threaten aquatic food system benefits

Michelle Tigchelaar^{1,20} , William W. L. Cheung^{2,20} , Essam Yassin Mohammed^{3,20}, Michael J. Phillips^{3,20} , Hanna J. Payne¹ , Elizabeth R. Selig¹ , Colette C. C. Wabnitz^{1,2} , Muhammed A. Oyinlola² , Thomas L. Frölicher^{4,5}, Jessica A. Gephart⁶ , Christopher D. Golden⁷ , Edward H. Allison³ , Abigail Bennett⁸, Ling Cao⁹, Jessica Fanzo^{10,11} , Benjamin S. Halpern^{12,13} , Vicky W. Y. Lam² , Fiorenza Micheli^{1,14} , Rosamond L. Naylor¹⁵ , U. Rashid Sumaila^{2,16} , Alessandro Tagliabue¹⁷ and Max Troell^{18,19}

Aquatic foods from marine and freshwater systems are critical to the nutrition, health, livelihoods, economies and cultures of billions of people worldwide, but climate-related hazards may compromise their ability to provide these benefits. Here, we estimate national-level aquatic food system climate risk using an integrative food systems approach that connects climate hazards impacting marine and freshwater capture fisheries and aquaculture to their contributions to sustainable food system outcomes. We show that without mitigation, climate hazards pose high risks to nutritional, social, economic and environmental outcomes worldwide—especially for wild-capture fisheries in Africa, South and Southeast Asia, and Small Island Developing States. For countries projected to experience compound climate risks, reducing societal vulnerabilities can lower climate risk by margins similar to meeting Paris Agreement mitigation targets. System-level interventions addressing dimensions such as governance, gender equity and poverty are needed to enhance aquatic and terrestrial food system resilience and provide investments with large co-benefits towards meeting the Sustainable Development Goals.

Climate change threatens all aspects of aquatic food systems, from production to consumption^{1–4}, endangering the cultures, livelihoods, economies, health and nutrition of billions of people around the world^{5–9}. To date, studies of climate change impacts on aquatic foods (that is, fish, invertebrates and algae captured or cultured in freshwater and marine ecosystems for food or feed) have failed to provide a full accounting of this risk, as they have largely focused on individual production systems (for example, marine fisheries¹⁰) and have rarely connected production system impacts to the differential contributions of aquatic foods to food system outcomes¹¹. Simultaneously, aquatic foods may have substantial but diverse roles to play in transformations towards sustainable and equitable food systems and healthy diets to address multiple forms of malnutrition, especially for coastal communities and the world's undernourished^{12–15}. Efforts to build climate-resilient food systems must ensure that key health, equity and sustainability goals¹⁶ are met at national, regional and global scales.

Environmental change caused by rising atmospheric greenhouse gas concentrations creates differential climate hazards for the production capacity of marine and freshwater systems,

aquafeed resources and supply, and post-production processes (Supplementary Table 11). For example, pelagic fisheries may increasingly have to contend with shifts in species distributions^{1,2,10}, coral reef fisheries and bivalve production with ocean acidification^{1,2,17}; inland fisheries with the timing and volume of freshwater availability^{1,18}; and fed aquaculture with terrestrial crop losses for feed^{17,19}. Here, we develop and apply an integrative food system approach^{11,20} (Supplementary Methods) to put all aquatic foods on the same table²¹ and quantify the risk that climate change poses to the potential for aquatic foods to contribute to sustainable development (key terms, including 'risk', are defined in the Supplementary Information).

From literature-identified climate impact pathways (Supplementary Table 11), we selected representative and well-understood variables projected by three Earth system models (ESMs) that participated in the Coupled Model Intercomparison Project Phase 6 (CMIP6) to calculate cumulative national-level climate hazard scores in the near future (2021–2040) as well as the middle (2041–2060) and end (2081–2100) of the twenty-first century under two contrasting emission scenarios. We then integrated these hazard scores with

¹Center for Ocean Solutions, Stanford University, Stanford, CA, USA. ²Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, British Columbia, Canada. ³WorldFish, Bayan Lepas, Malaysia. ⁴Climate and Environmental Physics, University of Bern, Bern, Switzerland. ⁵Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland. ⁶Department of Environmental Science, American University, Washington DC, USA. ⁷Department of Nutrition, Harvard T.H. Chan School of Public Health, Harvard University, Boston, MA, USA. ⁸Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, USA. ⁹School of Oceanography, Shanghai Jiao Tong University, Shanghai, China. ¹⁰Berman Institute of Bioethics, Johns Hopkins University, Baltimore, MD, USA. ¹¹Nitze School of Advanced International Studies, Johns Hopkins University, Washington DC, USA. ¹²National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, CA, USA. ¹³Bren School of Environmental Science and Management, University of California, Santa Barbara, CA, USA. ¹⁴Hopkins Marine Station, Stanford University, Pacific Grove, CA, USA. ¹⁵Department of Earth System Science, Stanford University, Stanford, CA, USA. ¹⁶School of Public Policy and Global Affairs, University of British Columbia, Vancouver, British Columbia, Canada. ¹⁷School of Environmental Sciences, University of Liverpool, Liverpool, UK. ¹⁸Beijer Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Stockholm, Sweden. ¹⁹Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden. ²⁰These authors contributed equally: Michelle Tigchelaar, William W. L. Cheung, Essam Yassin Mohammed, Michael J. Phillips. ✉e-mail: mtigch@stanford.edu

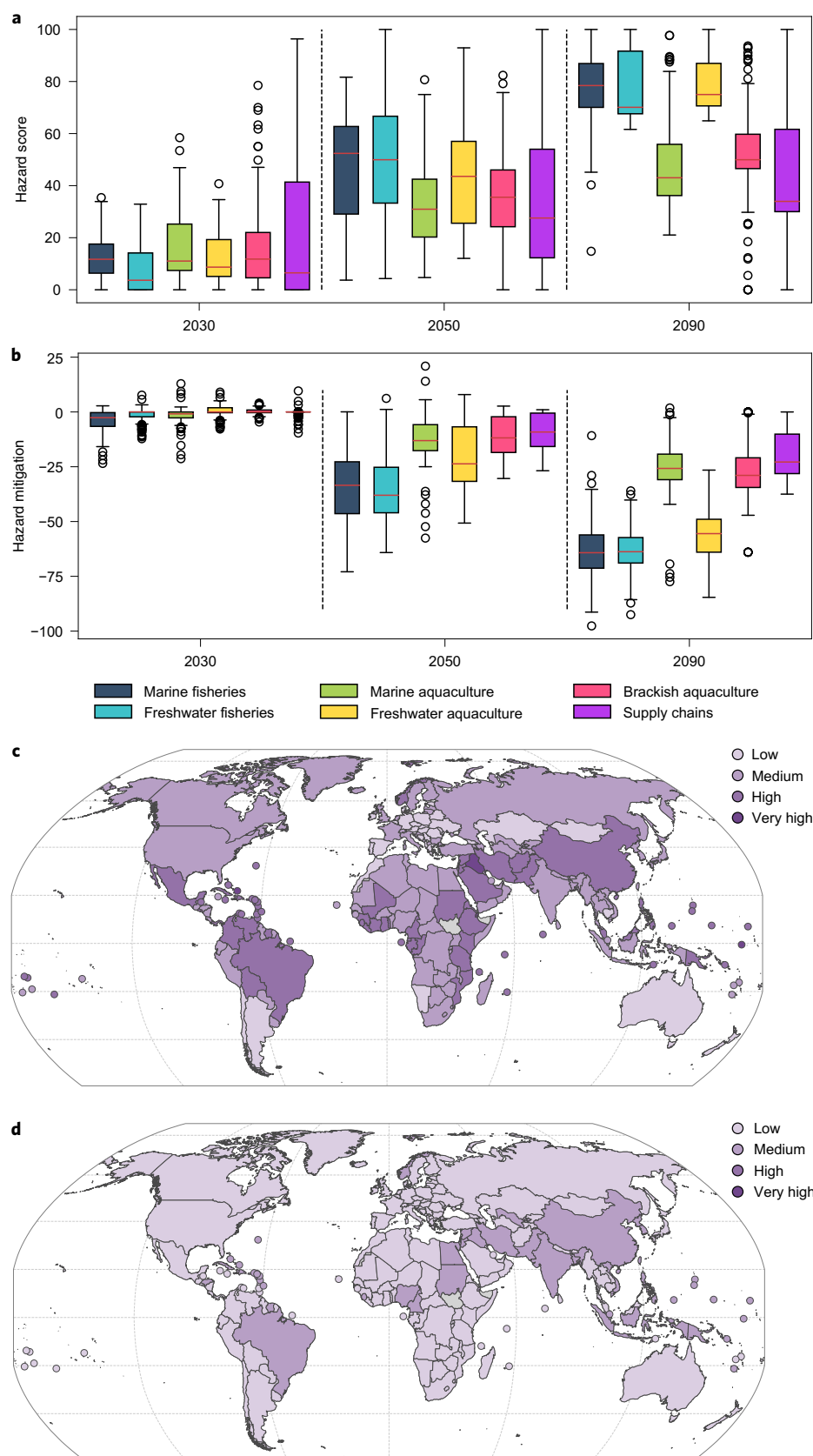


Fig. 1 | Projected climate hazard scores. **a**, Hazard scores for each food system component for a high-emissions scenario in 2021–2040 ('2030'), 2041–2060 ('2050') and 2081–2100 ('2090'). The box limits denote the 25th and 75th percentiles, the whiskers extend to 1.5x the interquartile range from the box edges, the red line indicates the median value and the circles represent outliers. **b**, Impact of emissions reduction on hazard scores for each of the components. **c,d**, Aggregate hazard across all components in 2050, weighted by present-day contributions, for a high-emissions scenario (**c**) and a low-emissions scenario (**d**); grey means no data. Scores <25 are classified as 'low', 25–50 as 'medium', 50–75 as 'high' and >75 as 'very high'.

measures of exposure and vulnerability to assess the overall climate risk of aquatic foods' contributions to nutrition and health, economic, social and environmental food system outcomes for 219 countries and territories (Supplementary Methods and Supplementary Fig. 2), and we evaluated where health and sustainability are most at risk at a national level and which types of aquatic food production contribute most to that risk. On the basis of this evaluation, we identify four distinct risk profiles and corresponding policy and management actions to enhance the climate resilience of aquatic food systems.

Results

Climate impacts on aquatic food systems. Under a high-emissions, no-mitigation scenario, capture fisheries in both marine and freshwater systems are projected to face the most severe hazards (Fig. 1). By the mid-twenty-first century, marine fishery hazards are classified as 'high' (Supplementary Table 3) in most of tropical Africa, Central America and Southeast Asia (Supplementary Methods and Extended Data Fig. 1). With a larger magnitude of warming on large continental land masses than in the ocean, freshwater fisheries in some countries are projected to face 'very high' hazards (Supplementary Table 3) by the mid-twenty-first century, especially in water-stressed areas such as northern Africa and the Middle East (Extended Data Fig. 1). 'High' or 'very high' hazard scores indicate that almost all climate variables impacting these aquatic food systems are outside the range of historical variability (Supplementary Table 3).

By 2100, the estimated hazards for freshwater aquaculture under a high-emissions scenario reach the same level as those for capture-fishery systems, so that all countries face 'high' or 'very high' hazard scores for marine and freshwater fisheries and freshwater aquaculture (Fig. 1a and Extended Data Fig. 1). In contrast, marine and brackish aquaculture face lower cumulative hazards (that is, most climate variables remain within historical ranges; Supplementary Table 4) throughout the twenty-first century (Fig. 1a). Many tropical countries—where climate hazards are the strongest—do not currently practise mariculture for food, and thus skew the average hazards that marine and brackish aquaculture face downwards (Supplementary Information). As managed farming operations, (fed) marine aquaculture and brackish aquaculture are generally less directly exposed to climate-induced changes in ecosystem productivity than capture fisheries²², but they are still projected to be at risk in areas with strong impacts from sea level rise and cyclones (Extended Data Fig. 1). These types of extreme events are also important drivers of high hazards for post-harvest activities, especially in places with a large percentage of small-scale actors involved in the sector (Fig. 1a and Extended Data Fig. 1). Not included in our model but important for aquaculture are potential climate-change-induced effects on aquatic diseases and food safety risks, such as changes in harmful algal bloom occurrence²³.

Strong climate mitigation efforts that are aligned with the target specified in the Paris Agreement of keeping global warming well below 2°C can limit the hazards faced by most systems to 'medium' or 'low' (Fig. 1b). In most cases, mitigation benefits will start to materialize by the mid-twenty-first century, though certain climate variables such as sea level rise have a slow response time and will continue to impact aquatic food systems throughout the twenty-first century and beyond, even with strong near-term climate actions.

When weighted by present-day production contributions, aggregate hazards are higher in the tropics and lower across latitudes >50° (north and south) (Fig. 1c). This finding is in line with previous studies on both marine and terrestrial environments that show that the future climate will exceed the range of historical variability soonest in mid-to-low latitudes^{2,24}. Many low-latitude communities in the least-developed or developing economies are strongly dependent—for nutrition or livelihoods or through sale to local and global markets^{6,25}—on the inland and marine fisheries that face the highest hazards (Extended Data Figs. 2 and 3). These least-developed or developing economies also have relatively larger social, economic and knowledge constraints (Extended Data Fig. 4) that limit them from expanding into new modes of production in the near future. For example, the development of lower-hazard offshore mariculture²⁶ or land-based recirculating aquaculture systems²⁷ may not be a viable climate-risk-reduction pathway for these capture-fishery-dependent countries because of the comparatively high cost and benefit concentration of these alternatives^{15,28}. Therefore, in addition to systemic shifts in modes of production, a priority for reducing climate hazards in these economies is to reduce local hazard and exposure levels in existing production systems. Examples of such hazard reduction strategies for capture fisheries include improved water resources management, mangrove and wetland restoration²⁹, facilitating shifts in fishing grounds³⁰ and improved post-harvest technologies. At the same time, rapid carbon mitigation efforts by high-emitting countries can keep hazard levels to 'low' or 'medium' across production systems (Fig. 1d) and can therefore substantially reduce the risk of impacting sustainable development efforts and losing aquatic food contributions.

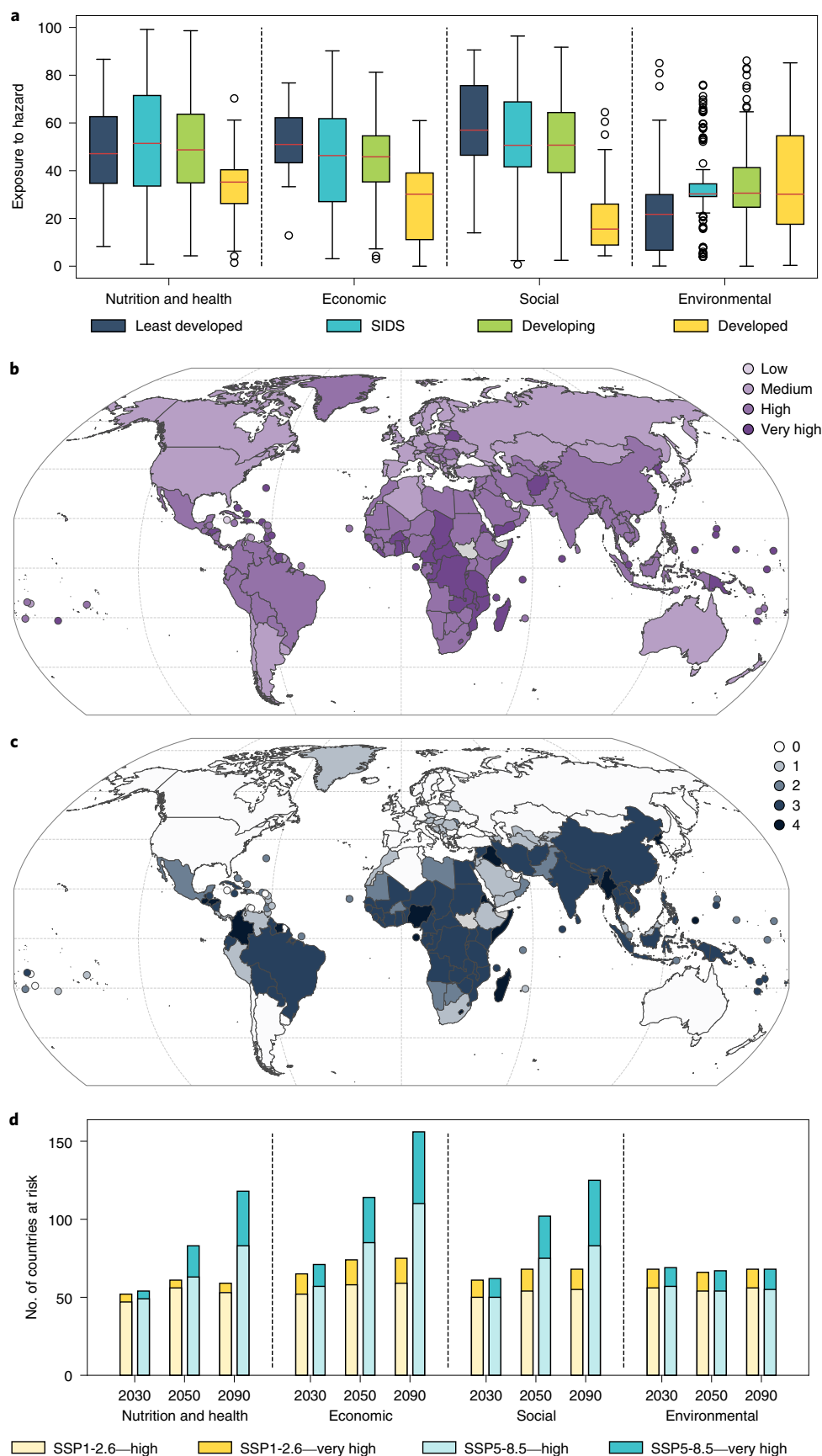
Compound risks to aquatic food systems. Aquatic food systems contribute comparatively more to food system outcomes in developing countries, including Small Island Developing States (SIDS), with generally higher consumption of marine and freshwater foods^{8,9}; higher dependence on production, trade and value chain revenue^{7,31}; and higher numbers of aquatic food-dependent livelihoods^{5–7} (Extended Data Fig. 3). Combined with the concentration of climate hazards in the tropics and subtropics (Fig. 1), this greater dependence leads to a double jeopardy in exposure to climate hazards for nutrition and health, economic and social outcomes (Fig. 2a). Though the pattern of higher exposure to hazards in low latitudes holds true generally, national contexts play an important role in shaping differences between countries and between outcomes⁶. Iceland and Japan, for instance, stand out as high-latitude countries with high nutritional dependence on fish, while Brazil, as a large tropical terrestrial food producer, derives relatively low (national) nutritional and economic contributions from aquatic foods (Extended Data Fig. 3).

When each country's climate vulnerability—including economic output and inclusion, strength of social services, and metrics of food security and environmental integrity—is taken into account (Supplementary Methods and Extended Data Fig. 4), much of Africa, South and Southeast Asia, and the Indo-Pacific face 'high' to 'very high' climate risk for one or more food system outcomes by the middle of this century under a high-emissions scenario (Fig. 2b). In terms of nutrition, this may equate to reductions in aquatic food access, limiting iron, zinc, vitamin B₁₂ and omega-3 fatty acids in

Fig. 2 | Mid-century climate risk of food system outcomes under a high-emissions scenario. **a**, Exposure to hazard for each food system outcome, for least-developed, developing and developed countries and SIDS⁷⁸. The box limits denote the 25th and 75th percentiles, the whiskers extend to 1.5× the interquartile range from the box edges, the red line indicates the median value and the circles represent outliers. **b**, Maximum risk score across all outcomes. **c**, Number of outcomes for which the risk score is 'high' or 'very high'. **d**, Number of countries for which the risk score is 'high' (light shade) or 'very high' (dark shade) for a low-emissions scenario (yellow) and a high-emissions scenario (blue) in 2030, 2050 and 2090. Grey means no data. Scores <25 are classified as 'low', 25–50 as 'medium', 50–75 as 'high' and >75 as 'very high'.

populations that are already at thresholds for deficiency⁹, especially if climate change drives up food prices³² for households least likely to afford fish. In contrast, most countries in North America and

Europe, as well as Chile, Argentina, Australia and New Zealand, face 'low' to 'medium' climate risk across all food system outcomes for this period (Fig. 2c).



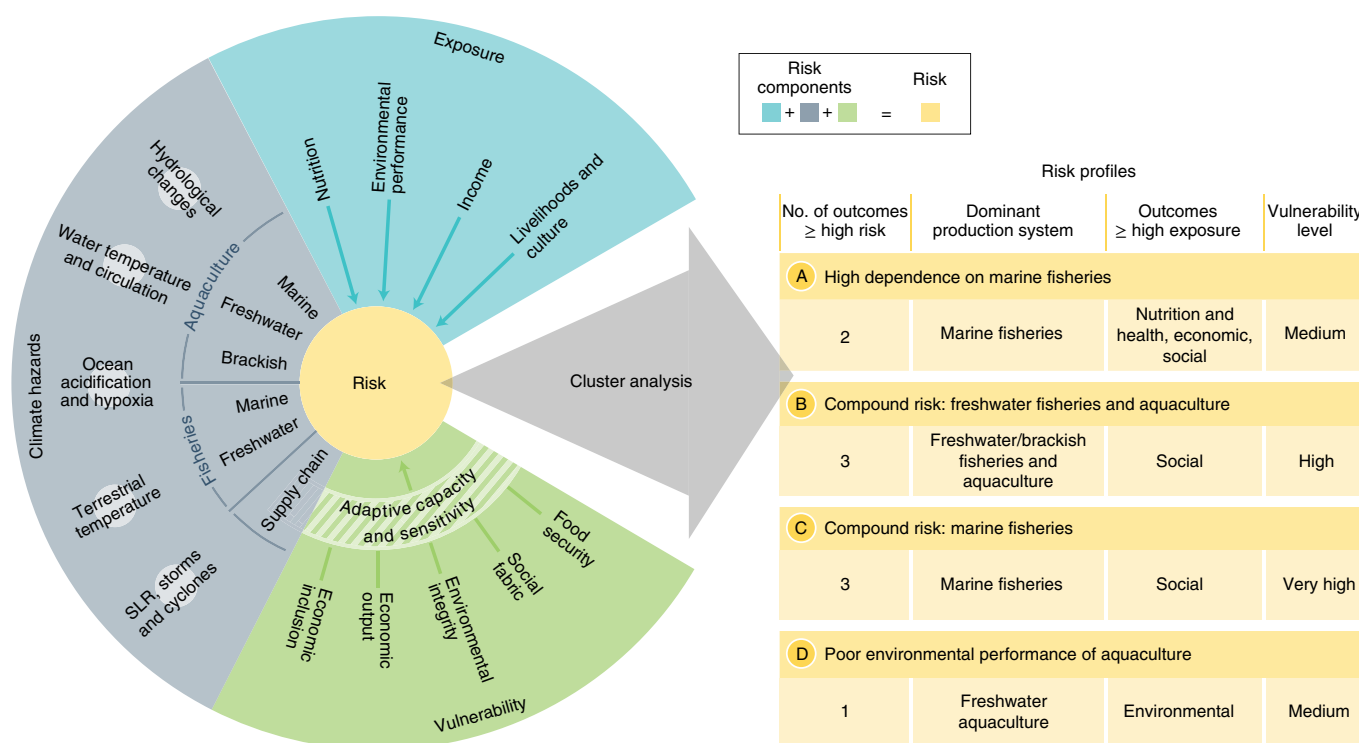


Fig. 3 | Climate risk profiles based on differences in hazards, exposure and vulnerability across food system outcomes. On the basis of a cluster analysis (Supplementary Information), we identify four climate risk profiles for aquatic food system outcomes. The profiles are based on the characteristics of countries that have ‘high’ or ‘very high’ climate risk for at least one food system outcome by mid-century under a high-emissions scenario. The profile descriptions are based on median indicator values for each profile (Extended Data Fig. 7). Individual countries within each cluster can deviate slightly from this characterization. SLR, sea level rise.

A rapid reduction in carbon emissions can avoid substantial increases in climate risk for many countries by the end of this century (Extended Data Figs. 5 and 6). Under a high-emissions scenario, the number of countries facing ‘high’ risk for nutrition and health, economic and social outcomes increases from about 50 to over 80 between the near future and the late twenty-first century, and those facing ‘very high’ risk increase from about 10 to about 40. Such an increase is largely prevented under a low-emissions scenario (Fig. 2d). Still, due to high vulnerability and aquatic-food dependence, at least 50 countries will experience ‘high’ or ‘very high’ risk throughout the twenty-first century in all carbon emission scenarios. Our findings thus show that multiple types of risk need attention through policy and investments (see next section) to ensure that beneficial aquatic food system outcomes are secured for the most vulnerable countries.

A cluster analysis of our modelling results (Supplementary Information) delineates four distinct climate risk profiles for countries that experience high risk in at least one food system outcome under high emissions by the mid-twenty-first century (Figs. 2b and 3, Table 1, and Extended Data Figs. 7 and 8). For many coastal countries and SIDS with high dependency on the marine fishery sector and medium vulnerability, climate risks are concentrated in the nutrition and health and/or economic food system outcomes. Similarly, some countries, primarily in Eastern Europe, generally face low hazards and display medium vulnerability but stand out for their poor environmental performance³³, leading to concentrated climate risks in the environmental dimension of food system outcomes. Countries with high climate vulnerability are projected to face compound climate risks^{34,35} across three or four of the food system outcomes, either in marine fisheries (primarily coastal Africa) or in freshwater and deltaic fisheries and aquaculture (South and Southeast Asia and Central Africa). These different

risk profiles across countries and regions call for region-specific and context-specific risk reduction interventions.

Towards climate-resilient aquatic foods. The high levels of climate risk for multiple outcomes across much of the developing world (Fig. 2) call for urgent action to support the long-term sustainability¹⁴, resilience³⁶ and equity^{13,15} of aquatic food systems. Enhanced resilience could, in principle, be achieved by the implementation of adaptive and/or transformative measures at any point along the risk chain, including reducing the actual climate hazards (for example, greenhouse gas emissions reductions), reducing the sensitivity of the production systems to these hazards (for example, farming climate-tolerant species with reduced feed dependence^{27,37}, and building barriers and restoring coastal ecosystems to protect against storms²⁷), reducing dependence on climate-sensitive aquatic foods and sectors (for example, diet and livelihood diversification³⁸), and reducing vulnerability through investments that benefit human development irrespective of climate change (for example, human capabilities investments, including gender considerations³⁹).

Climate mitigation activities will substantially reduce climate hazards (Fig. 1) but are insufficient to avoid negative aquatic food system outcomes, as a certain degree of climate change is unavoidable (Fig. 3). A sensitivity analysis on the vulnerability variables in our model (Supplementary Information) shows that reducing vulnerability results in similar levels of climate change risk reduction to meeting mitigation targets in the Paris Agreement, especially for countries that face compound climate risks (such as Malawi and El Salvador; Supplementary Table 12). These findings highlight the need to focus on the broader social–ecological context of each country, with actions building resilience that extend beyond aquatic food production⁴⁰. Priority strategies for building resilience, as well as policy and management considerations and potential trade-offs,

Table 1 | Climate resilience priorities, policy and management considerations, and trade-offs for four climate risk profiles

Resilience priorities	Policy and management considerations	Potential trade-offs for health, sustainability and equity
(A) High nutritional, economic and social dependency on marine fisheries (for example, Ghana, Palau, Peru, Timor-Leste and Viet Nam)		
Secure sustainable marine fishing practices and policies, ensure that benefits flow to vulnerable groups, and develop alternatives that increase adaptive capacity.	P: Shift to offshore resources; climate-smart and climate-just agreements for transboundary resources; policies to enable the utilization of nutrient-rich species in coastal communities. F&I: Conservation financing for small-scale fisheries; revised fishery subsidies to incentivize sustainability. T&I: Local adaptation measures for fisheries (for example, development of national pelagic fisheries); climate-informed and equitable vessel scheme days. B&S: Equitable and climate-responsive access agreements; export policies that ensure sufficient domestic supply.	• Nutritional content, economic value and stock sustainability of alternative species. • Local nutrition needs versus revenue generation from exports; revenue versus livelihoods. • Gender dimension of livelihood opportunities.
(B) Compound climate risk—freshwater/deltaic fisheries and aquaculture (for example, Bangladesh, Cambodia, Central African Republic and Malawi)		
Sustain threatened freshwaters while integrating climate-adaptive and sustainable aquatic food systems into socio-economic development efforts.	P: Protection and management of freshwater fisheries and wetland ecosystems; inclusion of small-scale fisheries in fisheries policies. F&I: Investment in the protection and management of natural capital; alternative livelihoods; collective loans and savings programmes. T&I: Freshwater aquaculture; integration of fish into water management structures, planning and management; sustainable intensification. B&S: Fair trade agreements for the benefits of local people (including intergenerational discounting); climate information services and early warning systems.	• Immediate needs and disaster risk reduction versus long-term adaptation and sustainability interventions. • Competition over freshwater resources. • Export versus local needs. • Fish as food versus feed. • Equity and gender dimensions of adaptive programming activities.
(C) Compound climate risk—marine fisheries (for example, Côte d'Ivoire, El Salvador and Madagascar)		
Sustain functions of critical marine systems while integrating climate-adaptive and sustainable aquatic food systems into socio-economic development efforts.	P: Co-management of resources that supports agency and empowers and engages marginalized groups. F&I: Financial incentives for fishers (credit support, minimum supportive price and so on); financial management through collectives and cooperatives; gender transformative adaptation opportunities. T&I: Infrastructure development, including technology such as cold storage. B&S: Equitable fisheries access agreements; climate information services and early warning systems.	• Immediate needs and disaster risk reduction versus long-term adaptation and sustainability interventions. • Export versus local needs. • Equity and gender dimensions of adaptive programming activities.
(D) Environmental performance risk of freshwater aquaculture (for example, Belarus, Bosnia and Herzegovina, and Israel)		
Improve environmental performance of aquatic food production systems.	P: Environmental regulations; aquaculture zoning; limitations on carrying capacity. F&I: Financing options for supply chain actors transitioning to low-impact practices. T&I: Solar energy; water-efficient systems; reductions in waste and losses along value chains; production optimization, including sustainable intensification. B&S: Incentivization schemes for sustainable farming practices (for example, certification).	• More environmentally sustainable production systems need to be climate adaptive and meet dietary and market demands. • Equitable access to knowledge, finance and technology.

We provide examples of high-level policy and management considerations in the following categories: policies (P), finance and investment (F&I), technology and innovation (T&I), and business and services (B&S). Resilience-enhancing activities are not exclusive to any particular risk profile, and knowledge exchange can occur both within and across profiles. The profile letters A–D correspond to the risk profiles in Fig. 3. References supporting particular policy and management considerations are listed in the Supplementary Information.

differ between countries belonging to each of our identified risk profiles (Table 1).

Countries with low to medium vulnerability (the ‘high dependence on marine fisheries’ and ‘poor environmental performance of aquaculture’ profiles; Fig. 3) tend to experience high climate risk for just one or two food system outcomes, meaning that targeted interventions in specific areas can reduce risk (Table 1). For countries with high marine fisheries dependence, including many SIDS, one of the challenges will be to design measures that strike an appropriate balance between supporting economic development aspirations through efficiency and revenue generation, and supporting food security through local and domestic consumption of fish^{41,42} (for example, climate-smart agreements for transboundary resources⁴³ and the development of climate-resilient aquaculture for food security⁴⁴). For countries where freshwater aquaculture contributes to

poor environmental outcomes, solutions may target the adoption of integrated farming solutions or of technological innovations such as resource-efficient production systems that can be isolated from the environment^{27,37}. In both contexts, solutions need support through enabling government policies, functional institutions at the national to community levels and sustainable, responsible financial investment⁴⁴.

Enhancing climate resilience for highly vulnerable countries facing compound climate risk (Table 1 and Extended Data Fig. 8)—from freshwater and deltaic fisheries and aquaculture or from marine fisheries (Fig. 3)—is most challenging and urgent given that these countries are projected to have the greatest number of food system outcomes experiencing high climate risk. For such countries, resilience efforts focused on aquatic food systems provide options (such as nature-based solutions (for example, mangrove, reef and

seagrass restoration to aid coastal storm protection and enhance aquatic ecosystem productivity)²⁹, sustainable intensification⁴⁵, livelihood diversification³⁸ and investments in local value chains⁴⁴), but these efforts need to be part of a more generalized resilience framework that addresses the social dimensions of vulnerability^{39,40,46,47} (for example, through strengthening governance, promoting gender equity and reducing poverty; Supplementary Table 12). It is worth noting that ‘no-regret’ investments³⁹ based on net social welfare gain have proven a challenge in practice—particularly where investments fail to deliver a ‘net political gain’, as determined by a set of complex value preferences. Climate solutions that require public sector investments must be able to deliver both social and political gains to increase their acceptability to the public choice-maker. Ultimately, a generalized resilience approach means enhancing the capacity of coastal and riparian people to become the agents of societally desired systems transformation^{40,47} and to recognize aquatic food systems as integral to socio-economic development efforts and nutrition policies⁴² and overall food system resilience^{48,49}.

Discussion

The availability of appropriate data and modelling tools for better understanding risks and resilience priorities at a global scale poses a challenge, especially for countries and systems considered most at risk. For example, in calculating hazard scores for freshwater systems and supply chains, we were unable to assess changes in climate variables at a subnational scale or to consider the varying sensitivities of different ecosystems or production types and post-production processes^{1,17,49}. For many SIDS, key indicators were missing from global databases (Supplementary Information), precluding holistic climate risk assessment⁵⁰. The risk of countries such as Bangladesh, Cambodia and the countries of the African Great Lakes region (which are among the largest freshwater-fish-producing nations in the world) may in reality be even higher given that inland fish production is substantially underestimated in many countries^{25,51}. Failing to address these gaps in data and understanding can perpetuate inequities, as resilience investments are likely to go to places and systems already assessed in the research and policy literature¹³.

Our analysis assumed that exposure and vulnerability remain unchanged in time, though different development trajectories could change climate risk in magnitudes commensurate with changes driven by different emission trajectories (as shown by our sensitivity analysis; Supplementary Table 12). Future work could build on the framework developed here to explore the impacts of various socio-economic pathways⁵² and their interactions with climate hazards. Similarly, climate change will also impact food systems outside the aquatic realm, with unknown implications for feedbacks, trade-offs, relative risk and adaptive options. While this research expands our understanding of the combined and comparative climate risk of all aquatic food systems, we ultimately need a holistic climate risk framework that makes our entire plate (staples, nuts and legumes, fruits and vegetables, livestock, and aquatic foods) resilient²¹.

Through an integrative climate and aquatic food systems modelling approach, we reveal four main climate risk profiles and identify key challenges and opportunities for building pathways towards climate-resilient aquatic food systems. Of the different environments in which aquatic foods are caught and produced, fisheries and freshwater aquaculture are projected to experience the highest cumulative hazards throughout the twenty-first century. Combined with a comparatively higher dependence on aquatic foods for nutrition, income and livelihoods—and greater vulnerability to the loss of these benefits—SIDS and countries in Africa, South Asia and Southeast Asia are projected to be at particularly high risk from climate change.

Differences in climate risk profiles call for resilience-enhancing actions that are region-specific and context-specific and are guided

by principles of equity and fairness^{13,15}. Most urgent are actions and investments for countries that face compound climate risk across aquatic food system outcomes, requiring transformative change to reduce societal vulnerability. Though we focused on countries with high climate risk, countries with low to medium risk will also face increasing climate hazards domestically and are connected to transboundary climate risk through species movement and trade of aquatic foods and inputs^{43,53}. This calls for justice-informed collaboration towards climate-proofing of aquatic food systems that transcends national and regional boundaries.

Methods

Assessment of climate impact pathways. We reviewed literature covering a wide range of geographic areas—from global reviews to regional and national case studies—to identify climate pathways that impact aquatic food systems in three different capacities: (1) aquatic food production systems, (2) aquatic food supply chains and (3) aquatic food system outcomes. In our review, we first focused on large assessment reports such as those produced by the Intergovernmental Panel on Climate Change², followed by comprehensive scientific reviews and meta-analyses (for example, refs. ^{1,4,17,54,55}) and the papers cited therein. We filled in remaining gaps using strategic keyword searches and the expert knowledge of our multidisciplinary team of co-authors. An overview and ranking of climate pathways for aquatic food production systems and supply chains, including key references, can be found in Supplementary Table 11, with a brief narrative summary in the Supplementary Methods.

Aquatic food production systems were split into capture fisheries and aquaculture and were further grouped by marine and freshwater production environments. The aquatic food supply chain was divided into seven components (input supply, production, post-harvest storage, processing, distribution, marketing and retail, and consumption and utilization¹¹), though most literature addressed only the production stage. For the different production systems, we ranked the impact of each climate change pathway by direction (positive impact, negative impact or varied impact) and degree of confidence (limited, medium or robust research). For the supply chain components, we just noted the presence or absence of an impact.

Hazard, exposure and vulnerability variables. We compute quantitative indices of climate risk for the four aquatic food system outcomes—nutrition and health, economic, social, and environmental—adopting a fuzzy logic modelling approach to implement the risk assessment framework used by the Intergovernmental Panel on Climate Change². In this framework, climate risk results from the interaction between climate-change-induced hazards, exposure to those climate hazards and vulnerabilities of components of the aquatic food systems. For our purposes, we conceptualize climate hazards as the dominant climate variables that impact aquatic food production and supply chains, exposure as the degree to which aquatic foods contribute to the various food system outcomes at a national level, and vulnerability as a combination of sensitivity to and adaptive capacity of the nationally aggregated food systems in the face of the loss of aquatic food contributions. Through two rounds of virtual workshops, our team of co-authors (selected for their expertise spanning marine and freshwater ecosystems, fisheries and aquaculture production systems, and multiple food system outcomes) selected hazard, exposure and vulnerability indicators on the basis of their expert knowledge, published literature and data availability for most of the 219 countries included in this study.

Climate hazards. From our literature assessment (Supplementary Table 11), we identified the most impactful and well-understood climatic drivers of changes in aquatic food production for which data and/or modelling tools are available at a global level. These drivers include changes in ocean temperature, circulation, net primary productivity and dissolved oxygen concentrations, which together are used to calculate projected changes in marine fisheries catch and aquaculture yield using a dynamic biological envelope model⁵⁶. Additionally, changes in ocean pH, the extent of sea ice and the cumulative mean intensity of marine heatwaves⁵⁷ are used as marine hazard variables. Inundation from projected sea level rise and the strength of tropical storms threaten marine and brackish aquaculture as well as supply chain processes. For freshwater systems, near-surface (2 m) air temperature changes over land and changes in precipitation are used. Finally, projected changes in fish meal availability and global crop land temperature capture the hazards (through cost of production) to feed-dependent aquaculture production. Some climate impact pathways, such as harmful algal blooms and their impacts on food safety, are known to be important but were excluded because (to our knowledge) no appropriate and published global model or dataset of national-level indicator variables is yet available. An overview of all hazard variables used in the model is presented in Supplementary Table 6.

To represent uncertainties in projections of environmental changes by different ESMs, where possible, we used projections from three ESMs available from CMIP6 (ref. ⁵⁸): Geophysical Fluid Dynamics Laboratory (GFDL)-ESM4 (ref. ⁵⁹),

the Institut Pierre-Simon Laplace (IPSL)-CM6A-LR⁶⁰ and Max Planck Institute (MPI)-ESM1-2-HR⁶¹. Outputs from GFDL-ESM4 and IPSL-CM6A-LR are also used by the Fisheries and Marine Ecosystem Impact Models Intercomparison Projects, while MPI-ESM1-2-HR is used additionally by the Dynamic Bioclimate Envelope Model to project future changes in maximum catch potential. We calculated climate hazards using two contrasting scenarios: Shared Socio-economic Pathway (SSP) 1—Representative Concentration Pathway (RCP) 2.6 (SSP1-2.6) and SSP5-8.5. SSP1-2.6 and SSP5-8.5 represent a 'strong mitigation' low-emissions pathway and a 'no mitigation' high-emissions pathway, respectively⁶². For the marine heatwave variable, CMIP6 results were not yet available, so CMIP5 equivalents were used⁵⁷.

Results are presented for the near future (2021–2040) and the middle (2041–2060) and end (2081–2100) of the twenty-first century. As we compute climate risk indices for 219 countries and territories, we focus on hazards that are most common across these geographies and for which global datasets are available. Some of the climate hazards (such as the impacts of harmful algal blooms and the spread of disease) are indirectly represented by environmental variables that drive these hazards (such as ocean temperature and dissolved oxygen level). While our modelling approach accounts for interactions between climate hazards in some components of the aquatic food systems (for example, marine capture fisheries and aquaculture production), the interacting effects of hazards on some other components are not well understood, so these are not explicitly represented in the risk assessment model.

Exposure. The exposure of countries or territories to climatic hazards through their aquatic food systems is positively associated with their level of dependency on aquatic foods to support nature and people. We selected indicators (Supplementary Table 7) for four food system outcomes: nutrition and health, economic, social and environment. For nutrition and health outcomes, the indicators are per capita supply of marine and freshwater aquatic foods and the percentage of a nation's consumption of vitamin B₁₂ and DHA + EPA fatty acids (types of omega-3 fatty acids specific to aquatic foods) that is derived from aquatic foods⁹. For economic outcomes, we use data on the contributions of aquatic food to gross domestic product (GDP)^{25,31,63,64}, estimates of economic multipliers of marine supply chains⁶⁵ and net aquatic food trade balance relative to GDP⁶⁶. As social outcome variables, we selected the contributions of marine fisheries, aquaculture and inland fisheries to employment^{5,25,67}, as well as the ratio of indigenous to national-average consumption of seafood as a metric of the cultural importance of aquatic foods⁶⁸. Finally, the environmental outcome variables are drawn from standardized estimates of the average greenhouse gas emissions, nitrogen and phosphorus emissions, and land use and freshwater use of different types of wild-capture and farmed aquatic food production³³.

Vulnerability. To capture the vulnerability of aquatic food system outcomes to climate hazards, we selected several variables (Supplementary Table 8) that represent the adaptive capacity of aquatic food systems and the sensitivity of aquatic food system outcomes in the face of climate change. As more generalized metrics of adaptive capacity and sensitivity, we include GDP per capita⁶⁹, an aggregate of the Worldwide Governance Indicators⁶⁹, educational attainment⁷⁰, percentage of the population below the national poverty line⁶³, the Gini coefficient⁶³, access to financial services⁷¹, research and development expenditure as a percentage of GDP⁶³, and the percentage of aquatic food landings from small-scale operations⁷². As outcome-specific metrics, we include the stunting rate of children under five⁷³ and summary exposure values for vitamin B₁₂ and DHA + EPA fatty acids⁹ for nutrition and health outcomes, and the Biodiversity and Habitat, Fisheries, and Climate Change indicators of the Environmental Performance Index⁷⁴ for environmental outcomes.

A more detailed accounting of each of the model variables, including justification and data processing steps as well as a statistical summary, can be found in the Supplementary Methods. For each of the risk components, scores were calculated using whichever of the indicator variables were available.

Fuzzy logic system. We apply a fuzzy logic modelling approach to compute climate risks and account for the inherent data and knowledge uncertainties present in determining climate risks of national food system outcomes. Such an approach has been previously applied to study the conservation risk of marine fish stocks from fishing⁷⁰ and climate change^{75,76}. In brief, the fuzzy logic algorithm is divided into three steps³⁰:

1. Fuzzification: Indicator values are categorized into one or more levels of 'low', 'medium', 'high' and 'very high' (hazard, exposure and vulnerability) simultaneously, with the degree of membership in each level defined by fuzzy membership functions (Supplementary Fig. 1 and Supplementary Table 9).
2. Fuzzy reasoning: For each subcomponent of climate risk (hazard, exposure and vulnerability), the degree of membership associated with each level is cumulated using an algorithm called MYCIN³⁰:

$$\text{AccMem}_{i+1} = \text{AccMem}_i + \text{Membership}_{i+1} \times (1 - \text{AccMem}_i)$$

where AccMem is the accumulated membership of a particular level (for example, high vulnerability) and i denotes the indicator variable contributing to the

subcomponent. Then, hazard, exposure and vulnerability are aggregated into a combined risk level using predefined heuristic rules (Supplementary Table 2). Where data availability allows, information is kept segregated on the basis of the relevant subsystem (such as fisheries versus aquaculture or marine versus freshwater).

3. Defuzzification: The climate risk of aquatic food system outcomes is ultimately expressed on a scale of 0 to 100, with 100 being the most at risk. The index values (Indval) corresponding to each level x are: 'low' = 1, 'moderate' = 25, 'high' = 75 and 'very high' = 100. The final risk index (FnInd) is calculated from the average of the index values, weighted by their accumulated membership³⁰:

$$\text{FnInd} = \frac{\sum_{x=1}^4 \text{AccMem}_x \times \text{Indval}_x}{\sum_{x=1}^4 \text{AccMem}_x}$$

A more detailed description of the various fuzzy logic modelling steps and assumptions and a schematic overview of the various model components are provided in the Supplementary Information.

Cluster analysis. To identify patterns in the types of climate risk that high-risk countries face, we perform a K -means clustering analysis on the outcomes of the fuzzy logic model, using the following input variables: the number of outcomes for which climate risk in 2050 is 'high' or 'very high' under SSP5-8.5, the climate hazard score in 2050 under SSP5-8.5, the percentage of production from marine environments⁶⁴, the percentage of production from aquaculture⁶⁴, exposure scores for each of the food system outcomes (nutrition and health, economic, social, and environmental) and vulnerability scores for each of the food system outcomes. Only countries for which at least one of the food system outcomes had 'high' or 'very high' risk in 2050 under SSP5-8.5 were included. We were not able to assign clusters for countries with missing values for any of these variables.

We find that using a total of four clusters leads to climate risk profiles that are distinct (Supplementary Fig. 3) and meaningful for describing policy considerations. The profiles that we identify are high dependency on marine fisheries (Cluster 2, 47 countries), compound climate risk from freshwater and brackish systems (Cluster 1, 38 countries), compound climate risk from marine fisheries (Cluster 3, 28 countries), and environmental performance risk from freshwater aquaculture (Cluster 4, 17 countries). The distribution of input variables for each of these clusters is shown in Extended Data Fig. 7 and summarized in Supplementary Table 13. A map of the cluster assignments is shown in Extended Data Fig. 8, with a complete list in Supplementary Table 14.

Statistics and reproducibility. No data were excluded from the analyses.

Data availability

Most of the model input data were retrieved from publicly accessible reports and databases, as outlined in Supplementary Tables 6–8. The model output data are provided on Dryad⁷⁷: <https://doi.org/10.5061/dryad.70rxwdbz3>. Source data are provided with this paper.

Code availability

All custom code produced for the analyses was generated using Python version 3.7.1 and R version 4.0.2 and is available from the corresponding author upon request.

Received: 23 March 2021; Accepted: 17 August 2021;

Published online: 15 September 2021

References

1. *Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options* Vol. 627 (FAO, 2019).
2. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (eds Pörtner, H.-O. et al.) (IPCC, 2019).
3. Fanzo, J., Davis, C., McLaren, R. & Choufani, J. The effect of climate change across food systems: implications for nutrition outcomes. *Glob. Food Sec.* **18**, 12–19 (2018).
4. Myers, S. S. et al. Climate change and global food systems: potential impacts on food security and undernutrition. *Annu. Rev. Public Health* **38**, 259–277 (2017).
5. Teh, L. C. L. & Sumaila, U. R. Contribution of marine fisheries to worldwide employment: global marine fisheries employment. *Fish Fish.* **14**, 77–88 (2013).
6. Selig, E. R. et al. Mapping global human dependence on marine ecosystems. *Conserv. Lett.* **309**, e12617 (2018).
7. *The State of World Fisheries and Aquaculture 2020: Sustainability in Action* (FAO, 2020); <https://doi.org/10.4060/ca9229en>
8. Bennett, A. et al. *Contribution of Fisheries to Food and Nutrition Security: Current Knowledge, Policy, and Research* (Duke University, 2018).

9. Golden, C. D. et al. Aquatic foods to nourish nations. *Nature* (in the press).
10. Cheung, W. W. L. et al. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Glob. Change Biol.* **16**, 24–35 (2010).
11. *Nutrition and Food Systems* (HLPE, 2017).
12. Hicks, C. C. et al. Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* **574**, 95–98 (2019).
13. Österblom, H. et al. Towards Ocean Equity (High Level Panel for a Sustainable Ocean Economy, 2020); <https://digitalarchive.worldfishcenter.org/bitstream/handle/20.500.12348/4486/71d48a67e55853a80e461c0ba5529caf.pdf>
14. *Sustainable Fisheries and Aquaculture for Food Security and Nutrition* (HLPE, 2014); <http://www.fao.org/3/a-i3844e.pdf>
15. Farmery, A. K. et al. Blind spots in visions of a ‘blue economy’ could undermine the ocean’s contribution to eliminating hunger and malnutrition. *One Earth* **4**, 28–38 (2021).
16. *Transforming Our World: The 2030 Agenda for Sustainable Development* (United Nations, 2015).
17. Reid, G. K. et al. Climate change and aquaculture: considering biological response and resources. *Aquac. Environ. Interact.* **11**, 569–602 (2019).
18. Myers, B. J. E. et al. Global synthesis of the documented and projected effects of climate change on inland fishes. *Rev. Fish Biol. Fish.* **27**, 339–361 (2017).
19. Froehlich, H. E., Runge, C. A., Gentry, R. R., Gaines, S. D. & Halpern, B. S. Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proc. Natl Acad. Sci. USA* **115**, 5295–5300 (2018).
20. Cheung, W. W. L., Pitcher, T. J. & Pauly, D. A fuzzy logic expert system to estimate intrinsic extinction vulnerabilities of marine fishes to fishing. *Biol. Conserv.* **124**, 97–111 (2005).
21. Halpern, B. S. et al. Opinion: putting all foods on the same table: achieving sustainable food systems requires full accounting. *Proc. Natl Acad. Sci. USA* **116**, 18152–18156 (2019).
22. Froehlich, H. E., Gentry, R. R. & Halpern, B. S. Global change in marine aquaculture production potential under climate change. *Nat. Ecol. Evol.* **2**, 1745–1750 (2018).
23. Brown, A. R. et al. Assessing risks and mitigating impacts of harmful algal blooms on mariculture and marine fisheries. *Rev. Aquac.* <https://doi.org/10.1111/raq.12403> (2019).
24. Battisti, D. S. & Naylor, R. L. Historical warnings of future food insecurity with unprecedented seasonal heat. *Science* **323**, 240–244 (2009).
25. Funge-Smith, S. *Review of the State of the World Fishery Resources: Inland Fisheries* (FAO, 2018); <http://www.fao.org/3/ca0388en/CA0388EN.pdf>
26. Gentry, R. R. et al. Mapping the global potential for marine aquaculture. *Nat. Ecol. Evol.* **1**, 1317–1324 (2017).
27. Reid, G. K. et al. Climate change and aquaculture: considering adaptation potential. *Aquac. Environ. Interact.* **11**, 603–624 (2019).
28. Belton, B. et al. Farming fish in the sea will not nourish the world. *Nat. Commun.* **11**, 5804 (2020).
29. Gattuso, J.-P. et al. Ocean solutions to address climate change and its effects on marine ecosystems. *Front. Mar. Sci.* **5**, 337 (2018).
30. Ojea, E., Lester, S. E. & Salgueiro-Otero, D. Adaptation of fishing communities to climate-driven shifts in target species. *One Earth* **2**, 544–556 (2020).
31. *Hidden Harvest: The Global Contribution of Capture Fisheries* (World Bank, 2012); <http://documents1.worldbank.org/curated/en/515701468152718292/pdf/664690ESWOP1210120HiddenHarvest0web.pdf>
32. Tigchelaar, M., Battisti, D. S., Naylor, R. L. & Ray, D. K. Future warming increases probability of globally synchronized maize production shocks. *Proc. Natl Acad. Sci. USA* **115**, 6644–6649 (2018).
33. Gephart, J. A. et al. Environmental performance of blue foods. *Nature* (in the press).
34. Phillips, C. A. et al. Compound climate risks in the COVID-19 pandemic. *Nat. Clim. Change* **10**, 586–588 (2020).
35. Cutter, S. L. The changing nature of hazard and disaster risk in the Anthropocene. *Ann. Assoc. Am. Geogr.* **111**, 819–827 (2021).
36. Tendall, D. M. et al. Food system resilience: defining the concept. *Glob. Food Sec.* **6**, 17–23 (2015).
37. Lebel, L. et al. Innovation, practice, and adaptation to climate in the aquaculture sector. *Rev. Fish. Sci. Aquac.* <https://doi.org/10.1080/23308249.2020.1869695> (2021).
38. Jørstad, H. & Webersik, C. Vulnerability to climate change and adaptation strategies of local communities in Malawi: experiences of women fish-processing groups in the Lake Chilwa Basin. *Earth Syst. Dyn.* **7**, 977–989 (2016).
39. Heltberg, R., Siegel, P. B. & Jorgensen, S. L. Addressing human vulnerability to climate change: toward a ‘no-regrets’ approach. *Glob. Environ. Change* **19**, 89–99 (2009).
40. Cinner, J. E. et al. Building adaptive capacity to climate change in tropical coastal communities. *Nat. Clim. Change* **8**, 117–123 (2018).
41. Bell, J. D. et al. Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. *Mar. Policy* **51**, 584–591 (2015).
42. Bennett, A. et al. Recognize fish as food in policy discourse and development funding. *Ambio* <https://doi.org/10.1007/s13280-020-01451-4> (2021).
43. Oremus, K. L. et al. Governance challenges for tropical nations losing fish species due to climate change. *Nat. Sustain.* **3**, 277–280 (2020).
44. Roscher, M. et al. *Building Adaptive Capacity to Climate Change: Approaches Applied in Five Diverse Fisheries Settings* (CGIAR, 2018); <https://digitalarchive.worldfishcenter.org/bitstream/handle/20.500.12348/2094/FISH-2018-18.pdf?sequence=2&isAllowed=y>
45. Belton, B., Reardon, T. & Zilberman, D. Sustainable commoditization of seafood. *Nat. Sustain.* <https://doi.org/10.1038/s41893-020-0540-7> (2020).
46. Thomas, K. et al. Explaining differential vulnerability to climate change: a social science review. *WIREs Clim. Change* **10**, e565 (2019).
47. Adger, W. N., Brown, K., Butler, C. & Quinn, T. Social ecological dynamics of catchment resilience. *Water* **13**, 349 (2021).
48. Troell, M. et al. Does aquaculture add resilience to the global food system? *Proc. Natl Acad. Sci. USA* **111**, 13257–13263 (2014).
49. Davis, K. F., Downs, S. & Gephart, J. A. Towards food supply chain resilience to environmental shocks. *Nat. Food* **2**, 54–65 (2021).
50. Monnereau, I. et al. The impact of methodological choices on the outcome of national-level climate change vulnerability assessments: an example from the global fisheries sector. *Fish Fish.* **18**, 717–731 (2017).
51. Fluet-Chouinard, E., Funge-Smith, S. & McIntyre, P. B. Global hidden harvest of freshwater fish revealed by household surveys. *Proc. Natl Acad. Sci. USA* **115**, 7623–7628 (2018).
52. Maury, O. et al. From shared socio-economic pathways (SSPs) to oceanic system pathways (OSPs): building policy-relevant scenarios for global oceanic ecosystems and fisheries. *Glob. Environ. Change* **45**, 203–216 (2017).
53. Gephart, J. A., Rovenskaya, E., Dieckmann, U., Pace, M. L. & Brännström, Å. Vulnerability to shocks in the global seafood trade network. *Environ. Res. Lett.* **11**, 035008 (2016).
54. Daw, T., Adger, W. N., Brown, K. & Badjeck, M.-C. in *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge* (eds Cochrane, K. et al.) 107–150 (FAO, 2009).
55. Gaines, S. et al. *The Expected Impacts of Climate Change on the Ocean Economy* (World Resources Institute, 2019).
56. Cheung, W. W. L. et al. Structural uncertainty in projecting global fisheries catches under climate change. *Ecol. Modell.* **325**, 57–66 (2016).
57. Frölicher, T. L., Fischer, E. M. & Gruber, N. Marine heatwaves under global warming. *Nature* **560**, 360–364 (2018).
58. Eyring, V. et al. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958 (2016).
59. Dunne, J. P. et al. The GFDL Earth System Model version 4.1 (GFDL-ESM 4.1): overall coupled model description and simulation characteristics. *J. Adv. Model. Earth Syst.* **12**, e2019MS002015 (2020).
60. Boucher, O. et al. Presentation and evaluation of the IPSL-CM6A-LR climate model. *J. Adv. Model. Earth Syst.* **12**, e2019MS002010 (2020).
61. Gütjahr, O. et al. Max Planck Institute Earth System Model (MPI-ESM1.2) for the High-Resolution Model Intercomparison Project (HighResMIP). *Geosci. Model Dev.* **12**, 3241–3281 (2019).
62. O’Neill, B. C. et al. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.* **9**, 3461–3482 (2016).
63. *World Development Indicators* (The World Bank, 2020).
64. *Fishery and Aquaculture Statistics: Global Production by Production Source, 1950–2018* (FAO, 2020).
65. Dyck, A. J. & Sumaila, U. R. Economic impact of ocean fish populations in the global fishery. *J. Bioecon.* **12**, 227–243 (2010).
66. *Fishery and Aquaculture Statistics: Global Fisheries Commodities Production and Trade, 1976–2018* (FAO, 2020).
67. *FAO Yearbook: Fishery and Aquaculture Statistics 2018* (FAO, 2020); <https://doi.org/10.4060/cb1213t>
68. Cisneros-Montemayor, A. M., Pauly, D., Weatherdon, L. V. & Ota, Y. A global estimate of seafood consumption by coastal indigenous peoples. *PLoS ONE* **11**, e0166681 (2016).
69. Kaufmann, D. & Kraay, A. *Worldwide Governance Indicators* (The World Bank, 2018).
70. *UN SDG Indicators* (United Nations, 2020).
71. Demirgüç-Kunt, A., Klapper, L., Singer, D., Ansar, S. & Hess, J. *The Global Findex Database 2017: Measuring Financial Inclusion and the Fintech Revolution* (The World Bank, 2018); <https://doi.org/10.1596/978-1-4648-1259-0>
72. *Sea Around Us Concepts, Design and Data* (Sea Around Us, 2020); searoundsus.org
73. *FAOSTAT Database* (FAO, 2019).
74. Wendling, Z. A. et al. *2020 Environmental Performance Index* (Yale Center for Environmental Law & Policy, 2020); <http://epi.yale.edu>

75. Cheung, W. W. L., Jones, M. C., Reygondeau, G. & Frölicher, T. L. Opportunities for climate-risk reduction through effective fisheries management. *Glob. Change Biol.* **24**, 5149–5163 (2018).
76. Jones, M. C. & Cheung, W. W. L. Using fuzzy logic to determine the vulnerability of marine species to climate change. *Glob. Change Biol.* **24**, e719–e731 (2018).
77. Tigchelaar, M. et al. Projected climate risk of aquatic food system benefits. *Dryad* <https://doi.org/10.5061/dryad.70rxwdbz3> (2021).
78. *World Economic Situation and Prospects 2020 – Statistical Annex* (United Nations, 2020); https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/WESP2020_Annex.pdf

Acknowledgements

This paper is part of the Blue Food Assessment (<https://www.bluefood.earth/>), a comprehensive examination of the role of aquatic foods in building healthy, sustainable and equitable food systems. The assessment was supported by the Builders Initiative, the MAVA Foundation, the Oak Foundation and the Walton Family Foundation, and it has benefited from the intellectual input of a wider group of scientists leading other components of the Blue Food Assessment work. Individual co-authors were supported by the CGIAR Research Program on Fish (E.Y.M. and M.J.P.); the CGIAR Research Program on Climate Change, Agriculture and Food Security (E.Y.M. and M.J.P.); the Swiss National Science Foundation (T.L.F., grant no. PP00P2_198897); the National Science Foundation (C.D.G., grant no. CNH 1826668); the John and Katie Hansen Family Foundation (C.D.G.); the Nippon Foundation Ocean Nexus Program (E.H.A.); Earthlab at the University of Washington (E.H.A.); the OceanCanada Partnership (U.R.S.); and the Social Science and Humanities Research Council of Canada (U.R.S.). We thank M. Aschwanden, A. Cisneros-Montemayor, S. Funge-Smith, J. Gee, D. Siegel and A. Thorpe for help accessing and analysing data.

Author contributions

M. Tigchelaar, W.W.L.C., E.Y.M. and M.J.P. co-led this study. M. Tigchelaar and W.W.L.C. conceived of the idea and designed the overall study together with E.Y.M., M.J.P. and E.R.S. M. Tigchelaar and H.J.P. reviewed the literature. M. Tigchelaar, W.W.L.C., M.A.O., T.L.F., J.A.G. and C.D.G. compiled the data. M. Tigchelaar and W.W.L.C. developed the model and analysed the data. M. Tigchelaar, W.W.L.C., E.Y.M., M.J.P., E.R.S., C.C.C.W., E.H.A. and A.B. conceived of the policy analysis and discussion. All authors reviewed the results and developed the main conclusions. M. Tigchelaar, W.W.L.C., E.Y.M. and M.J.P. wrote the manuscript draft, and all authors contributed to and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at <https://doi.org/10.1038/s43016-021-00368-9>.

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s43016-021-00368-9>.

Correspondence and requests for materials should be addressed to Michelle Tigchelaar.

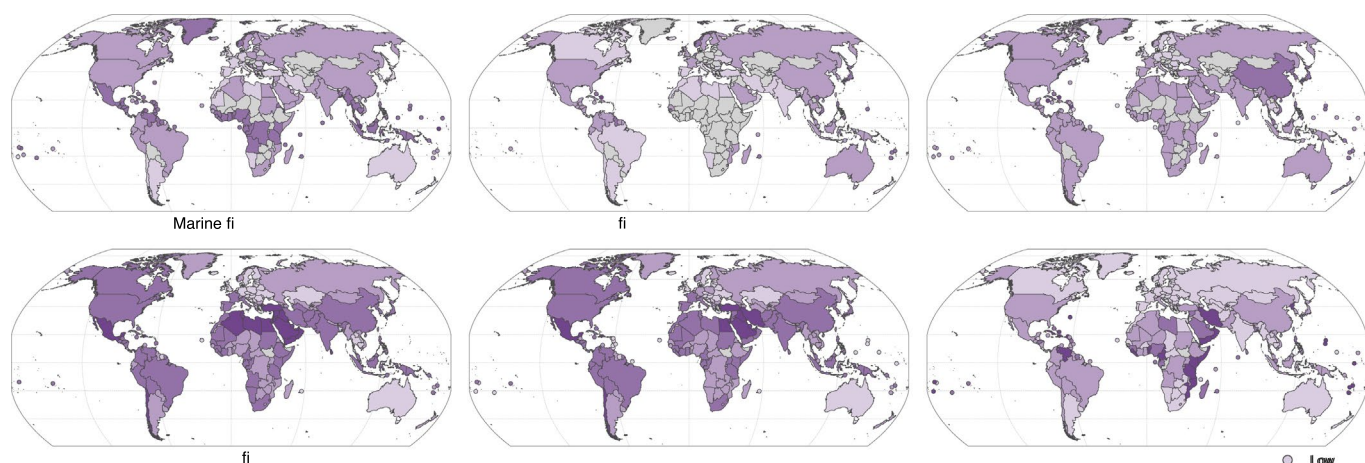
Peer review information *Nature Food* thanks William Travis, Salvador Lluch-Cota and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

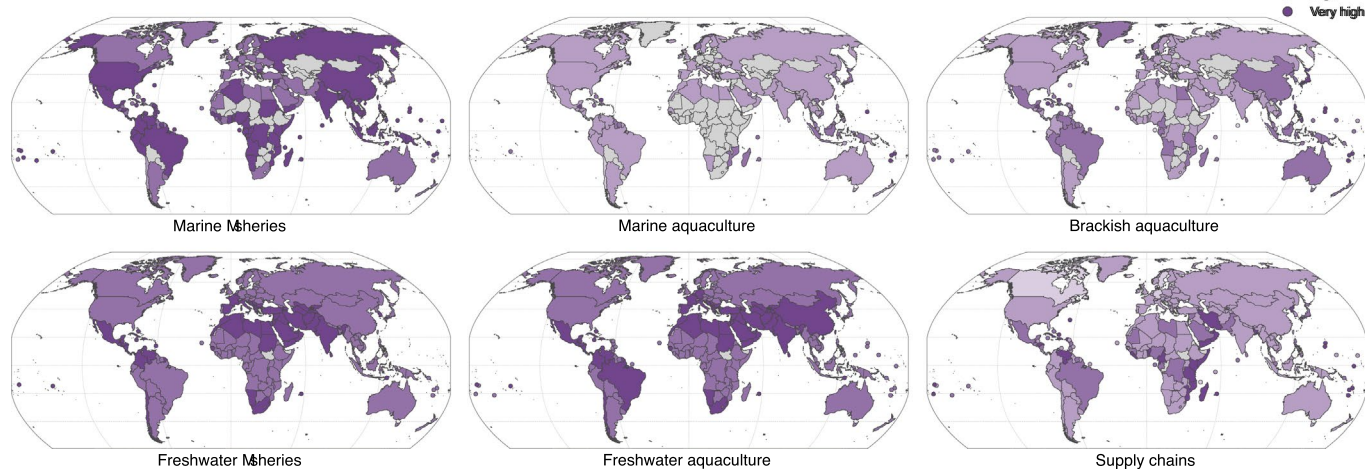
Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2021

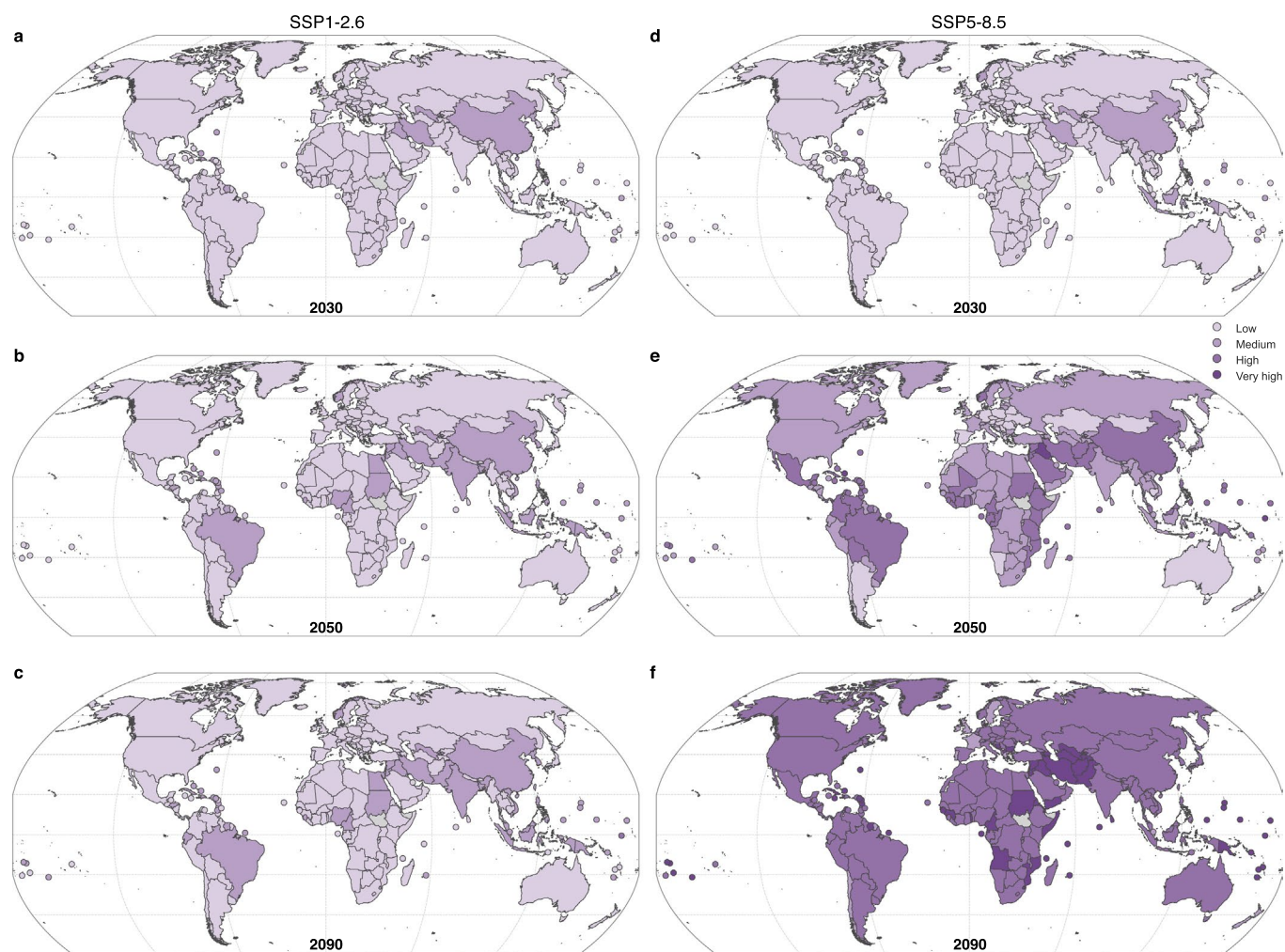
Hazard scores for scenario SSP5-8.5 in 2050



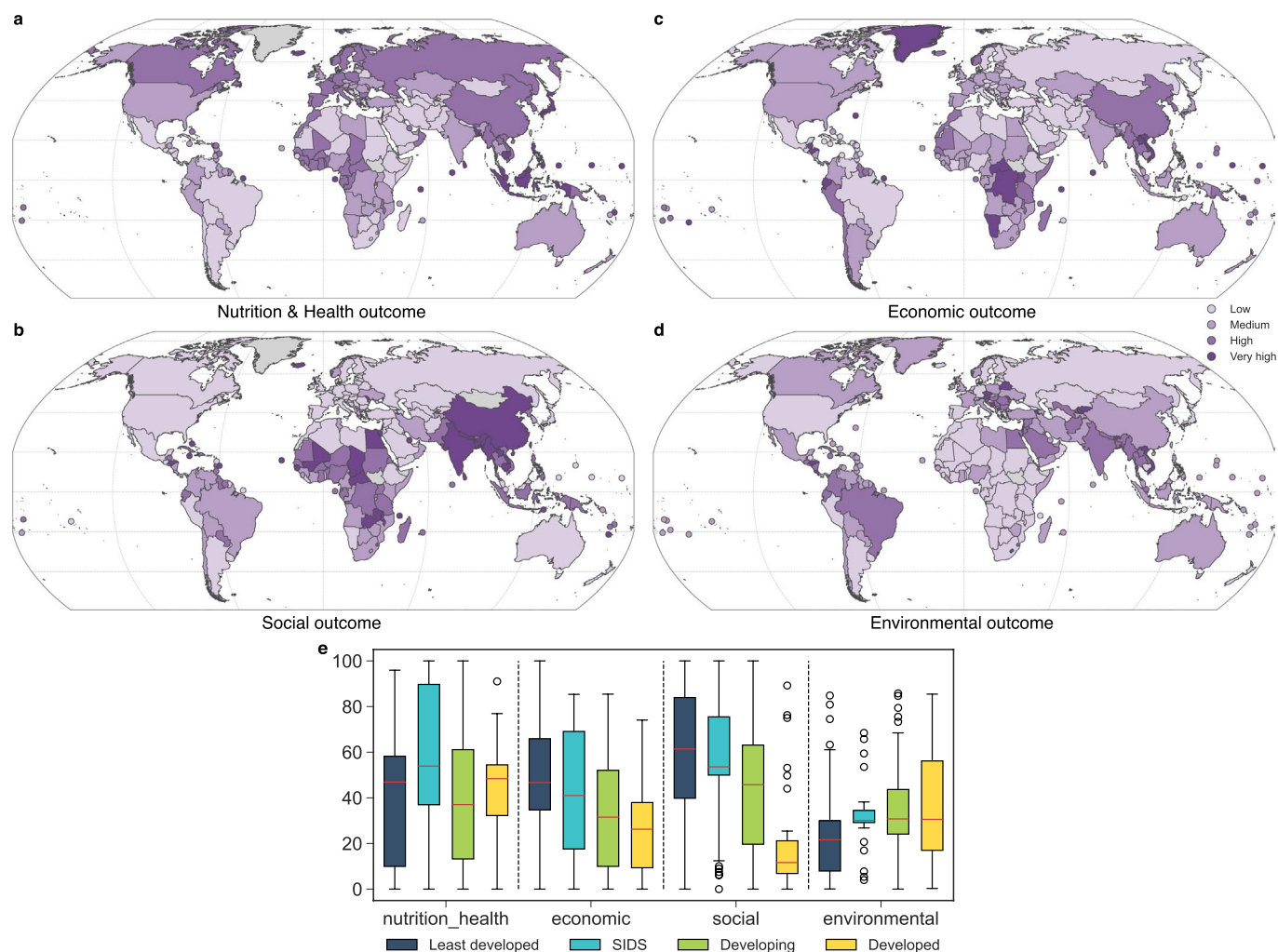
Hazard scores for scenario SSP5-8.5 in 2090



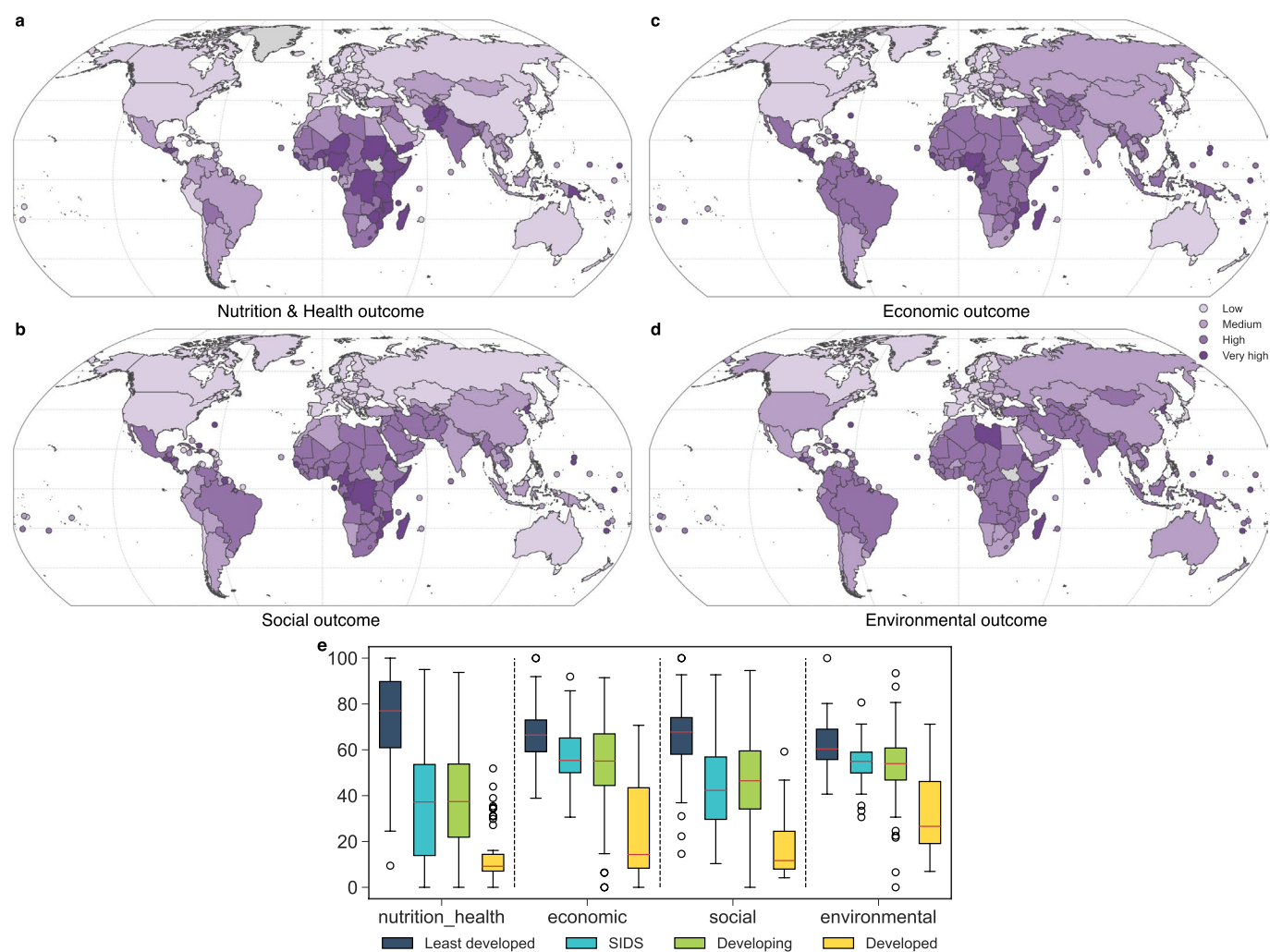
Extended Data Fig. 1 | Projected climate hazard scores by food system component. Hazard scores for each of the aquatic food system components under a high-emissions scenario (SSP5-8.5) in 2041-2060 ('2050', top) and 2081-2100 ('2090', bottom). Gray means no data. Scores <25 are classified as 'low', 25-50 as 'medium', 50-75 as 'high', >75 as 'very high'.



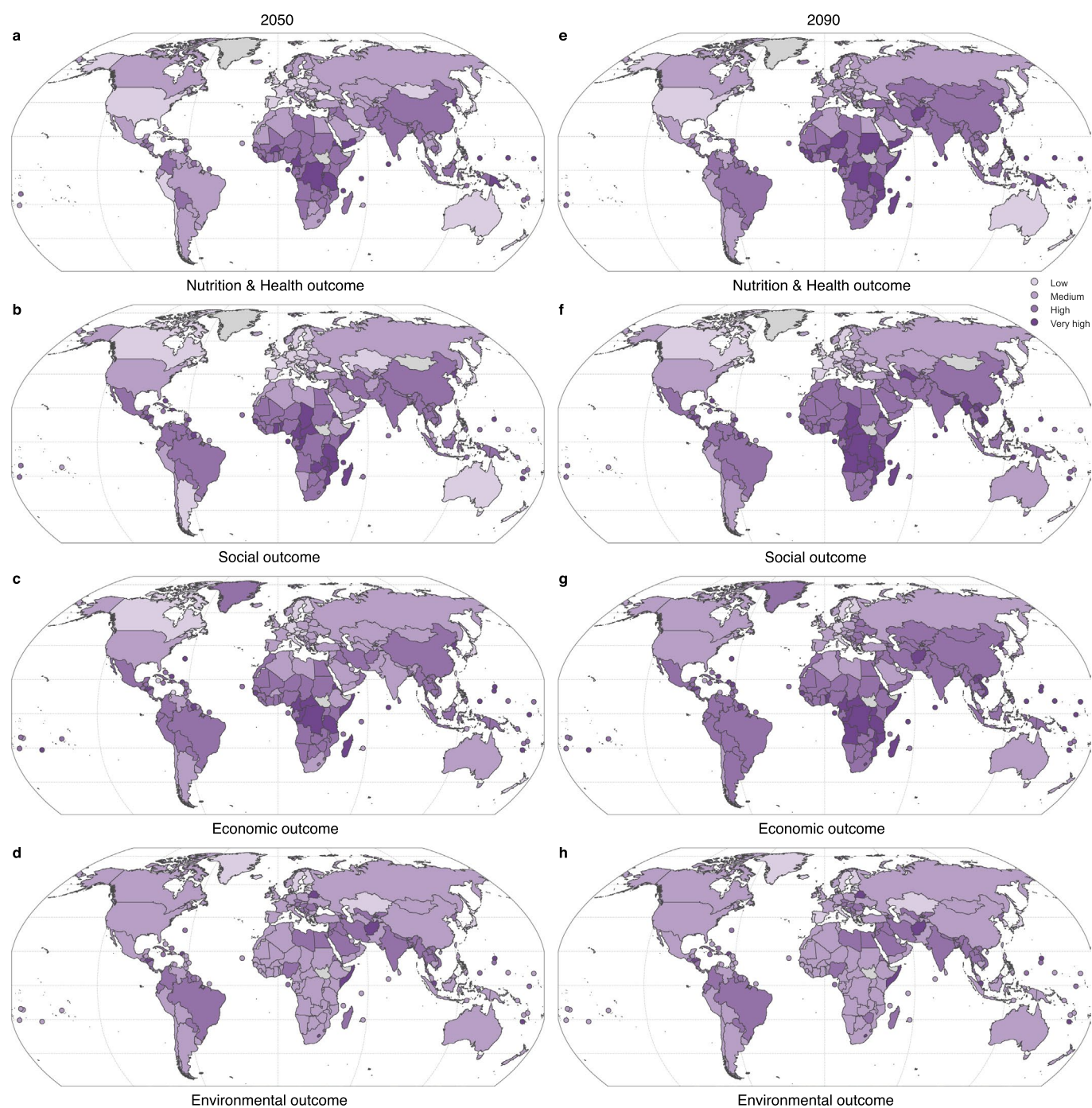
Extended Data Fig. 2 | Projected climate hazard scores in different scenarios and timeframes. Aggregate hazard score based on present-day production weights for a low-emissions scenario (SSP1-2.6, left) and a high-emissions scenario (SSP5-8.5, right) in 2021-2040 ('2030', top), 2041-2060 ('2050', middle) and 2081-2100 ('2090', bottom). **a.** SSP1-2.6 in 2030. **b.** SSP1-2.6 in 2050. **c.** SSP1-2.6 in 2090. **d.** SSP5-8.5 in 2030. **e.** SSP5-8.5 in 2050. **f.** SSP5-8.5 in 2090. Gray means no data. Scores <25 are classified as 'low', 25-50 as 'medium', 50-75 as 'high', >75 as 'very high'.



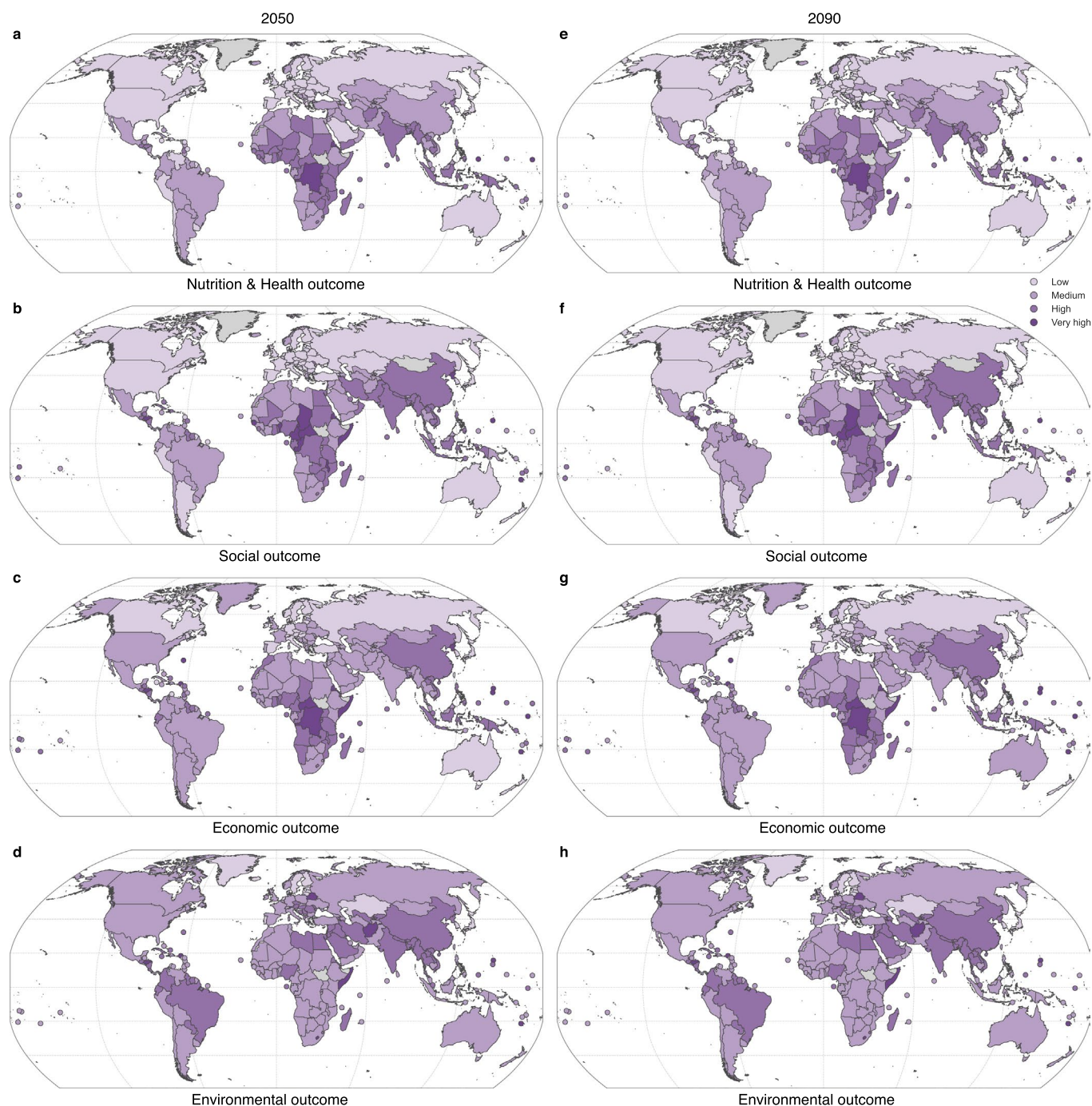
Extended Data Fig. 3 | Exposure scores for each of the food system outcomes. **a.** Scores for nutrition and health outcome; **b.** Scores for social outcome; **c.** Scores for economic outcome; **d.** Scores for environmental outcome; **e.** Exposure scores by development status. Gray means no data. Scores <25 are classified as 'low', 25-50 as 'medium', 50-75 as 'high', >75 as 'very high'. Box limits denote 25th and 75th percentiles; whiskers extend 1.5x the interquartile range from box edges; red line indicates median value and circles represent outliers.



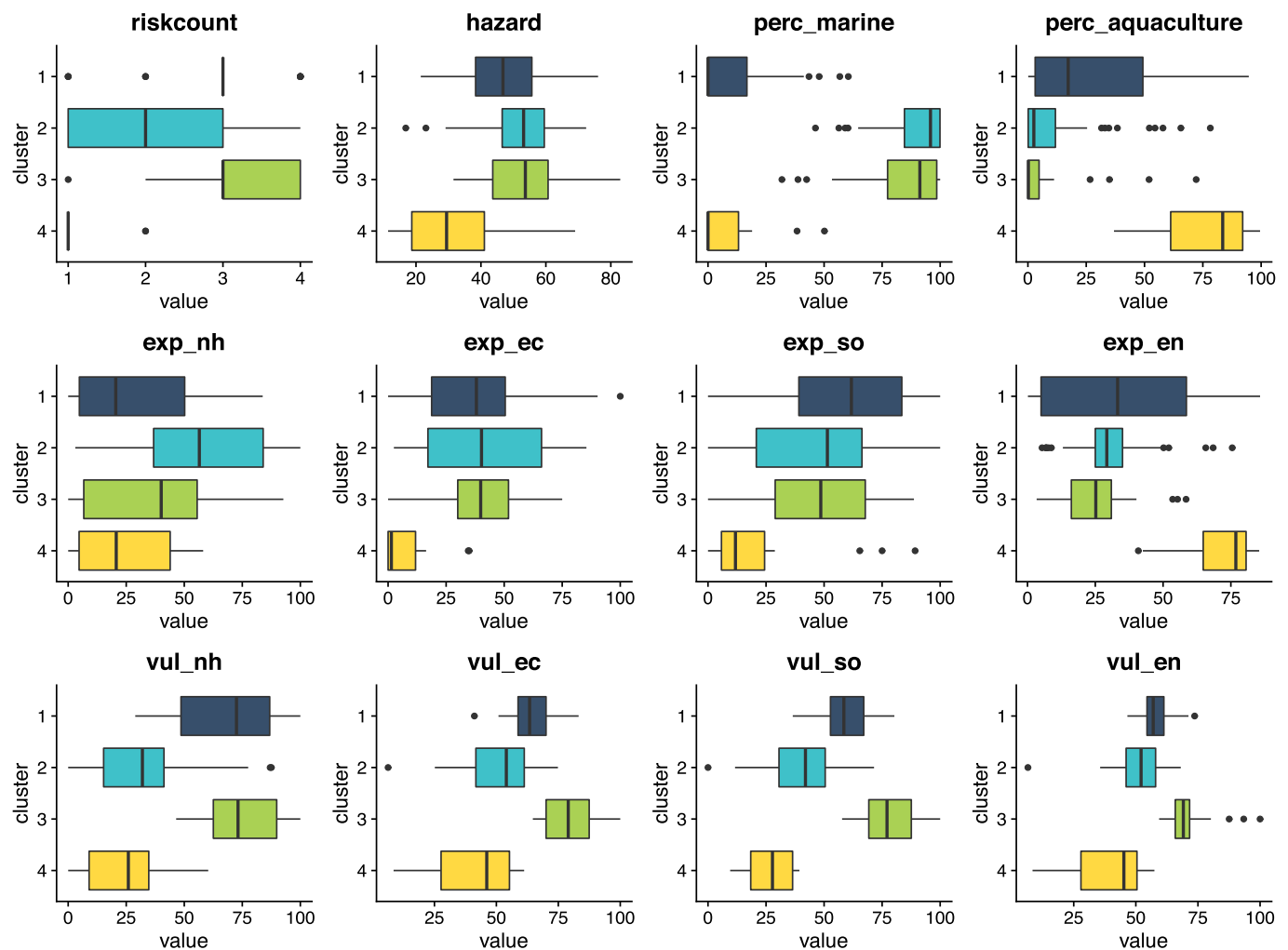
Extended Data Fig. 4 | Vulnerability scores for each of the food system outcomes. a. Scores for nutrition and health outcome; **b.** Scores for social outcome; **c.** Scores for economic outcome; **d.** Scores for environmental outcome; **e.** Vulnerability scores by development status. Gray means no data. Scores <25 are classified as 'low', 25-50 as 'medium', 50-75 as 'high', >75 as 'very high'. Box limits denote 25th and 75th percentiles; whiskers extend 1.5x the interquartile range from box edges; red line indicates median value and circles represent outliers.



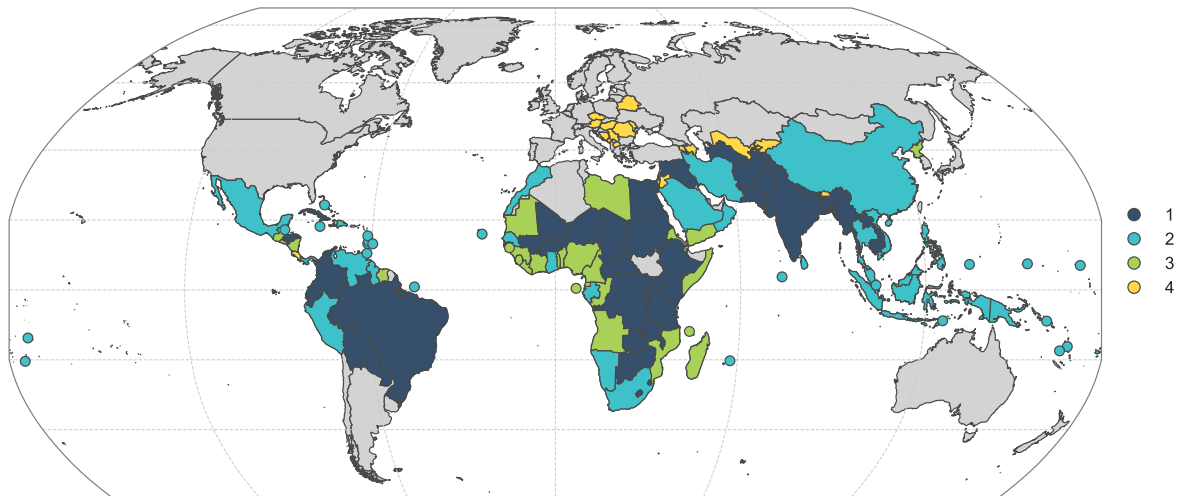
Extended Data Fig. 5 | Risk scores for each of the food system outcomes under high emissions. Projected climate risk for a high-emissions scenario (SSP5-8.5) in 2041-2060 ('2050', left) and 2081-2100 ('2090', right). **a and e.** Scores for nutrition and health outcome; **b and f.** Scores for social outcome; **c and g.** Scores for economic outcome; **d and h.** Scores for environmental outcome. Gray means no data. Scores <25 are classified as 'low', 25-50 as 'medium', 50-75 as 'high', >75 as 'very high'.



Extended Data Fig. 6 | Risk scores for each of the food system outcomes under low emissions. Projected climate risk for a low-emissions scenario (SSP1-2.6) in 2041-2060 ('2050', left) and 2081-2100 ('2090', right). **a and e.** Scores for nutrition and health outcome; **b and f.** Scores for social outcome; **c and g.** Scores for economic outcome; **d and h.** Scores for environmental outcome. Gray means no data. Scores <25 are classified as 'low', 25-50 as 'medium', 50-75 as 'high', >75 as 'very high'.



Extended Data Fig. 7 | Distribution of input variables for each climate risk cluster. The variables used in the cluster analysis are the number of outcomes for which climate risk in 2050 is 'high' or 'very high' under SSP5-8.5 ('riskcount'); the climate hazard score in 2050 under SSP5-8.5 ('hazard'); the percentage of production from marine environments ('perc_marine'); the percentage of production from aquaculture ('perc_aqua'); exposure scores for each of the food system outcomes (nutrition and health, economic, social, and environmental - 'exp_nh', 'exp_ec', 'exp_so' and 'exp_en'); and vulnerability scores for each of the food system outcomes ('vul_nh', 'vul_ec', 'vul_so' and 'vul_en'). We summarize the clusters as: Cluster 1 = Compound risk - freshwater & deltaic system; Cluster 2 = High marine dependence; Cluster 3 = Compound risk - marine fisheries; Cluster 4 = Environmental performance risk. Box limits denote 25th and 75th percentiles; whiskers extend 1.5x the interquartile range from box edges; black line indicates median value and circles represent outliers.



Extended Data Fig. 8 | Cluster assignment for each of the high risk countries. Cluster analysis was done only on countries that are projected to have 'high' or 'very high' risk in at least one of the food system outcomes and that had no missing data for any of the input variables. Cluster numbers correspond to the numbers in Extended Data Fig. 7 and the Supplemental Methods. Cluster 1 = Compound risk - freshwater & deltaic system; Cluster 2 = High marine dependence; Cluster 3 = Compound risk - marine fisheries; Cluster 4 = Environmental performance risk. Grey shading represents no data.

Supplementary information

Compound climate risks threaten aquatic food system benefits

In the format provided by the
authors and unedited

Supplemental Information

SI Table 1 – Glossary of terms.

Term	Definition
Climate Risk	The potential for climate change to lead to adverse consequences for human or ecological systems. In the context of this paper, climate risk signifies the potential for food systems to fail to provide sufficient, appropriate, and accessible food to all (i.e., to deliver nutrition and health benefits) or for their economic, social, and environmental outcomes to worsen. Climate risk results from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards ⁷⁹ .
Climate Hazard	The potential occurrence of a natural or human-induced physical and biogeochemical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources ⁷⁹ .
Exposure	The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected ⁷⁹ .
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt ⁷⁹ .
Sensitivity	The predisposition of society and ecosystems to suffer harm, resulting from intrinsic and context conditions, making it plausible that such systems will collapse or experience major harm and damage due to a hazard event ⁸⁰ .
Adaptive Capacity	The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences ⁷⁹ . Adaptive capacity is often understood to be a component of resilience ³⁶ .
Resilience	Many definitions of resilience exist, often related to the capacity of the system to withstand and/or adapt to disturbances over time and continue fulfilling its functions and providing its services or desirable outcomes. In the context of food systems, resilience can be understood as the capacity over time of a food system and its units at multiple levels, to provide sufficient, appropriate and accessible food to all, in the face of various and even unforeseen disturbances ³⁶ .
Climate Variable	Stressors on ecosystems, environments, and socio-ecological systems that are driven by anthropogenic and naturally occurring climate change (e.g., sea level rise, ocean acidification and deoxygenation, rising temperatures, etc.).
Hazard score, exposure score, vulnerability score, climate risk score	Specific value calculated by the fuzzy logic model on a scale of 0 to 100 that expresses the cumulative hazard/exposure/vulnerability/risk across all hazard/exposure/vulnerability/risk variables. See Fuzzy Logic Model below.
Food system	A food system gathers all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production,

	processing, distribution, preparation and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes ¹¹ .
Food system outcome	The contributions to food security, environmental safety, social welfare, etc. that emerge from food system activities (from production through consumption) ⁸¹ .

Summary of climate impact pathways

Environmental change caused by rising atmospheric greenhouse gas concentrations creates short-term shocks to, and long-term shifts in, the production capacity of marine and freshwater systems, as well as the functioning of feed supply (both from terrestrial and aquatic systems) and post-production processes (SI Table 11). For marine fisheries, progressive warming and marine heatwaves, decreases in dissolved oxygen, and changes in nutrient conditions alter the distribution and abundance of species. Such changes lead to shifts in community composition, a reduction in biomass and species richness in the tropics, and an increase in abundance, including introduction of new species, at high latitudes^{1,2}. While marine aquaculture may be less impacted by these changes in productivity, it faces linked hazards through increased spread of pathogens and parasites, increased frequency of harmful algal blooms, and its dependency on small pelagics and terrestrial crops for feed^{17,22,48}. Increasing temperature and ocean acidification impairs growth rates in corals and shell-forming organisms, threatening the contributions of coral reef fisheries and, without management intervention, may constrain further growth of the bivalve sector^{1,2}. Coastal fisheries and aquaculture, including also brackish ponds, are projected to be exposed to increased flooding from sea level rise and structural damage from strengthening storms, especially in tropical cyclone regions^{1,2,17,82,83}.

Inland fisheries display high sensitivity to warming and are impacted by changes in the hydrological cycle, such as extreme precipitation, drought, and shifts in the timing of river flows^{1,18}. Freshwater ecosystems are already subject to a wide range of interacting non-climatic anthropogenic drivers, such as pollution, freshwater extraction and the construction of dams⁸⁴. Aquaculture production in lakes and ponds faces some of the same challenges as inland fisheries, in addition to feed dependencies for more intensive production systems^{1,17}.

Climate change impacts on non-production stages of aquatic food supply chains are less well understood⁴⁹ (SI Table 11), but include destruction of supporting infrastructure through sea level rise and extreme events^{17,82,85}, impacts on food safety and quality through toxic algal blooms and ocean acidification^{3,23,86}, and occupational health hazards resulting from heat extremes and increased storm intensity^{85,87}. As the COVID-19 pandemic has exemplified^{88,89}, shock events can severely disrupt production and existing networks of distribution^{49,90}, with the potential to exacerbate vulnerabilities of people living in poverty and marginalized groups, including women and indigenous communities⁹⁰.

Fuzzy logic model

As outlined in the Methods, the fuzzy logic modeling system consists of three steps: 1) categorizing each indicator variable into one or more levels of 'low', 'medium', 'high' and 'very high' simultaneously, with the degree of membership defined by fuzzy membership functions

(“fuzzification”); 2) accumulating the degree of membership associated with each level using the MYCIN algorithm for each of the subcomponents of climate risk (hazard, exposure and vulnerability) and applying a set of heuristic rules to combine the components into an aggregate risk score (“fuzzy reasoning”); and 3) calculating a final score from the accumulated memberships in order to express climate risk on a scale from 0 to 100 (“defuzzification”)^{20,75,76}.

SI Tables 6-8 provide an overview of which variables were included for the hazard, exposure, and vulnerability scores. For the first fuzzy logic step, we chose membership functions that are trapezoidal for the ‘low’ and ‘very high’ levels, and triangular for the ‘medium’ and ‘high’ levels (SI Fig. 1)²⁰, with SI Table 9 listing the membership function limits for each of the variables. The limits were chosen based on the statistical distribution of the indicator values, as listed in SI Table 10. To omit conclusions based on a very low level of membership, we implement a minimum membership threshold value of 0.2²⁰.

Next, we accumulate the degree of membership associated with each level (‘low’, ‘medium’, ‘high’, or ‘very high’) for each of the different risk components, production systems and outcomes according to the so-called MYCIN algorithm²⁰:

$$AccMem(i + 1) = AccMem(i) + Membership(i + 1)(1 - AccMem(i)) \quad (1)$$

where *AccMem* is the accumulated membership of a particular level (e.g., high vulnerability) and *i* denotes the indicator variable contributing to the subcomponent.

For the hazard variables, we calculate different hazard scores for each of marine fisheries, freshwater fisheries, marine aquaculture, freshwater aquaculture, brackish aquaculture, and supply chain processes. SI Table 6 lists which of the variables apply to which of the production systems. For marine fisheries and aquaculture, some of the variables (such as maximum catch potential) are available on a species and/or Exclusive Economic Zone (EEZ) level. We therefore first calculate hazard membership levels for each species and EEZ separately, counting species-specific variables (e.g., marine heat wave intensity) equally for each of the species. We then cumulate each of the marine hazard membership assignments to the national level using present-day production weights from Sea Around Us⁷². For all of the variables we assume an accumulation weight of 0.5²⁰, except for global crop land temperature for which we use an accumulation weight of 0.1 as the impacts on feed price and availability are much more indirect.

For a handful of variables, assigning membership levels is contingent on the sensitivity of a species, system or country to that variable. These variables include pH for marine capture fisheries, which is contingent on species sensitivity; all of the hazard variables for the supply chain processes, which we assume to be contingent on the proportion of production from small-scale operations; and changes in freshwater balance for freshwater fisheries, which we assume to be contingent on freshwater extractions rates (SI Table 6). In this case, the conditional categories (e.g., pH and species sensitivity) are joined by the heuristic rules shown in SI Table 2. For example, IF the change in pH is ‘very high’ AND the species sensitivity is ‘very high’ THEN the hazard level for this species is ‘very high’. For this we use the minimum membership to each of the conditional categories between the two variables, so if variable 1 for instance has a ‘very high’

For hazards, we accumulate the evidence for each of the production systems. For marine fisheries and aquaculture, evidence is available at a species and EEZ level. For each species we either use species-specific values (e.g., maximum catch potential), general values with

species-specific sensitivity (e.g., pH) or general values (e.g., marine heat wave intensity). We accumulate the evidence for each species to EEZ level based on the SAU EEZ catch data by species, and then accumulate it to national level based on the SAU national catch data by EEZ. For supply chain and precipitation variables we assign hazard levels based on the combination of environmental hazard values and sensitivity values.

SI Table 2 – Matrix of heuristic rules that determine the level of membership to conditional categories based on two input variables.

	Low	Medium	High	Very high
Low	Low	Low	Medium	High
Medium	Low	Medium	High	High
High	Medium	High	High	Very high
Very high	High	High	Very high	Very high

For the exposure variables, we calculate different exposure scores for each of the production systems and food system outcomes. SI Table 7 lists which of the variables apply to which of the outcomes. For the nutrition & health, economic and social outcomes, the production system categories are again marine and freshwater fisheries, marine, freshwater and brackish aquaculture, and supply chains, where all exposure variables are assumed to translate to supply chain exposure. For the environmental outcomes, we accumulate exposure scores for each of the aquaculture and capture fisheries species groups for which environmental impact data are available³³. For the vulnerability variables, we calculate different vulnerability scores for each of the food system outcomes, according to the assignment in SI Table 8.

As a next step, we combine the production system and outcome-specific hazard and exposure scores into a combined ‘exposure to hazard’ score. For the nutrition & health, economic, and social outcomes, we do this by applying the heuristic rules of SI Table 2, according to the principles outlined above. Then, we accumulate the evidence for each of these three food system outcomes across the six production systems (marine and freshwater fisheries, marine, freshwater and brackish aquaculture, and supply chains) using the MYCIN algorithm (SI Eq. 1), weighted by the present-day contribution of each system to total production in each country⁶⁴. We assume the weight of supply chain exposure to hazard to be 0.1.

For the environmental outcomes we take a slightly different approach. We assume that as the climate changes, production systems will shift towards the ones that are least impacted. We therefore adjust the present-day production weights⁶⁴ of the aquaculture and capture fisheries species groups for which environmental impact data are available³³, based on the level of hazard that each of these production systems is projected to experience. We reduce the relative production weight by 25, 50 and 75% for medium, high and very high hazard respectively. Then we standardize the sum of the total production weights in each country to equal one and accumulate according to the MYCIN algorithm (SI Eq. 1).

The two final steps are to combine the exposure to hazard score and the vulnerability score into a climate risk score for each of the food system outcomes, again using the heuristic rules in SI Table 2. Then finally, we express the hazard, exposure, vulnerability and risk scores on a scale

from 0 to 100, with 100 being the most at risk. The index values *IndVal* corresponding to each level *x* are: 'low' = 1, 'moderate' = 25, 'high' = 75, and 'very high' = 100. The final risk score is calculated from the average of the index values, weighted by their accumulated membership²⁰:

$$FnInd = \frac{\sum_1^4 AccMem_x IndVal_x}{\sum_1^4 AccMem_x} \quad (2)$$

We indicate what the final model scores can be interpreted to mean for aquatic food systems and food systems in SI Table 3 (hazard) and SI Table 4 (risk).

SI Table 3 – Heuristic interpretation of climatic hazard scores as estimated by the fuzzy logic model.

Hazard level	Scores	Heuristic interpretation
Low	1 - 25	Changes in almost all climatic stressors that the relevant aquatic food system is exposed to are within the range of historical variability (1951-2010)
Medium	26 - 50	Changes in some climatic stressors that the relevant aquatic food system is exposed to are outside the historical range of variability (1951-2010), while others are still within the historical range
High	51 - 75	Changes in almost all climatic stressors that the relevant aquatic food system is exposed to are outside the range of historical variability (1951-2010)
Very high	76 - 100	Changes in almost all climatic stressors that the relevant aquatic food system is exposed to are well outside the range of variability (1951-2010)

SI Table 4 – Heuristic interpretation of climatic risk scores of aquatic food system outcomes (environmental, social, economic, nutrition & health) as estimated by the fuzzy logic model.

Risk level	Scores	Heuristic interpretation
Low	1 - 25	Negligible or minor reduction in the potential contributions of aquatic food systems to sustainable and equitable food systems that produce healthy diets
Medium	26 - 50	Some reduction in the potential contributions of aquatic food systems to sustainable and equitable food systems that produce healthy diets
High	51 - 75	Large reduction in the potential contributions of aquatic food systems to sustainable and equitable food systems that produce healthy diets
Very high	76 - 100	Almost complete loss of the potential contributions of aquatic food systems to sustainable and equitable food systems that produce healthy diets

Sensitivity analysis

To test the sensitivity of the climate risk score to the values of the vulnerability indicators, we adjust sets of vulnerability variables to the average value for those variables in the countries that

have an aggregate vulnerability that is one category lower. For example, for countries with a 'very high' vulnerability for economic outcomes, we might increase the GDP per capita to the average value of countries with a 'high' vulnerability for economic outcomes. The same goes for adjustments from 'high' to 'medium', and from 'medium' to 'low'. If in a given 'very high' vulnerability country the GDP already exceeds that of the average 'high' vulnerability country, we keep its original value. We adjust sets of variables in the following categories:

- Economic growth: GDP per capita (PPP); and proportion of landings from small-scale operations
- Economic inclusion: proportion of people below the national poverty line; GINI coefficient; and proportion of people with a bank account
- Social fabric: governance; educational attainment; and proportion of GDP spent on R&D
- Food security: stunting rate in children under five; Summary Exposure Value for Vitamin B-12; and Summary Exposure Value for Omega-3 fatty acids
- Environmental management: EPI Biodiversity & Habitat index; EPI Fisheries index; and EPI Climate Change index
- All: all vulnerability variables

We then recalculate the vulnerability and risk scores with the updated vulnerability variables. Results of the sensitivity analysis are shown in SI Table 12.

SI Table 5 – Additional references associated with Climate Resilience Priorities, Policy and Management Considerations, and Trade-Offs (Table 1).

Associated Cluster	Associated Column	Statement
High nutritional, economic, and social dependency on marine fisheries	Policy and Management Considerations	(P) Shift to offshore resources^{1,91,92}; climate-smart and -just agreements for transboundary resources^{43,92,93}; policies⁴⁰ to enable utilization^{44,94,95} of nutrient-rich species in coastal communities (F&I) Conservation financing for small-scale fisheries^{96,97}; revise fishery subsidies^{98,99} to incentivize sustainability (T&I) Local adaptation measures for fisheries, e.g., develop national pelagic fisheries⁹¹, climate-informed¹⁰⁰ and equitable vessel scheme days^{93,101} and early warning systems^{40,90}
Compound climate risk – freshwater/deltaic fisheries & aquaculture	Policy and Management Considerations	(F&I) Investment in protection & management of natural capital; alternative livelihoods³⁸; collective loans and savings programmes¹⁰² (T&I) Freshwater aquaculture⁴⁴; sustainable intensification^{45,103}
Compound climate risk – freshwater/deltaic fisheries & aquaculture	Potential trade-offs for health, sustainability & equity	Fish as food ^{42,94,104,105} vs. feed Equity ¹⁰⁶ dimensions of adaptive programming activities
Compound climate risk –	Policy and Management	(P) Co-management ⁴⁴ of resources

marine fisheries	Considerations	that supports agency and empowers and engages marginalized groups¹⁰⁷ <i>(F&I)</i> financial management⁴⁴ through collectives and cooperatives; gender transformative adaptation opportunities^{108–110} <i>(B&S)</i> Equitable fisheries access agreements^{111,112}; climate information services & early warning systems^{40,90}
------------------	----------------	---

SI Table 6 – Hazard variables. Systems: MF = marine fisheries; FF = freshwater fisheries; MA = marine aquaculture; FA = freshwater aquaculture; BA = brackish aquaculture; SC = supply chain.

Indicator variable	System						Year	Source	Resolution	Description
	M F	F F	M A	F A	B A	S C				
Change in maximum catch potential	x						2021-2040, 2041-2060 & 2081-2100 rel. to 1996-2015	CMIP6	Calculated by species and EEZ; aggregated to national level based on present-day catch contributions ⁷²	We used the Dynamic Bioclimate Envelope Model (DBEM) to simulate changes in distribution, abundance and catches of exploited marine fishes and invertebrates ^{10,56} . The DBEM was forced by projected changes in ocean temperature, circulation, dissolved oxygen, net primary production in the top 100m, salinity and sea ice from output of three CMIP6 Earth system models: GFDL-ESM4 ⁵⁹ , IPSL-CM6A-LR ⁶⁰ , and MPI-ESM1-2-HR ⁶¹ . We use the multi-model mean of changes in maximum catch potential as the input variable to the fuzzy logic model.
Change in maximum mariculture potential			x				2021-2040, 2041-2060 & 2081-2100 rel. to 1996-2015	CMIP6	Calculated by species and EEZ; aggregated to national level based on present-day production contributions ⁷²	We used the Global Mariculture production Potential Model (GOMAP) to simulate changes in mariculture production potential of finfish and molluscs ¹¹³ . The model accounts for changing ocean conditions, suitable marine area for farming, fishmeal and fish oil production, the dietary demand of farm species, farmed gate price, global seafood demand and characteristics of the farm species to project mariculture production potential (MPP) with input from two CMIP6 Earth system models: GFDL-ESM4 ⁵⁹ and IPSL-CM6A-LR ⁶⁰ . We use the multi-model mean of changes in MPP as the input variable to the fuzzy logic model.
Change in surface and bottom pH	x						2021-2040, 2041-2060 & 2081-2100 rel. to 1991-2010	CMIP6	Averaged from climate model grid to EEZ; aggregated to national level based on present-day catch contributions ⁷²	Ocean acidification poses a substantial threat to especially shell-bearing organisms and corals but is not currently included in the DBEM catch potential calculations of exploited marine fishes and invertebrates. It is therefore included separately, using species-specific sensitivity ⁷⁶ . We use sea surface pH values for pelagic species and bottom values for demersal species. We use multi-model mean values from three CMIP6 Earth system models: GFDL-ESM4 ⁵⁹ , IPSL-CM6A-LR ⁶⁰ , and MPI-ESM1-2-HR ⁶¹ .
Change in sea ice extent						x	2021-2040, 2041-2060 & 2081-2100 rel. to 1991-2010	CMIP6	Averaged from climate model grid to EEZ; aggregated to national level based	The direct impacts of changes in sea ice extent on catch potential are included in the DBEM calculations, but reduction in sea ice poses an additional indirect threat through coastal erosion and loss of access to food ¹¹⁴ . It is therefore included broadly under the

									on present-day catch contributions ⁷²	'supply chain' category. We use multi-model mean values from three CMIP6 Earth system models: GFDL-ESM4 ⁵⁹ , IPSL-CM6A-LR ⁶⁰ , and MPI-ESM1-2-HR ⁶¹ .
Change in marine heatwave frequency	x		x					2021-2040, 2041-2060 & 2081-2100 rel. to 1991-2010	CMIP5 Averaged from climate model grid to EEZ; aggregated to national level based on present-day catch contributions ⁷²	Prolonged periods of extreme heat are associated with mass mortality and species range shifts ¹¹⁵ . As a metric for marine heatwave hazard, we use yearly mean cumulative mean heatwave intensity (units in °C day) ⁵⁷ . We use multi-model mean values from three CMIP5 Earth system models: GFDL-ESM2M, IPSL-CM5A-LR, and MPI-ESM-MR.
% of population inundated by sea level rise			x		x	x		1m SLR scaled to projected values in 2030, 2050 & 2090	2,116,117 National total from gridded inundation and population data at 1/120° resolution	As a metric for the impact of sea level rise and associated flooding on production systems and infrastructure we calculate the percentage of a country's present-day population ¹¹⁷ that would be inundated with 1-m of global sea level rise, based on the Global Land One-km Base Elevation (GLOBE) digital elevation model (DEM) ¹¹⁶ . We then linearly scale this percentage to global sea level rise projections for the two different emission scenarios and three different time periods ² .
Cyclone strength in Low Elevation Coastal Zone			x		x	x		2010, scaled by ΔT in 2030, 2050 & 2090	117–120 National average from gridded cyclone data at 1/6° resolution	Projections of future cyclone strength and frequency are highly uncertain ² , so we use historical observed storm strength as a proxy of where enhanced storm damage is most likely to occur in the future. We calculate the average cyclone strength ¹¹⁸ in the Low Elevation Coastal Zone ¹¹⁹ , weighted by the population in each grid cell ¹¹⁷ . To differentiate between future scenarios, we increase storm strength by 10% for each degree of global warming ¹²⁰ , based on the fact that storms are projected to produce at least 7% more rainfall per degree of warming, and increase in intensity by 1-10% for every 2 °C ² .
Change in near surface (2m) air temperature		x		x	x	x		2021-2040, 2041-2060 & 2081-2100 rel. to 1996-2015	CMIP6 National average from climate model grid	Because we don't have detailed information on the projected warming of the many rivers, lakes and wetlands that contribute to global inland fisheries, we use national average changes in annual mean atmospheric continental surface temperature as a broad metric for the impacts of warming waters on freshwater ecosystems. This variable also applies to supply chain processes as a measure of heat stress on aquatic food supply chain workers. We use multi-model mean values from three CMIP6 Earth system models: GFDL-ESM4 ⁵⁹ , IPSL-CM6A-LR ⁶⁰ , and MPI-ESM1-2-HR ⁶¹ .

Change in freshwater balance (P-E)		x		x			2021-2040, 2041-2060 & 2081-2100 rel. to 1991-2010	CMIP6	National average from climate model grid	Because we don't have detailed information on the projected changes in hydrology of the many rivers, lakes and wetlands that contribute to global inland fisheries, we use national average changes in annual mean freshwater balance (precipitation minus evaporation) as a broad metric for the impacts of reduced water availability on freshwater ecosystems. We use multi-model mean values from three CMIP6 Earth system models: GFDL-ESM4 ⁵⁹ , IPSL-CM6A-LR ⁶⁰ , and MPI-ESM1-2-HR ⁶¹ .
Percent extraction of renewable freshwater		x		x			Average 2000-2017	14	National	Reductions in freshwater availability will mostly impact freshwater systems in places where there is already high freshwater stress or competition over freshwater resources. We therefore use the percentage of renewable freshwater resources that is extracted in each country ⁷⁰ as a sensitivity variable to the projected changes in freshwater balance.
Global cropland temperature			x	x	x		2021-2040, 2041-2060 & 2081-2100 rel. to 1991-2010	CMIP6	Global average from climate model grid, weighted by area of crop production ¹²¹	For fed aquaculture, changes in the availability and price of feed ingredients as a result of climate-induced changes in crop production pose an additional threat to aquatic production systems. There are many variables that determine the overall productivity of terrestrial agriculture, but here we use the average annual mean near surface (2m) air temperature over the crop lands currently producing the most important aquaculture feed ingredients (barley, maize, wheat, pulses, cassava, rapeseed, soybeans ¹⁹). We use multi-model mean values from three Earth system models: GFDL-ESM4 ⁵⁹ , IPSL-CM6A-LR ⁶⁰ , and MPI-ESM1-2-HR ⁶¹ .
Fishmeal and fish oil availability				x	x		2021-2040, 2041-2060 & 2081-2100 rel. to 1996-2015	CMIP6	Global	Feeds for fed aquaculture species rely on the inclusion of fishmeal and fish oil (FMFO) from forage fish. We modeled FMFO availability using the Dynamic Bioclimate Envelope Model ^{10,56} to project the global maximum catch potential of the major FMFO forage fish species and extracted the current percentage used for FMFO production ¹²² . We use multi-model mean values from three Earth system models: GFDL-ESM4 ⁵⁹ , IPSL-CM6A-LR ⁶⁰ , and MPI-ESM1-2-HR ⁶¹ .
Crude Protein index for marine and freshwater & brackish			x	x	x		1996-2015		Calculated by species by country by year	Countries that produce aquaculture species with a higher reliance on feeds will be more sensitive to changes in feed availability. As a measure of feed use, we used the feed formulation model (FEM) based on Pearson Square (PS) calculation to estimate the total amount of crude protein (CP) required to produce the total

											number of tonnes for the historical years of each species. We focused on the CP from fishmeal to meet the required crude protein target for the aquafeed needed by the species and assumed that total the energy feedstuff (e.g maize, barley, oats etc) CP level needed by the species equals 10% irrespective of the energy feedstuff used for the aquafeed. We then calculated a CP index, which expresses the proportion of total CP required for each species per country per year in terms of total global CP fishmeal produced.
% of landings from small-scale operations							x	Average 2012-2016	72	National	Supply chains with a higher number of workers and more low-tech assets will more directly experience the harmful impacts of storms, sea level rise, extreme heat and loss of access. We therefore use the percentage of marine landings from small-scale operations ⁷² as a sensitivity variable to the hazard variables impacting post-production systems.

SI Table 7 – Exposure variables. Outcomes: NH = nutrition & health; EC = economic; SO = social; EN = environmental.

Indicator variable	Outcome				Year	Source	Resolution	Description
	NH	EC	SO	EN				
Per capita aquatic food consumption – marine, freshwater	o				2017	⁹	National	One measure of the contribution of aquatic foods to nutrition and health is the average aquatic food consumption per capita per year. We use values estimated from the Global Nutrition Database for 2017, split out by marine and freshwater species ⁹ . For countries in the European Union, data are only available at EU-level, so we apply the EU-aggregates to each of the EU countries.
% Vitamin-B12 and Omega-3 fatty acids from aquatic food consumption	o				2017	⁹	National	In addition to absolute consumption of aquatic foods, we also consider the relative contributions of aquatic foods to total consumption of key nutrients, namely Vitamin-B12 and Omega-3 fatty acids. For both aquatic and total consumption of each nutrient we use values estimated from the Global Nutrition Database for 2017 ⁹ . For countries in the European Union, data are only available at EU-level, so we apply the EU-aggregates to each of the EU countries.
Aquatic food production value relative to total GDP – marine fisheries		o			2012	³¹	National	One measure of the contribution of aquatic foods to the economic outcomes of food systems is the value of aquatic food production relative to total GDP. The FishStatJ database only contains production values for aquaculture, so for marine capture fisheries we use estimates from the WorldBank collected in 2012 ³¹ .
Aquatic food production value relative to total GDP – aquaculture		o			2019	^{63,64}	National	One measure of the contribution of aquatic foods to the economic outcomes of food systems is the value of aquatic food production relative to total GDP. For aquaculture, production value data were obtained from the FishStatJ database ⁶⁴ . We used the most recently available data, which is 2019, and calculated these as a percentage of the most recently available GDP data ⁶³ .
Aquatic food production value relative to agriculture, forestry and fishing GDP – freshwater fisheries		o			2018	^{25,63}	National	One measure of the contribution of aquatic foods to the economic outcomes of food systems is the value of aquatic food production relative to GDP. The FishStatJ database only contains production values for aquaculture, so for freshwater fisheries we use estimates from the FAO calculated in 2018 ²⁵ . Because inland fisheries primarily contribute at a local or district level, there is a

							risk of their contribution getting lost when compared to national GDP. We therefore calculate the production value compared to the most recently available agriculture, forestry and fishing GDP ⁶³ .
Economic multipliers for marine fishery supply chains		o			2010	⁶⁵	National Economic contributions of aquatic food systems extend far beyond the direct production value of fisheries and aquaculture systems, including through secondary economic activities ranging from boat building to the transportation sector. As a metric of the total output in an economy that is (partially) dependent on fisheries output, we use estimates of economic multipliers for marine fisheries from 2010 ⁶⁵ .
Net trade balance relative to GDP		o			2019	^{63,66}	National For certain countries, the export of high-value aquatic food products provides an important addition to national budgets. To capture this, we include the net trade balance of all aquatic foods in 2019 ⁶⁶ relative to the most recently available total national GDP ⁶³ .
% aquatic food related jobs per capita – marine fisheries			o		2013	^{5,123}	National Aquatic food systems are a source of livelihoods to millions of people around the world, which here we conceptualize as being part of the social outcomes component of food systems. For livelihoods from marine fisheries we draw from a 2013 dataset that adds the contributions of small-scale fishers that may have been omitted from FAO statistics ⁵ . Livelihood contributions are expressed as a percentage of the most recently available total labor force ¹²³ .
% aquatic food related jobs per capita – aquaculture			o		2019	^{67,123}	National For livelihoods from aquaculture we use the 2019 data from the FAO Yearbook ⁶⁷ . Livelihood contributions are expressed as a percentage of the most recently available total labor force ¹²³ .
% aquatic food related jobs per capita – freshwater fisheries			o		2018	^{25,123}	National For livelihoods from freshwater fisheries we use 2018 data compiled by the FAO inland fisheries division ²⁵ . Livelihood contributions are expressed as a percentage of the most recently available total labor force ¹²³ .
Ratio of indigenous sea food consumption to national average seafood consumption			o		2016	^{9,68}	National Aquatic foods make important cultural contributions, many of which are difficult to quantify in national-level indicators. As one metric of the cultural contributions of aquatic foods we use the ratio of coastal indigenous consumption of seafood ⁶⁸ to national average aquatic food consumption ⁹ .

Environmental impact by species group – greenhouse gas emissions, nitrogen emissions, phosphorus emissions, land use, freshwater use				o	2020	33	Global, weighted for each country by present-day production contributions ⁶⁴	As a measure of the impacts of aquatic food systems on the environment we use recently compiled data from Life Cycle Assessments, split out by aquaculture and capture fisheries and aggregated by species group ³³ . The environmental impact categories are: greenhouse gas emissions, nitrogen emissions, phosphorus emissions, land use and freshwater use. For capture fisheries, only greenhouse gas emissions are recorded so we assume the other four variables are 0. About 80% of aquaculture production and 67% of capture production is covered by these data. Values for freshwater fisheries are notably missing altogether, so for these we assume a greenhouse gas emissions equivalent to those of small pelagics ³³ . For each country, total environmental impacts are estimated based on present-day contributions from each species group by volume ⁶⁴ .
--	--	--	--	---	------	----	---	--

SI Table 8 – Vulnerability variables. Outcomes: NH = nutrition & health; EC = economic; SO = social; EN = environmental.

Indicator variable	Outcome				Year	Source	Resolution	Description
	NH	EC	SO	EN				
GDP per capita (PPP) in 2017 USD		o		o	Most recent	63	National	We use per capita Gross Domestic Product (based on purchasing power parity) as a measure of ability to buffer economic shocks as well as to prioritize environmental sustainability in production and consumption, where higher values mean lower vulnerability. We use the most recently available data for each country, expressed in 2017 USD ⁶³ .
% of population below national poverty line	o		o		Most recent	63	National	Poverty is associated with reduced access to healthy and nutritious foods ¹²⁴ and higher vulnerability to loss of employment. We therefore use the proportion of a country that is below the national poverty line as a vulnerability metric for nutrition and health and social outcomes, where higher values mean higher vulnerability. We use the most recently available data for each country ⁶³ .
GINI coefficient		o	o	o	Most recent	63	National	As a metric of how equally the economic, social and environmental outcomes of aquatic food systems and disruptions in those are distributed amongst the population, we use the most recently available values of the GINI coefficient ⁶³ . Higher values mean higher vulnerability.
% of population 15 years and older with bank account		o	o		2017	71	National	We use the proportion of a country's population that has a bank account as a measure of access to financial services and economic inclusivity, where a higher percentage means lower vulnerability to loss of economic and social benefits from aquatic food systems. Data are derived from the Global Findex Database, most recently available for 2017 ⁷¹ .
R&D expenditures relative to GDP		o		o	Most recent	63	National	The percentage of GDP in each country that is spent on research and development is used as a proxy for access to technology and technical capacity, which contributes to economic growth and sustainable development. Higher values mean lower vulnerability. We use the most recently available data for each country ⁶³ .

Average of Worldwide Governance Indicators		o	o	o	2018	⁶⁹	National	Strong governance is associated with enhanced ability to respond to and anticipate disruptions in economic, social and environmental outcomes. We use the average for 2018 across the six Worldwide Governance Indicators ⁶⁹ – Voice and Accountability; Political Stability; Government Effectiveness; Regulatory Quality; Rule of Law; and Control of Corruption – where higher values mean lower vulnerability.
% educational attainment, secondary	o		o		Average 2000-2018	⁷⁰	National	Higher educational attainment, in particular attainment of secondary education ⁷⁰ , is associated with improved nutritional outcomes ¹²⁵ and higher labor mobility. We use average values from 2000 to 2018.
% stunted children under 5	o				Average 2000-2019	⁷³	National	As a measure of malnutrition, and therefore the relative importance of the nutritional contributions of aquatic foods, we use the stunting rate in children under five years of age ⁷³ , where higher values mean higher vulnerability. We use the average from 2000 to 2019.
Summary Exposure Value – Vitamin-B12, Omega-3 fatty acids	o				2017	⁹	National	Summary Exposure Values provide an estimate of what percentage of the population consumes insufficient amounts of specific nutrients. Here we use Summary Exposure Values of Vitamin-B12 and Omega-3 fatty acids ⁹ – nutrients to which aquatic foods contribute substantially – as a measure of the critical importance of aquatic foods, where high values imply high vulnerability. We use aggregate values across age groups and sexes for 2017.
EPI – Biodiversity & Habitat; Fisheries; and Climate Change				o	2020	⁷⁴	National	The Environmental Performance Index ⁷⁴ provides an assessment of key aspects of environmental health and sustainability. It is comprised of several sub-indices that assess a suite of environmental health dimensions. Here we use the Biodiversity & Habitat index as a measure of how well countries are protecting natural ecosystems; the Fisheries index as a measure of the state and sustainability of marine fish stocks; and the Climate Change index as a measure of the action countries are taking towards reducing greenhouse gas emissions. Values were published in 2020. A higher score on each of the indices means lower environmental vulnerability.
% of landings from small-scale operations		o	o	o	Average 2012-2016	⁷²	National	Supply chains with a higher number of small-scale actors might be more vulnerable to economic shocks, more directly experience social impacts, and have lower capacity to implement sustainable

								production practices ³¹ . We therefore use the proportion of landings from small-scale marine fishery operations ⁷² as a measure for economic, social and environmental vulnerability, with higher values indicating higher vulnerability. We average over the last five years of available data, from 2012 to 2016.
--	--	--	--	--	--	--	--	--

SI Table 9 – Fuzzy logic membership function limits for each of the indicator variables. The values in the table correspond to the minimum and maximum extent of each membership function as illustrated in SI Fig. 1.

Variable	Unit	Low	Medium	High	Very High
<i>Hazard</i>					
Change in marine catch potential	%	$-20 < x$	$-50 < x < 0$	$-80 < x < -20$	$-50 > x$
Change in mariculture yield potential	%	$-20 < x$	$-50 < x < 0$	$-80 < x < -20$	$-50 > x$
Change in pH	σ (1991-2010)	$-2 < x$	$-3 < x < -1$	$-4 < x < -2$	$-3 > x$
Change in sea ice extent	% of total area	$-10 < x$	$-15 < x < -2$	$-20 < x < -10$	$-15 > x$
Change in cumulative marine heatwave intensity	$^{\circ}\text{C day}$	$50 > x$	$20 < x < 100$	$50 < x < 400$	$100 < x$
Exposure to cyclone impacts	scale 1-10	$3 > x$	$1 < x < 6$	$3 < x < 8$	$6 < x$
Population inundated by sea level rise	%	$0.5 > x$	$0.1 < x < 5$	$0.5 < x < 15$	$5 < x$
Change in atmospheric temperature	σ (1991-2010)	$3 > x$	$2 < x < 4$	$3 < x < 5$	$4 < x$
Change in freshwater balance	σ (1991-2010)	$-0.5 < x$	$-1 < x < 0$	$-2 < x < -0.5$	$-1 > x$
Change in global fishmeal availability	σ (1996-2015)	$-1.25 < x$	$-1.5 < x < -1$	$-1.75 < x < -1.25$	$-1.5 > x$
Change in global mean cropland temperature	σ (1991-2010)	$3 > x$	$2 < x < 4$	$3 < x < 5$	$4 < x$
<i>Exposure</i>					
Aquatic food consumption, marine	kg / cap / year	$10 > x$	$5 < x < 20$	$10 < x < 40$	$20 < x$
Aquatic food consumption, freshwater	kg / cap / year	$1.5 > x$	$1 < x < 5$	$1.5 < x < 10$	$5 < x$
Vitamin B-12 consumption from aquatic foods	%	$0.2 > x$	$0.05 < x < 0.35$	$0.2 < x < 0.5$	$0.35 < x$
Omega-3 consumption from aquatic foods	%	$0.2 > x$	$0.05 < x < 0.35$	$0.2 < x < 0.5$	$0.35 < x$
Aquaculture production value	% GDP	$0.1 > x$	$0.05 < x < 0.5$	$0.1 < x < 1$	$0.5 < x$
Marine fisheries production value	% GDP	$1 > x$	$0.25 < x < 2.5$	$1 < x < 7.5$	$2.5 < x$
Inland fisheries production value	% AgFF GDP	$0.5 > x$	$0.1 < x < 1$	$0.5 < x < 5$	$1 < x$
Economic multiplier for fisheries	-	$2 > x$	$1 < x < 3$	$2 < x < 5$	$3 < x$
Value of net trade balance	% GDP	$0.2 > x$	$0 < x < 0.5$	$0.2 < x < 4$	$0.5 < x$

Marine fisheries jobs	per cap	$0.01 > x$	$0.001 < x < 0.025$	$0.01 < x < 0.1$	$0.025 < x$
Aquaculture jobs	per cap	$0.0005 > x$	$0.0001 < x < 0.001$	$0.0005 < x < 0.005$	$0.001 < x$
Inland fisheries jobs	per cap	$0.001 > x$	$0.0001 < x < 0.005$	$0.001 < x < 0.025$	$0.005 < x$
Ratio of indigenous to national average seafood consumption	-	$4 > x$	$1.2 < x < 10$	$4 < x < 40$	$10 < x$
Environmental impact – GHG emissions	kg CO ₂ -eq / tonne	$2500 > x$	$1500 < x < 3500$	$2500 < x < 4500$	$3500 < x$
Environmental impact – Nitrogen emissions	kg N / tonne	$0.2 > x$	$0 < x < 5$	$0.2 < x < 40$	$5 < x$
Environmental impact – Phosphorus emissions	kg P / tonne	$0.02 > x$	$0 < x < 0.7$	$0.02 < x < 6$	$0.7 < x$
Environmental impact – land use	m ² / tonne	$30 > x$	$0 < x < 400$	$30 < x < 3000$	$400 < x$
Environmental impact – freshwater use	m ³ / tonne	$1 > x$	$0 < x < 15$	$1 < x < 150$	$15 < x$
<i>Vulnerability</i>					
GDP per capita in PPP	2017 USD	$35000 < x$	$25000 < x < 50000$	$15000 < x < 35000$	$25000 > x$
Population below national poverty line	%	$20 > x$	$5 < x < 40$	$20 < x < 60$	$40 < x$
GINI coefficient	-	$40 > x$	$30 < x < 40$	$40 < x < 55$	$45 < x$
Governance index	-	$0.5 < x$	$-0.5 < x < 1$	$-1.5 < x < 0.5$	$-0.5 > x$
Population that completed secondary education	%	$60 < x$	$40 < x < 75$	$20 < x < 60$	$40 > x$
Stunting rate in children under 5	%	$20 > x$	$5 < x < 30$	$20 < x < 40$	$30 < x$
Summary Exposure Value for vitamin B-12	%	$5 > x$	$1 < x < 10$	$5 < x < 60$	$10 < x$
Summary Exposure Value for Omega-3	%	$15 > x$	$5 < x < 60$	$15 < x < 80$	$60 < x$
Catch from small-scale fisheries	%	$40 > x$	$15 < x < 70$	$40 < x < 90$	$70 < x$
Access to financial accounts	%	$60 < x$	$40 < x < 85$	$25 < x < 60$	$40 > x$
R&D expenditure	% GDP	$0.5 < x$	$0.25 < x < 1.5$	$0.05 < x < 0.5$	$0.25 > x$
Environmental Performance Index: Biodiversity & Habitat	-	$60 < x$	$40 < x < 80$	$20 < x < 60$	$40 > x$
Environmental Performance Index: Fisheries	-	$20 < x$	$10 < x < 50$	$5 < x < 20$	$10 > x$

Environmental Performance Index: Climate Change	-	$50 < x$	$40 < x < 70$	$20 < x < 50$	$40 > x$
--	---	----------	---------------	---------------	----------

SI Table 10 – Statistical distribution of each of the indicator variables. For the hazard variables, ‘nobs’ indicates the number of values available for each of the two emissions scenarios and three time periods. All other statistical measures are across scenarios and periods.

Variable	Unit	Mean	Min	Max	5 th	25 th	50 th	75 th	95 th	nobs
Hazard										
Change in marine catch potential	%	-6.05	-100.00	197.69	-43.10	-13.28	-3.97	2.00	18.90	254
Change in mariculture yield potential	%	28.83	-100.00	200.00	-76.46	-32.91	17.56	77.27	200.00	74
Change in surface pH	σ (1991-2010)	-7.44	-33.42	-0.07	-25.00	-8.13	-5.02	-3.65	-1.18	260
Change in bottom pH	σ (1991-2010)	-1.95	-30.36	0.44	-8.38	-2.08	-0.47	-0.12	-0.03	260
Change in sea ice extent	% of total area	-6.62	-35.41	0.33	-17.32	-8.70	-4.79	-2.11	-0.84	21
Change in cumulative marine heatwave intensity	°C day	87.47	-3.31	3222.43	9.42	21.67	36.61	84.01	344.32	256
Exposure to cyclone impacts	scale 1-10	0.97	0.00	9.22	0.00	0.00	0.00	0.32	6.53	230
Population inundated by sea level rise	%	2.93	0.00	70.83	0.00	0.00	0.19	1.25	17.57	227
Change in atmospheric temperature	σ (1991-2010)	3.63	0.59	14.13	1.26	1.91	2.43	3.85	10.45	179
Change in freshwater balance	σ (1991-2010)	-0.06	-3.43	3.80	-1.04	-0.35	-0.05	0.23	0.83	179
Change in global fishmeal availability	σ (1996-2015)	-1.36	-1.81	-1.14	only one value for each scenario & period					1
Change in global mean cropland temperature	σ (1991-2010)	5.43	2.72	13.92	only one value for each scenario & period					1
Exposure										
Aquatic food consumption, marine	kg / cap / year	16.92	0.00	116.85	0.52	4.07	12.81	22.02	49.65	191
Aquatic food consumption, freshwater	kg / cap / year	3.59	0.01	33.35	0.08	0.67	1.47	4.19	15.41	191
Vitamin B-12 consumption from aquatic foods	%	0.16	0.01	0.76	0.02	0.06	0.15	0.20	0.39	163
Omega-3 consumption from aquatic foods	%	0.28	0.02	0.82	0.04	0.11	0.31	0.37	0.62	163
Aquaculture production value	% GDP	0.33	0.00	17.64	0.00	0.01	0.03	0.12	1.13	172
Marine fisheries production value	% GDP	2.55	0.00	30.00	0.00	0.23	1.22	2.93	8.86	130
Inland fisheries production value	% AgFF GDP	1.04	0.00	25.87	0.00	0.00	0.07	0.71	4.87	187

Economic multiplier for fisheries	-	2.55	0.28	18.34	1.02	1.22	2.49	3.34	4.30	183
Value of net trade balance	% GDP	1.01	-0.64	30.47	-0.38	-0.15	-0.02	0.18	4.44	174
Marine fisheries jobs	per cap	0.030	0.000	0.224	0.001	0.003	0.008	0.025	0.169	134
Aquaculture jobs	per cap	0.002	0.000	0.044	0.000	0.000	0.000	0.001	0.008	164
Inland fisheries jobs	per cap	0.009	0.000	0.276	0.000	0.000	0.001	0.005	0.045	115
Ratio of indigenous to national average seafood consumption	-	12.3	0.5	153.4	1.1	2.3	4.1	10.5	50.7	74
Environmental impact – GHG emissions	kg CO ₂ -eq / tonne	3087.0	0.0	8274.1	1323.3	2279.1	3083.8	3854.1	5169.0	233
Environmental impact – Nitrogen emissions	kg N / tonne	11.4	-22.3	75.0	-1.1	0.0	1.3	16.4	56.6	233
Environmental impact – Phosphorus emissions	kg P / tonne	1.6	-15.8	13.3	-0.6	0.0	0.1	3.3	9.3	233
Environmental impact – land use	m ² / tonne	946.2	0.0	6088.6	0.0	5.9	118.2	1421.2	4244.3	233
Environmental impact – freshwater use	m ³ / tonne	40.9	0.0	414.1	0.0	0.1	4.3	43.3	215.3	233
<i>Vulnerability</i>										
GDP per capita in PPP	2017 USD	21706	752	123965	1682	5170	14404	31858	62313	191
Population below national poverty line	%	27.8	0.6	82.3	5.9	15.5	23.0	39.1	60.2	154
GINI coefficient	-	38.2	24.2	63.0	27.0	32.8	37.0	42.9	53.4	159
Governance index	-	0.0	-2.1	1.8	-1.6	-0.6	-0.1	0.6	1.6	196
Population that completed secondary education	%	48.0	1.3	95.4	6.2	17.9	50.9	79.7	92.1	155
Stunting rate in children under 5	%	24.2	1.5	57.9	3.2	11.2	24.0	34.8	46.6	145
Summary Exposure Value for vitamin B-12	%	31.7	0.0	93.8	0.0	5.6	18.1	59.3	84.7	164
Summary Exposure Value for Omega-3	%	10.3	0.0	75.8	0.0	0.0	0.2	10.6	58.8	164
Catch from small-scale fisheries	%	52.2	0.0	100.0	2.2	17.1	48.0	93.0	100.0	189
Access to financial accounts	%	61.4	8.6	99.9	21.3	40.0	58.7	86.4	99.2	143
R&D expenditure	% GDP	0.8	0.0	5.0	0.0	0.2	0.4	1.0	3.0	149

Environmental Performance Index: Biodiversity & Habitat	-	57.6	6.5	91.6	19.2	39.0	60.5	75.9	87.4	180
Environmental Performance Index: Fisheries	-	16.1	0.0	71.4	5.2	9.1	12.8	17.0	46.7	136
Environmental Performance Index: Climate Change	-	49.8	12.1	95.0	23.3	36.9	50.9	63.2	76.3	180

SI Table 11 | Overview table of climate change impact pathways and supporting literature. Summary of climate drivers and associated impacts on blue food production systems and supply chain components. Legend for degree of confidence regarding impact: * indicates limited supporting research, ** indicates medium supporting research, and *** indicates robust supporting research. Legend for direction of impact: blank cells indicate no impact, blue cells indicate a positive impact, orange cells indicate a negative impact, and blue/orange striped cells indicate varied positive and negative impacts; in supply chain components columns, X indicates impact present and a blank cell indicates no impact present.

Climate Driver	Climate Impact	Production System												Supply Chain							Key References	
		Wild-Caught Fisheries							Aquaculture					Input supply	Production	Postharvest storage	Processing	Distribution	Marketing & Retail	Consumption & Utilization		
		Pelagic	Benthic	Coastal	Reef	Shellfish	Freshwater	Brackish	Marine			Brackish	Freshwater									
									Finfish	Shellfish	Algae		Land-Based									In Situ
First-Order Impacts																						
Rising Temperatures	Change in species density/abundance (<i>High latitudes</i>)	***					***	*						***		X						2,17,126–132
	Change in species density/abundance (<i>Low latitudes</i>)	***	***	***	***	***	***			**				*		X						2,17,126–129,131,132
	Change in base of aquatic food webs & phenology & net primary production	***		***	***					*	*			*	X	X						131,133–136
	Coral bleaching				***											X						2,134,137,138
	Change in functional diversity	*	*	*			*									X						139,140
	Harmful algal blooms, incl. sargassum (leads to mortality, toxicity, reduced quality)			***	***	***	***		***	***				*	***	X	X			X	X	2,23,131,132,141,142
	Increased stratification	**	**	**										*		X						127,131,143–145
	Life cycle changes (increased growth rate, changes in breeding season length, mortality in juveniles, etc.)	***		***			*		***	***		*		***	X	X						1,17,23,82,127,128,131,132,146
	Marine heatwaves (mass mortality, disease, etc.)	***	*	***	***		***	*	***	**	**	**		**		X						2,17,82,127,130,131,134,147,148
	Migration of non-native species increasing competition	***	***	***			*	*						*		X						131,140,144
	Shift in species distribution (<i>High latitudes</i>)	***	***	***			***	*						**		X						1,2,17,130–132,134,136
	Shift in species distribution (<i>Low latitudes</i>)	***	***	***	***		***							**		X						1,2,17,131,132,134,136
	Shift in suitable habitat and/or climate	***		***	***		***	*					**	*		X						2,126,130–132,134,139
	Spread of disease			*			*			*			*	**		X				X		17,131
Sea Level Rise	Coastal erosion			***		***			***	***	*	***	***			X	X	X	X			2,17,83,131
	Destruction of coastal infrastructure			***			***		***			***	***	X		X	X	X		X		2,17,82,83
	Destruction of mangroves, reefs, and seagrass beds			**	**	**			**	**				X	X						2,17	
	Saltwater intrusion						*					*		*		X					131,149–151	
	Storm surge			*			*	*	**	**		*		*								114,150
Ocean Acidification	Impaired/slower growth rates in shell-bearing organisms and corals			***	***	***			***	***						X				X	X	2,17,114,137,152
	Impaired growth in some marine finfish, especially embryonic and larval stages	*	*	*	*				*							X						1,17

Reduction in Dissolved Oxygen	Higher sensitivity to other drivers	***	***	***		***	***		***					***		X						2,17,131
	Hypoxia	***	***	**		***	***	*	**			*		***		X						2,17,130–132,139
	More frequent mortality events								*					*		X						17,131
Sea Ice Loss	Coastal erosion			*									*				X	X	X			114
	Mortality	**	**	**			**									X						2,142,153,154
	Shift in species abundance due to expansion OR loss of suitable habitat	**		**												X						2,114,129,153
	Shift in species distribution	**	**	**												X						2,114,129,153
Changes in Ocean Currents	Changes in migration patterns	*		*												X						155
	Shift it species density	**		**		**										X						155,156
Increased Hurricanes and Cyclones	Changes in inland water salinity					**							**	**		X						17,82,131,148
	Coastal erosion			**													X	X	X			2,82,83
	Destruction of coastal infrastructure & equipment			***		***	*	***	***		*	***	***			X	X	X	X		X	17,82,83,86,132,148,157,158
	Destruction of mangroves, reefs, and seagrass beds			**	**										X	X						2,17,137
	Escapes from aquaculture and introduction of disease/predators to aquaculture systems			*		*		**			*	**	**	X	X					X		17,23,82,132
Changes in Hydrological Cycle	Changes in lake and river volume and seasonality			***		***	*				*		***	X	X	X						2,17,82,83,131,132,136
	Changing ocean/brackish salinity			*	*	*		*	*	*	*				X							130
	Competition for water resources			**		***						**	**		X	X	X					17,82,131,132,147
	Flood-associated risks and mortality			**	**	**	***		**	**	**	**	***	X	X	X	X					17,83,131,132,146,148,157
	Increased drought					**	***				*	**	**		X							82,131,132,148,159
	Increased run-off & changes in water quality during extreme precipitation events			*	*	*	*	**	*	*	**		**		X					X		17,130,131,146,148
	Shifts in species distribution/abundance	*		*	*	*	*				*		*		X							2,130,131
Second-Order Impacts																						
Multiple climate drivers	Occupational health risks	*	*	**		**	**		**			**	**		X	X	X	X				85,87,160,161
Multiple climate drivers	Nutrition-related health risks			**	**	**	**	*	**		*		**							X		131,162–164
Multiple climate drivers	Aquaculture feed risks via terrestrial crop systems							**			*	**	*	X	X	X	X	X				4,19,48,165–168
Unintended consequences of adaptation/mitigation measures				***		**	***					**	***		X		X			X		54,131,169–171
Interaction with other anthropogenic drivers such as overfishing, pollution, etc.		***		***	***	***	***	**	***	***	***	**	***	***	X		X					2,54,128,129,131,138,153,154,172

SI Table 12 | Impacts of vulnerability reduction and climate mitigation on overall climate risk. Median change in climate risk by cluster and time period for each of the sensitivity runs under SSP5-8.5 (see Supplemental Methods) and climate mitigation (SSP1-2.6 – SSP5-8.5).

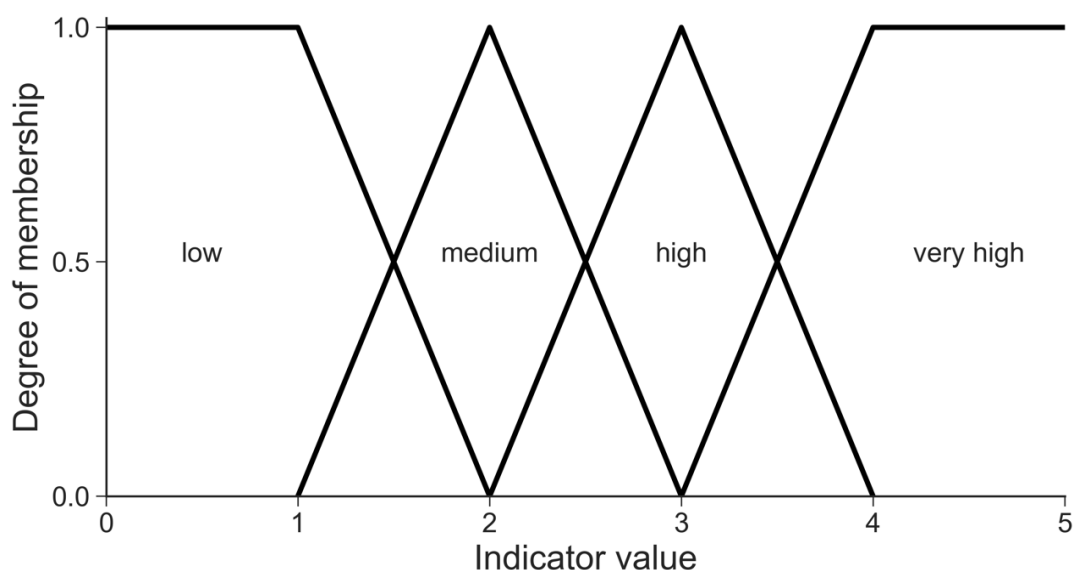
		2030				2050				2090			
		Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 1	Cluster 2	Cluster 3	Cluster 4
nutrition & health	economic growth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	economic inclusion	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	social fabric	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	food security	-11.2	0.0	-0.2	0.0	-11.2	0.0	-0.4	0.0	-9.5	0.0	-0.1	-0.7
	environmental mgmt.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	all vulnerability	-16.9	-6.0	-14.5	-5.7	-16.7	-8.7	-10.7	-5.5	-11.3	-8.4	-9.5	-4.6
	mitigation	0.0	-0.7	-0.5	0.0	-8.5	-11.7	-10.2	-3.7	-18.7	-18.9	-17.5	-21.8
economic	economic growth	0.0	-11.0	0.0	-2.6	0.0	-9.5	0.0	-1.7	0.0	-8.0	0.0	-5.8
	economic inclusion	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	social fabric	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	food security	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	environmental mgmt.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	all vulnerability	-12.3	-14.2	-7.6	-15.6	-10.7	-12.0	-7.6	-14.6	-9.4	-11.7	-4.7	-12.8
	mitigation	0.0	-0.8	-0.8	0.0	-8.0	-10.0	-10.6	-1.4	-18.7	-18.3	-18.2	-22.9
social	economic growth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	economic inclusion	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	social fabric	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	food security	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	environmental mgmt.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	all vulnerability	-10.5	-12.0	-11.8	-12.0	-9.8	-11.4	-9.6	-13.0	-7.2	-9.6	-8.6	-10.8
	mitigation	0.0	-0.7	-0.4	0.0	-7.8	-11.1	-10.8	-2.7	-14.5	-18.8	-16.3	-20.7
environmental	economic growth	0.0	-2.4	-3.9	-0.8	0.0	-2.4	-4.1	-0.8	0.0	-2.4	-4.2	-0.8
	economic inclusion	0.0	0.0	-1.6	0.0	0.0	0.0	-1.6	0.0	0.0	0.0	-1.6	0.0
	social fabric	0.0	0.0	-2.2	0.0	0.0	0.0	-2.2	0.0	0.0	0.0	-2.2	0.0
	food security	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	environmental mgmt.	0.0	0.0	-2.8	0.0	0.0	0.0	-2.8	0.0	0.0	0.0	-2.8	0.0
	all vulnerability	-13.6	-17.8	-19.0	-9.9	-13.4	-17.8	-19.0	-9.9	-13.4	-17.6	-19.0	-9.9
	mitigation	0.0	0.0	0.0	-0.1	-0.4	0.0	-0.2	-0.4	-0.4	0.0	-0.2	-0.5

SI Table 13 – Median and mean values of input variables for each of the four risk profile clusters. The variables used in the cluster analysis are the number of outcomes for which climate risk in 2050 is ‘high’ or ‘very high’ under SSP5-8.5 (‘risk count’); the climate hazard score in 2050 under SSP5-8.5 (‘hazard’); the percentage of production from marine environments (‘perc marine’); the percentage of production from aquaculture (‘perc aqua’); exposure scores for each of the food system outcomes (nutrition & health, economic, social, and environmental – ‘exp_nh’, ‘exp_ec’, ‘exp_so’ and ‘exp_en’); and vulnerability scores for each of the food system outcomes (‘vul_nh’, ‘vul_ec’, ‘vul_so’ and ‘vul_en’).

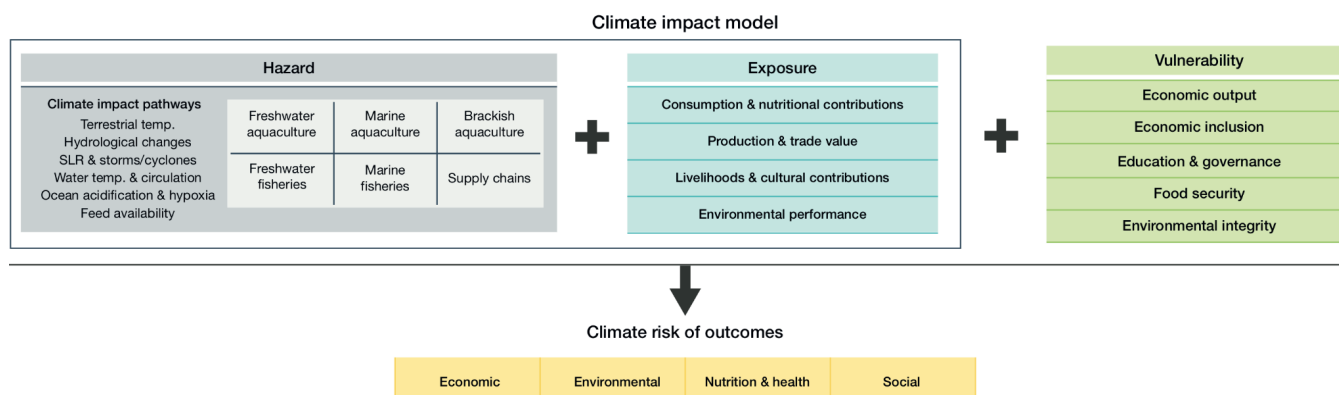
cluster	risk count	hazard	perc marine	perc aqua	exp_nh	exp_ec	exp_so	exp_en	vul_nh	vul_ec	vul_so	vul_en
<i>median values</i>												
1	3	46.8	0.0	17.3	20.5	38.0	61.8	33.2	72.5	63.4	58.5	57.0
2	2	53.1	95.8	2.5	56.5	40.2	51.4	29.2	32.0	54.0	42.0	52.1
3	3	53.7	91.3	0.2	40.1	39.9	48.6	25.2	73.2	79.0	77.1	69.1
4	1	29.4	0.0	83.5	20.7	1.4	11.8	76.8	25.9	46.1	27.8	45.2
<i>mean values</i>												
1	2.9	47.1	10.8	27.8	26.2	39.4	58.5	33.9	68.3	63.4	59.9	58.2
2	2.1	52.1	88.9	12.3	56.3	43.4	45.2	30.7	31.7	52.3	40.5	51.3
3	3.2	53.3	83.2	7.8	35.6	41.3	47.7	25.3	74.0	79.4	77.9	71.1
4	1.1	32.1	8.0	75.0	24.4	7.8	22.2	71.1	24.4	40.8	26.7	39.3

SI Table 14 – List of countries in each of the four risk profile clusters. The risk profiles for each of the clusters can be described as high dependency on marine fisheries (Cluster 2); compound climate risk from freshwater and brackish systems (Cluster 1); compound climate risk from marine fisheries (Cluster 3); and environmental performance risk from freshwater aquaculture (Cluster 4).

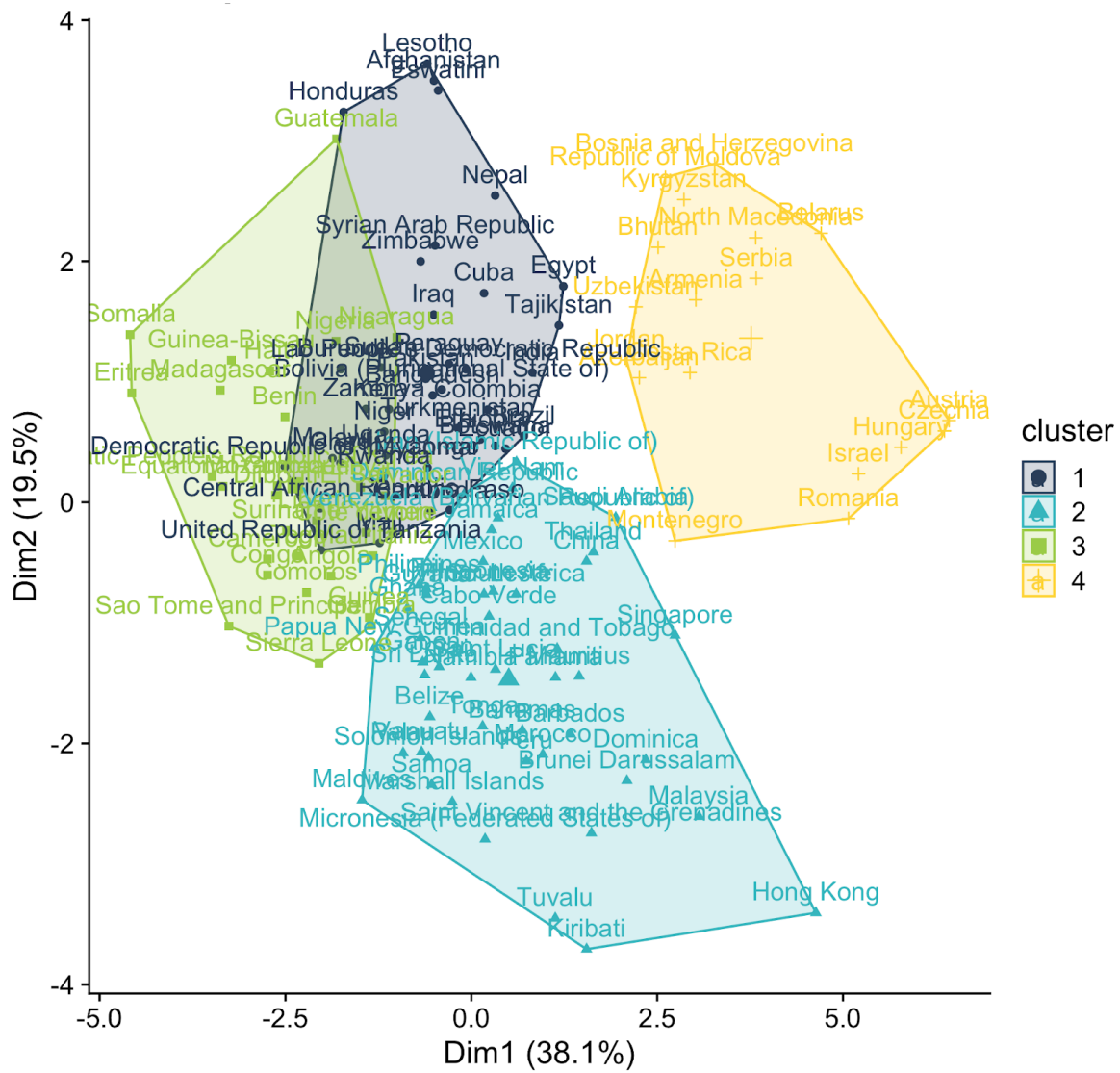
cluster 1	cluster 2	cluster 3	cluster 4
Afghanistan	Bahamas	Angola	Armenia
Bangladesh	Barbados	Benin	Austria
Bolivia	Belize	Cameroon	Azerbaijan
Botswana	Brunei Darussalam	Comoros	Belarus
Brazil	Cabo Verde	Congo	Bhutan
Burkina Faso	China	Côte d'Ivoire	Bosnia and Herzegovina
Burundi	Dominica	DPR of Korea	Costa Rica
Cambodia	Dominican Republic	Djibouti	Czech Republic
Central African Republic	Fiji	El Salvador	Hungary
Chad	Gabon	Equatorial Guinea	Israel
Colombia	Ghana	Eritrea	Jordan
Cuba	Guyana	Gambia	Kyrgyzstan
DR of the Congo	Hong Kong	Guatemala	Montenegro
Ecuador	Indonesia	Guinea	North Macedonia
Egypt	Iran (Islamic Republic of)	Guinea-Bissau	Republic of Moldova
Eswatini	Jamaica	Haiti	Romania
Ethiopia	Kiribati	Liberia	Republic of Serbia
Honduras	Malaysia	Libya	Uzbekistan
India	Maldives	Madagascar	
Iraq	Marshall Islands	Mauritania	
Kenya	Mauritius	Mozambique	
Lao PDR	Mexico	Nicaragua	
Lesotho	Federated States of Micronesia	Nigeria	
Malawi	Morocco	São Tomé and Príncipe	
Mali	Namibia	Sierra Leone	
Myanmar	Oman	Somalia	
Nepal	Palau	Suriname	
Niger	Panama	Togo	
Pakistan	Papua New Guinea	Yemen	
Paraguay	Peru		
Rwanda	Philippines		
Sudan	Saint Lucia		
Syrian Arab Republic	St Vincent & the Grenadines		
Tajikistan	Samoa		
Turkmenistan	Saudi Arabia		
Uganda	Senegal		
Tanzania	Singapore		
Zambia	Solomon Islands		
Zimbabwe	South Africa		
	Sri Lanka		
	Thailand		
	Timor-Leste		
	Tonga		
	Trinidad and Tobago		
	Tuvalu		
	Vanuatu		
	Venezuela		
	Viet Nam		



SI Fig. 1 – Schematic of fuzzy logic membership functions and categories. For a hypothetical variable with values ranging from 0 to 5, the schematic shows how membership to the categories ‘low’, ‘medium’, ‘high’, and ‘very high’ is assigned based on user-defined membership functions. The values listed in SI Table 5 indicate the minimum and maximum limits of each of the membership functions.



SI Fig. 2 | Schematic of fuzzy logic model structure. We first calculate hazard scores for each of the aquatic food system components (marine and freshwater fisheries; marine, freshwater and brackish aquaculture; supply chains) using a number of different environmental variables (SI Table 6). Together with exposure scores for each of the four food system outcomes (variables in SI Table 7), we combine this into an ‘exposure to hazard’ score, which ultimately is combined with vulnerability variables (SI Table 8) into climate risk scores for each food system outcome. See Methods and SI for details.



SI Fig. 3 – Distribution of clusters for the first two Principal Components of the K-means clustering output. Results were created using the `fviz_cluster()` function in the *factoextra* package in *R*^{173,174}.

References

1. *Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options*. vol. 627 (FAO, 2019).
2. IPCC. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. (2019).
3. Fanzo, J., Davis, C., McLaren, R. & Choufani, J. The effect of climate change across food systems: Implications for nutrition outcomes. *Global Food Security* **18**, 12–19 (2018).
4. Myers, S. S. *et al.* Climate change and global food systems: Potential impacts on food security and undernutrition. *Annual Reviews of Public Health* **38**, 259–277 (2017).
5. Teh, L. C. L. & Sumaila, U. R. Contribution of marine fisheries to worldwide employment: Global marine fisheries employment. *Fish. Fish.* **14**, 77–88 (2013).
6. Selig, E. R. *et al.* Mapping global human dependence on marine ecosystems. *Conservation Letters* **309**, e12617 (2018).
7. FAO. *The State of World Fisheries and Aquaculture 2020. Sustainability in Action*. <http://www.fao.org/3/ca9229en/ca9229en.pdf> (2020) doi:10.4060/ca9229en.
8. Bennett, A. *et al.* *Contribution of fisheries to food and nutrition security: Current knowledge, policy, and research*. (2018).
9. Golden, C. D. *et al.* Aquatic foods to nourish nations. *Nature* (accepted).
10. Cheung, W. W. L. *et al.* Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Glob. Chang. Biol.* **16**, 24–35 (2010).
11. HLPE. *Nutrition and food systems*. (2017).
12. Hicks, C. C. *et al.* Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* **574**, 95–98 (2019).
13. Österblom, H. *et al.* *Towards ocean equity*. <https://digitalarchive.worldfishcenter.org/bitstream/handle/20.500.12348/4486/71d48a67e55853a80e461c0ba5529caf.pdf> (2020).
14. HLPE. *Sustainable fisheries and aquaculture for food security and nutrition*. <http://www.fao.org/3/a-i3844e.pdf> (2014).
15. Farmery, A. K. *et al.* Blind spots in visions of a 'blue economy' could undermine the ocean's contribution to eliminating hunger and malnutrition. *One Earth* **4**, 28–38 (2021).
16. United Nations. *Transforming our world: the 2030 Agenda for Sustainable Development*. (2015).
17. Reid, G. K. *et al.* Climate change and aquaculture: considering biological response and resources. *Aquacult. Environ. Interact.* **11**, 569–602 (2019).
18. Myers, B. J. E. *et al.* Global synthesis of the documented and projected effects of climate change on inland fishes. *Rev. Fish Biol. Fish.* **27**, 339–361 (2017).
19. Froehlich, H. E., Runge, C. A., Gentry, R. R., Gaines, S. D. & Halpern, B. S. Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 5295–5300 (2018).
20. Cheung, W. W. L., Pitcher, T. J. & Pauly, D. A fuzzy logic expert system to estimate intrinsic extinction vulnerabilities of marine fishes to fishing. *Biol. Conserv.* **124**, 97–111 (2005).
21. Halpern, B. S. *et al.* Opinion: Putting all foods on the same table: Achieving sustainable food systems requires full accounting. *Proc. Natl. Acad. Sci. U. S. A.* **116**, 18152–18156 (2019).
22. Froehlich, H. E., Gentry, R. R. & Halpern, B. S. Global change in marine aquaculture production potential under climate change. *Nat. Ecol. Evol.* **2**, 1745–1750 (2018).
23. Brown, A. R. *et al.* Assessing risks and mitigating impacts of harmful algal blooms on mariculture and marine fisheries. *Rev. Aquac.* (2019) doi:10.1111/raq.12403.
24. Battisti, D. S. & Naylor, R. L. Historical warnings of future food insecurity with unprecedented

- seasonal heat. *Science* **323**, 240–244 (2009).
25. Funge-Smith, S. *Review of the state of the world fishery resources: Inland fisheries*. <http://www.fao.org/3/ca0388en/CA0388EN.pdf> (2018).
 26. Gentry, R. R. *et al.* Mapping the global potential for marine aquaculture. *Nat Ecol Evol* **1**, 1317–1324 (2017).
 27. Reid, G. K. *et al.* Climate change and aquaculture: considering adaptation potential. *Aquacult. Environ. Interact.* **11**, 603–624 (2019).
 28. Belton, B. *et al.* Farming fish in the sea will not nourish the world. *Nat. Commun.* **11**, 5804 (2020).
 29. Gattuso, J.-P. *et al.* Ocean solutions to address climate change and its effects on marine ecosystems. *Frontiers in Marine Science* **5**, 337 (2018).
 30. Ojea, E., Lester, S. E. & Salgueiro-Otero, D. Adaptation of fishing communities to climate-driven shifts in target species. *One Earth* **2**, 544–556 (2020).
 31. The World Bank. *Hidden harvest: The global contribution of capture fisheries*. <http://documents1.worldbank.org/curated/en/515701468152718292/pdf/664690ESW0P1210120HiddenHarvest0web.pdf> (2012).
 32. Tigchelaar, M., Battisti, D. S., Naylor, R. L. & Ray, D. K. Future warming increases probability of globally synchronized maize production shocks. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 6644–6649 (2018).
 33. Gephart, J. A. *et al.* Environmental performance of blue foods. *Nature* (accepted).
 34. Phillips, C. A. *et al.* Compound climate risks in the COVID-19 pandemic. *Nat. Clim. Chang.* **10**, 586–588 (2020).
 35. Cutter, S. L. The changing nature of hazard and disaster risk in the Anthropocene. *Ann. Assoc. Am. Geogr.* 1–9 (2020).
 36. Tendall, D. M. *et al.* Food system resilience: Defining the concept. *Global Food Security* **6**, 17–23 (2015).
 37. Lebel, L. *et al.* Innovation, practice, and adaptation to climate in the aquaculture sector. *Reviews in Fisheries Science & Aquaculture* 1–29 (2021).
 38. Jørstad, H. & Webersik, C. Vulnerability to climate change and adaptation strategies of local communities in Malawi: experiences of women fish-processing groups in the Lake Chilwa Basin. *Earth Syst. Dyn.* **7**, 977–989 (2016).
 39. Heltberg, R., Siegel, P. B. & Jorgensen, S. L. Addressing human vulnerability to climate change: Toward a ‘no-regrets’ approach. *Glob. Environ. Change* **19**, 89–99 (2009).
 40. Cinner, J. E. *et al.* Building adaptive capacity to climate change in tropical coastal communities. *Nat. Clim. Chang.* **8**, 117–123 (2018).
 41. Bell, J. D. *et al.* Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. *Mar. Policy* **51**, 584–591 (2015).
 42. Bennett, A. *et al.* Recognize fish as food in policy discourse and development funding. *Ambio* (2021) doi:10.1007/s13280-020-01451-4.
 43. Oremus, K. L. *et al.* Governance challenges for tropical nations losing fish species due to climate change. *Nature Sustainability* 1–4 (2020).
 44. Roscher, M. *et al.* *Building adaptive capacity to climate change: approaches applied in five diverse fisheries settings*. <https://digitalarchive.worldfishcenter.org/bitstream/handle/20.500.12348/2094/FISH-2018-18.pdf?sequence=2&isAllowed=y> (2018).
 45. Belton, B., Reardon, T. & Zilberman, D. Sustainable commoditization of seafood. *Nature Sustainability* (2020) doi:10.1038/s41893-020-0540-7.
 46. Thomas, K. *et al.* Explaining differential vulnerability to climate change: A social science review. *Wiley Interdiscip. Rev. Clim. Change* **10**, e565 (2019).
 47. Adger, W. N., Brown, K., Butler, C. & Quinn, T. Social ecological dynamics of catchment resilience.

- Water* **13**, 349 (2021).
48. Troell, M. *et al.* Does aquaculture add resilience to the global food system? *Proc. Natl. Acad. Sci.* **111**, 13257–13263 (2014).
 49. Davis, K. F., Downs, S. & Gephart, J. A. Towards food supply chain resilience to environmental shocks. *Nature Food* **2**, 54–65 (2021).
 50. Monnereau, I. *et al.* The impact of methodological choices on the outcome of national-level climate change vulnerability assessments: An example from the global fisheries sector. *Fish. Fish.* **18**, 717–731 (2017).
 51. Fluet-Chouinard, E., Funge-Smith, S. & McIntyre, P. B. Global hidden harvest of freshwater fish revealed by household surveys. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 7623–7628 (2018).
 52. Maury, O. *et al.* From shared socio-economic pathways (SSPs) to oceanic system pathways (OSPs): Building policy-relevant scenarios for global oceanic ecosystems and fisheries. *Glob. Environ. Change* **45**, 203–216 (2017).
 53. Gephart, J. A., Rovenskaya, E., Dieckmann, U., Pace, M. L. & Brännström, Å. Vulnerability to shocks in the global seafood trade network. *Environ. Res. Lett.* **11**, 035008 (2016).
 54. Daw, T., Adger, W. N., Brown, K. & Badjeck, M.-C. Climate change and capture fisheries: potential impacts, adaptation and mitigation. (2009).
 55. Gaines, S., Cabral, R., Free, C. M., Golbuu, Y. & *et al.* *The Expected Impacts of Climate Change on the Ocean Economy*. (2019).
 56. Cheung, W. W. L. *et al.* Structural uncertainty in projecting global fisheries catches under climate change. *Ecol. Modell.* **325**, 57–66 (2016).
 57. Frölicher, T. L., Fischer, E. M. & Gruber, N. Marine heatwaves under global warming. *Nature* **560**, 360–364 (2018).
 58. Eyring, V. *et al.* Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development* **9**, 1937–1958 (2016).
 59. Dunne, J. P. *et al.* The GFDL earth system model version 4.1 (GFDL-ESM 4.1): Overall coupled model description and simulation characteristics. *J. Adv. Model. Earth Syst.* **12**, (2020).
 60. Boucher, O. *et al.* Presentation and evaluation of the IPSL-CM6A-LR climate model. *J. Adv. Model. Earth Syst.* **12**, (2020).
 61. Gutjahr, O. *et al.* Max Planck Institute Earth system model (MPI-ESM1.2) for the high-resolution model intercomparison project (HighResMIP). *Geosci. Model Dev.* **12**, 3241–3281 (2019).
 62. O'Neill, B. C. *et al.* The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development* **9**, 3461–3482 (2016).
 63. The World Bank. World Development Indicators.
 64. FAO. Fishery and Aquaculture Statistics. Global production by production source 1950-2018 (FishstatJ). *FAO Fisheries Division [online]* (2020).
 65. Dyck, A. J. & Sumaila, U. R. Economic impact of ocean fish populations in the global fishery. *J. Bioecon.* **12**, 227–243 (2010).
 66. FAO. Fishery and Aquaculture Statistics. Global Fisheries commodities production and trade 1976-2018 (FishstatJ). *FAO Fisheries Division [online]* (2020).
 67. FAO. *FAO Yearbook. Fishery and Aquaculture Statistics 2018/FAO annuaire. Statistiques des pêches et de l'aquaculture 2018/FAO anuario. Estadísticas de pesca y acuicultura 2018.* <http://dx.doi.org/10.4060/cb1213t> (2020) doi:10.4060/cb1213t.
 68. Cisneros-Montemayor, A. M., Pauly, D., Weatherdon, L. V. & Ota, Y. A Global Estimate of Seafood Consumption by Coastal Indigenous Peoples. *PLoS One* **11**, e0166681 (2016).
 69. Kaufmann, D. & Kraay, A. Worldwide Governance Indicators. (2018).
 70. United Nations. UN SDG Indicators. (2020).
 71. Demirgüç-Kunt, A., Klapper, L., Singer, D., Ansar, S. & Hess, J. *The Global Findex Database 2017: Measuring financial inclusion and the Fintech revolution.* <http://dx.doi.org/10.1596/978-1-4648-1259->

- 0 (2018) doi:10.1596/978-1-4648-1259-0.
72. Sea Around Us. *Sea Around Us Concepts, Design and Data* (seararoundus.org). (2020).
 73. Food and Agriculture Organization of the United Nations. FAOSTAT Database. (2019).
 74. Wendling, Z. A., Emerson, J. W., de Sherbinin, A., Esty, D. C. & et al. *2020 Environmental Performance Index*. <http://epi.yale.edu> (2020).
 75. Cheung, W. W. L., Jones, M. C., Reygondeau, G. & Frölicher, T. L. Opportunities for climate-risk reduction through effective fisheries management. *Glob. Chang. Biol.* **24**, 5149–5163 (2018).
 76. Jones, M. C. & Cheung, W. W. L. Using fuzzy logic to determine the vulnerability of marine species to climate change. *Glob. Chang. Biol.* **24**, e719–e731 (2018).
 77. Tigchelaar, M. *et al.* Projected climate risk of aquatic food system benefits. *Dryad* (2021) doi:10.5061/dryad.70rxwdbz3.
 78. United Nations. *World Economic Situation and Prospects 2020 – Statistical Annex*. https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/WESP2020_Annex.pdf (2020).
 79. IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC, 2014).
 80. IPCC. *Managing the risks of extreme events and disasters to advance climate change adaptation*. (Cambridge University Press, 2012).
 81. Ericksen, P. J. Conceptualizing food systems for global environmental change research. *Glob. Environ. Change* **18**, 234–245 (2008).
 82. Das, M. K., Sharma, A. P., Sahu, S. K., Srivastava, P. K. & Rej, A. Impacts and vulnerability of inland fisheries to climate change in the Ganga River system in India. *Aquat. Ecosyst. Health Manag.* **16**, 415–424 (2013).
 83. Islam, M. M., Sallu, S., Hubacek, K. & Paavola, J. Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: insights from coastal Bangladesh. *Regional Environ. Change* **14**, 281–294 (2014).
 84. Reid, A. J. *et al.* Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biol. Rev. Camb. Philos. Soc.* **94**, 849–873 (2019).
 85. Sainsbury, N. C. *et al.* Changing storminess and global capture fisheries. *Nat. Clim. Chang.* **8**, 655–659 (2018).
 86. Stewart-Sinclair, P. J., Last, K. S., Payne, B. L. & Wilding, T. A. A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. *Ecol. Evol.* **10**, 3518–3534 (2020).
 87. Applebaum, K. M. *et al.* An overview of occupational risks from climate change. *Curr. Environ. Health Rep.* **3**, 13–22 (2016).
 88. Belton, B. *et al.* *COVID-19 impacts and adaptations in Asia and Africa's aquatic food value chains*. (2021).
 89. Love, D. C. *et al.* Emerging COVID-19 impacts, responses, and lessons for building resilience in the seafood system. *Global Food Security* **28**, 100494 (2021).
 90. Turner, R., McConney, P. & Monnereau, I. Climate change adaptation and extreme weather in the small-scale fisheries of Dominica. *Coast. Manage.* **48**, 436–455 (2020).
 91. Pinnegar, J. K., Engelhard, G. H., Norris, N. J., Theophille, D. & Sebastien, R. D. Assessing vulnerability and adaptive capacity of the fisheries sector in Dominica: long-term climate change and catastrophic hurricanes. *ICES J. Mar. Sci.* **76**, 1353–1367 (2019).
 92. Bell, J. D. *et al.* Optimising the use of nearshore fish aggregating devices for food security in the Pacific Islands. *Mar. Policy* **56**, 98–105 (2015).
 93. McDonald, J. & Torrens, S. M. Governing Pacific fisheries under climate change. in *Research Handbook on Climate Change, Oceans and Coasts* (Edward Elgar Publishing, 2020).
 94. Belton, B., van Asseldonk, I. J. M. & Thilsted, S. H. Faltering fisheries and ascendant aquaculture:

- Implications for food and nutrition security in Bangladesh. *Food Policy* **44**, 77–87 (2014).
95. Fletcher, R. Can aquaculture help to alleviate poverty and malnutrition in Timor-Leste? <https://thefishsite.com/articles/can-aquaculture-help-to-alleviate-poverty-and-malnutrition-in-timor-leste> (2021).
 96. Pomeroy, R., Arango, C., Lomboy, C. G. & Box, S. Financial inclusion to build economic resilience in small-scale fisheries. *Mar. Policy* **118**, 103982 (2020).
 97. Lomboy, C. G. *et al.* Building household economic resilience to secure a future for near shore fishers in the Philippines. *Mar. Policy* **99**, 334–342 (2019).
 98. Cisneros-Montemayor, A. M., Sanjurjo, E., Munro, G. R., Hernández-Trejo, V. & Rashid Sumaila, U. Strategies and rationale for fishery subsidy reform. *Mar. Policy* **69**, 229–236 (2016).
 99. Cisneros-Montemayor, A. M. *et al.* Changing the narrative on fisheries subsidies reform: Enabling transitions to achieve SDG 14.6 and beyond. *Mar. Policy* **117**, 103970 (2020).
 100. Dunstan, P. K. *et al.* How can climate predictions improve sustainability of coastal fisheries in Pacific Small-Island Developing States? *Mar. Policy* **88**, 295–302 (2018).
 101. Lam, V. W. Y. *et al.* Climate change, tropical fisheries and prospects for sustainable development. *Nature Reviews Earth & Environment* **1**, 440–454 (2020).
 102. Rahman, H. M. T. & Hickey, G. M. What does autonomous adaptation to climate change have to teach public policy and planning about avoiding the risks of maladaptation in Bangladesh? *Front. Environ. Sci. Eng. China* **7**, 2 (2019).
 103. Henriksson, P. J. G., Dickson, M., Allah, A. N., Al-Kenawy, D. & Phillips, M. Benchmarking the environmental performance of best management practice and genetic improvements in Egyptian aquaculture using life cycle assessment. *Aquaculture* **468**, 53–59 (2017).
 104. Bogard, J. R. *et al.* Higher fish but lower micronutrient intakes: Temporal changes in fish consumption from capture fisheries and aquaculture in Bangladesh. *PLoS One* **12**, e0175098 (2017).
 105. Thilsted, S. H. *et al.* Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy* **61**, 126–131 (2016).
 106. Paprocki, K. & Huq, S. Shrimp and coastal adaptation: on the politics of climate justice. *Climate and Development* **10**, 1–3 (2018).
 107. De la Cruz-González, F. J., Patiño-Valencia, J. L., Luna-Raya, M. C. & Cisneros-Montemayor, A. M. Self-empowerment and successful co-management in an artisanal fishing community: Santa Cruz de Miramar, Mexico. *Ocean Coast. Manag.* **154**, 96–102 (2018).
 108. Kleiber, D., Cohen, P., Gomeze, C. & McDougall, C. *Gender integrated research for development in Pacific coastal fisheries*. <https://digitalarchive.worldfishcenter.org/handle/20.500.12348/2826> (2019).
 109. Cole, S. M. *et al.* Gender accommodative versus transformative approaches: a comparative assessment within a post-harvest fish loss reduction intervention. *Gend. Technol. Dev.* **24**, 48–65 (2020).
 110. Stacey, N. *et al.* Enhancing coastal livelihoods in Indonesia: an evaluation of recent initiatives on gender, women and sustainable livelihoods in small-scale fisheries. *Marit. Stud.* **18**, 359–371 (2019).
 111. Belhabib, D. *et al.* Catching industrial fishing incursions into inshore waters of Africa from space. *Fish. Fish.* **21**, 379–392 (2020).
 112. Le Manach, F. *et al.* Unreported fishing, hungry people and political turmoil: the recipe for a food security crisis in Madagascar? *Mar. Policy* **36**, 218–225 (2012).
 113. Cheung, W. W. L. & Oyinlola, M. A. *Dynamic Integrated Marine Climate, Biodiversity, Fisheries, Aquaculture and Seafood Market Model (DIVERSE)*. vol. 27 (2019).
 114. Himes-Cornell, A. & Kasperski, S. Assessing climate change vulnerability in Alaska's fishing communities. *Fish. Res.* **162**, 1–11 (2015).
 115. Cavole, L. *et al.* Biological impacts of the 2013–2015 warm-water anomaly in the northeast pacific: Winners, losers, and the future. *Oceanography* **29**, (2016).

116. Braaten, D. *et al.* Sea Level Rise Inundation Maps. *Center for Remote Sensing of Ice Sheets (CReSIS)* <https://cresis.ku.edu/content/research/maps> (2006).
117. WorldPop (www.worldpop.org-School of Geography and Environmental Science, University of Southampton Department of Geography and Geosciences, University of Louisville, Departement de Geographie, Universite de Namur) & Center for International Earth Science Information Network (CIESIN), Columbia University. The spatial distribution of population in 2020. *WorldPop* <https://www.worldpop.org/doi/10.5258/SOTON/WP00647> (2018) doi:10.5258/SOTON/WP00647.
118. Center for Hazards and Risk Research - CHRR - Columbia University, Center for International Earth Science Information Network - CIESIN - Columbia University, International Bank for Reconstruction and Development - The World Bank & United Nations Environment Programme Global Resource Information Database Geneva - UNEP GRID-Geneva. Global Cyclone Hazard Frequency and Distribution. (2005) doi:10.7927/H4CZ353K.
119. Jones, H. P., Hole, D. G. & Zavaleta, E. S. Harnessing nature to help people adapt to climate change. *Nat. Clim. Chang.* **2**, 504–509 (2012).
120. KNMI & WMO. Climate Explorer. *KNMI Climate Explorer* <https://climexp.knmi.nl/start.cgi> (2020).
121. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000: Global crop areas and yields in 2000. *Global Biogeochem. Cycles* **22**, (2008).
122. Cashion, T., Le Manach, F., Zeller, D. & Pauly, D. Most fish destined for fishmeal production are food-grade fish. *Fish. Fish.* **18**, 837–844 (2017).
123. ILO. ILOSTAT Data catalogue. *ILOSTAT* <https://ilostat ilo.org/data/> (2020).
124. FAO, IFAD, UNICEF, WFP and WHO. *The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets.* <http://dx.doi.org/10.4060/ca9692en> (2020) doi:10.4060/ca9692en.
125. Alderman, H. & Headey, D. D. How important is parental education for child nutrition? *World Dev.* **94**, 448–464 (2017).
126. Asch, R. G., Cheung, W. W. L. & Reygondeau, G. Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. *Mar. Policy* **88**, 285–294 (2018).
127. Barbeaux, S. J., Holsman, K. & Zador, S. Marine heatwave stress test of ecosystem-based fisheries management in the Gulf of Alaska Pacific cod. *Frontiers in Marine Science* **7**, (2020).
128. Free, C. M. *et al.* Impacts of historical warming on marine fisheries production. *Science* **363**, 979–983 (2019).
129. Stram, D. L. & Evans, D. C. K. Fishery management responses to climate change in the North Pacific. *ICES J. Mar. Sci.* **66**, 1633–1639 (2009).
130. Mackenzie, B. R., Gislason, H., Mollmann, C. & Koster, F. W. Impact of 21st century climate change on the Baltic Sea fish community and fisheries. *Glob. Chang. Biol.* **13**, 1348–1367 (2007).
131. Ficke, A. D., Myrick, C. A. & Hansen, L. J. Potential impacts of global climate change on freshwater fisheries. *Rev. Fish Biol. Fish.* **17**, 581–613 (2007).
132. Karmakar, S., Purkait, S., Das, A., Samanta, R. & Kumar, K. Climate change and Inland fisheries: impact and mitigation strategies. *J. Exp. Zoology India* **21**, 329–335 (2018).
133. Merino, G. *et al.* Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? *Glob. Environ. Change* **22**, 795–806 (2012).
134. Smale, D. A. *et al.* Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nat. Clim. Chang.* **9**, 306–312 (2019).
135. Thiault, L. *et al.* Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries. *Sci Adv* **5**, eaaw9976 (2019).
136. Liu, S. *et al.* Impact of climate change on wintering ground of Japanese anchovy (*Engraulis japonicus*) using marine geospatial statistics. *Frontiers in Marine Science* **7**, (2020).

137. M. Finkbeiner, E. *et al.* Exploring trade-offs in climate change response in the context of Pacific Island fisheries. *Mar. Policy* **88**, 359–364 (2018).
138. Wabnitz, C. C. C., Cisneros-Montemayor, A. M., Hanich, Q. & Ota, Y. Ecotourism, climate change and reef fish consumption in Palau: Benefits, trade-offs and adaptation strategies. *Mar. Policy* **88**, 323–332 (2018).
139. Oliveira, A. G. de *et al.* Coupling environment and physiology to predict effects of climate change on the taxonomic and functional diversity of fish assemblages in the Murray-Darling Basin, Australia. *PLoS One* **14**, e0225128 (2019).
140. Clark, N. J., Kerry, J. T. & Fraser, C. I. Rapid winter warming could disrupt coastal marine fish community structure. *Nat. Clim. Chang.* **10**, 862–+ (2020).
141. Jardine, S. L., Fisher, M. C., Moore, S. K. & Samhoury, J. F. Inequality in the Economic Impacts from Climate Shocks in Fisheries: The Case of Harmful Algal Blooms. *Ecol. Econ.* **176**, 106691 (2020).
142. Moore, S. K. *et al.* Impacts of climate variability and future climate change on harmful algal blooms and human health. *Environ. Health* **7 Suppl 2**, S4 (2008).
143. Petrik, C. M., Stock, C. A., Andersen, K. H., van Denderen, P. D. & Watson, J. R. Large Pelagic Fish Are Most Sensitive to Climate Change Despite Pelagification of Ocean Food Webs. *Frontiers in Marine Science* **7**, 1023 (2020).
144. Bell, J. D. *et al.* Effects of climate change on oceanic fisheries in the tropical Pacific: implications for economic development and food security. *Clim. Change* **119**, 199–212 (2013).
145. Martínez Arroyo, A., Manzanilla Naim, S. & Zavala Hidalgo, J. Vulnerability to climate change of marine and coastal fisheries in México. *Atmósfera* **24**, 103–123 (2011).
146. Hamdan, R., Othman, A. & Kari, F. Climate change effects on aquaculture production performance in Malaysia: An environmental performance analysis. *International Journal of Business and Society* **16**, 364–385 (2015).
147. Thomsen, M. S. *et al.* Local extinction of bull kelp (*Durvillaea spp.*) due to a marine heatwave. *Frontiers in Marine Science* **6**, 84 (2019).
148. Handisyde, N., Telfer, T. C. & Ross, L. G. Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. *Fish Fish* **18**, 466–488 (2017).
149. Joseph, V., Thornton, A., Pearson, S. & Paull, D. Occupational transitions in three coastal villages in Central Java, Indonesia, in the context of sea level rise: a case study. *Nat. Hazards* **69**, 675–694 (2013).
150. Bricknell, I. R. *et al.* Resilience of cold water aquaculture: a review of likely scenarios as climate changes in the Gulf of Maine. *Reviews in Aquaculture* **13**, 460–503 (2021).
151. Hanich, Q. *et al.* Small-scale fisheries under climate change in the Pacific Islands region. *Mar. Policy* **88**, 279–284 (2018).
152. Martin, V. A. S. *et al.* Linking social preferences and ocean acidification impacts in mussel aquaculture. *Sci. Rep.* **9**, 4719 (2019).
153. Reiss, C. S. *et al.* Overwinter habitat selection by Antarctic krill under varying sea-ice conditions: implications for top predators and fishery management. *Mar. Ecol. Prog. Ser.* **568**, 1–16 (2017).
154. Zhu, Y. *et al.* Modelling spatiotemporal trends in range shifts of marine commercial fish species driven by climate change surrounding the Antarctic Peninsula. *Sci. Total Environ.* **737**, 140258 (2020).
155. Ho, C.-H., Yagi, N. & Tian, Y. An impact and adaptation assessment of changing coastal fishing grounds and fishery industry under global change. *Mitigation and Adaptation Strategies for Global Change* **25**, 1073–1102 (2020).
156. Young, M. A. *et al.* Using species distribution models to assess the long-term impacts of changing oceanographic conditions on abalone density in south east Australia. *Ecography* **43**, 1052–1064 (2020).
157. Rutkayová, J. *et al.* Fish stock losses due to extreme floods - findings from pond-based aquaculture

- in the Czech Republic. *J Flood Risk Management* **11**, 351–359 (2018).
158. Momtaz, S. & Schreider, M. Assessing the vulnerability of small-scale fishery communities in the estuarine areas of Central Vietnam in the context of increasing climate risks. *Ocean Coast. Manag.* **196**, (2020).
 159. Morrongiello, J. R., Crook, D. A., King, A. J., Ramsey, D. S. L. & Brown, P. Impacts of drought and predicted effects of climate change on fish growth in temperate Australian lakes. *Glob. Chang. Biol.* **17**, 745–755 (2011).
 160. Schulte, P. A. *et al.* Advancing the framework for considering the effects of climate change on worker safety and health. *J. Occup. Environ. Hyg.* **13**, 847–865 (2016).
 161. Semenza, J. C. *et al.* Environmental Suitability of *Vibrio* Infections in a Warming Climate: An Early Warning System. *Environ. Health Perspect.* **125**, 107004 (2017).
 162. Alava, J. J., Cheung, W. W. L., Ross, P. S. & Sumaila, U. R. Climate change-contaminant interactions in marine food webs: Toward a conceptual framework. *Glob. Chang. Biol.* **23**, 3984–4001 (2017).
 163. Grace, K., Davenport, F., Hanson, H., Funk, C. & Shukla, S. Linking climate change and health outcomes: Examining the relationship between temperature, precipitation and birth weight in Africa. *Glob. Environ. Change* **35**, 125–137 (2015).
 164. Zheng, L., Gatti, C. M. I., Garrido Gamarro, E., Suzuki, A. & Teah, H. Y. Modeling the time-lag effect of sea surface temperatures on ciguatera poisoning in the South Pacific: Implications for surveillance and response. *Toxicon* **182**, 21–29 (2020).
 165. De Silva, S. S. & Soto, D. Climate change and aquaculture: potential impacts, adaptation and mitigation. in *Climate change implications for fisheries and aquaculture: overview of current scientific knowledge* (eds. Cochrane, K., De Young, C., Soto, D. & Bahri, T.) vol. 530 151–212 (FAO, 2009).
 166. Porter, J. R. *et al.* Food security and food production systems. in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Field, C. B. *et al.*) 485–533 (Cambridge University Press, 2014).
 167. Bueno, P. B. & Soto, D. *Adaptation strategies of the aquaculture sector to the impacts of climate change*. <http://www.fao.org/3/i6943e/i6943e.pdf> (2017).
 168. Timmers, B. *Impacts of Climate Change and Variability on Fish Value Chains in Uganda*. http://pubs.iclarm.net/resource_centre/WF_3139.pdf (2012).
 169. Halls, A. S., Payne, A. I., Alam, S. S. & Barman, S. K. Impacts of flood control schemes on inland fisheries in Bangladesh: guidelines for mitigation. *Hydrobiologia* **609**, 45 (2008).
 170. Shelton, C. Climate change adaptation in fisheries and aquaculture: compilation of initial examples. *FAO Fish. Aquac. Circ.* **1** (2014).
 171. Neil Adger, W., Arnell, N. W. & Tompkins, E. L. Successful adaptation to climate change across scales. *Glob. Environ. Change* **15**, 77–86 (2005).
 172. Ainsworth, C. H. *et al.* Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries. *ICES J. Mar. Sci.* **68**, 1217–1229 (2011).
 173. Kassambara, A. & Mundt, F. *factoextra: Extract and Visualize the Results of Multivariate Data Analyses*. <https://CRAN.R-project.org/package=factoextra> (2020).
 174. R Core Team. *R: A Language and Environment for Statistical Computing*. <https://www.R-project.org> (2020).