Research priorities for seafood-dependent livelihoods under ocean climate change extreme events

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Research priorities for seafood-dependent livelihoods under ocean climate change extreme events

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The current magnitude of ocean extreme events already exceeds the end-of-the-decade scenario estimates, and therefore incremental adaptation measures will render insufficient for seafood-dependent livelihoods. Nevertheless, transformational change is deemed promising, but uncertainties remain as to what activates such processes and how maladaptation outcomes can be avoided. While the science on extreme events is advancing fast, little is known about livelihood adaptation and transformation processes in the context of single or compound ocean extreme events. We identify a set of research priorities: 1) the identification of hotspot areas for coastal compound extreme events, 2) the development of bottom-up case study analysis of adaptation to extreme events, 3) the identification of constrainers and enablers to livelihood adaptation and transformation under abrupt change, and 4) directing research to contribute to climate-change policy. An effort addressing these key gaps will inform seafood-dependent livelihood adaptation policies for the 2030 Agenda and beyond.

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Introduction

The world ocean supports the livelihoods of 37.9 million people that are directly engaged in capture fisheries and 20.7 million in aquaculture. Both sectors ensure our seafood supply and critically contribute to the nutrition and food security of a growing population [24,37]. In addition to direct fishers and harvesters, aquaculture and seafood systems together support around 600 million livelihoods that partially depend on these sectors [25]. This number illustrates the magnitude of seafood-dependent communities, where livelihoods rely on seafood for nutrition, income-generating activities (fishing, selling, trading, processing, etc.) (Figure 1), and other

Figure 1

Definition of seafood livelihoods, illustrating the types of seafood direct and indirect dependent livelihoods.

ocean-related activities such as tourism, recreation, or sustaining cultural values [21]. Fisheries and mariculture are a vital food provisioning to end malnourishment and food insecurity, now and in the future [22,29]. Currently, the oceans produce 178 million tons of fish from capture fisheries and aquaculture, of which 88% are used for direct human consumption [24]. In seafood systems, capture fisheries contribute with 90.3 million tonnes per year and mariculture provides 68.1 million tonnes [24]. The future of fish for nutrition and livelihood support is currently under threat by unsustainable practices [64], together with the threats of climate change and increasing global seafood demand [22,24]. Recent analyses point to geopolitical tensions and extreme weather events as the main shocks to seafood systems [23].

The science on ocean climate-change extreme events is advancing fast [51,62], increasingly providing better hindcasts and new projections for marine heatwaves (MHWs), extreme sea- level events, or the intensification of *El Niño* and *La Niña* events [42,47]. To date, climate impacts and adaptation research for seafood-dependent livelihood systems has focused on the consequences of incremental trends in mean climate variables [62], such as climate velocity in fisheries [29] or ocean acidification in aquaculture [29]. As a result, there is little empirical evidence on the livelihood adaptation responses to extreme events [20,38,53]. While strong social cohesion, a highly flexible labor force, and tenure and access rights to natural resources are often linked to a desirable state of seafood systems [44,48], there is a question of how communities can achieve resilience [14,34]. The Intergovernmental Panel on Climate Change (IPCC) sixth Assessment Report defines Incremental adaptation as the "adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale", while Transformational adaptation is defined as the "adaptation that changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts" [55]. Efforts up to date have focused on incremental adaptation [55], but extreme events may render this incremental adaptation insufficient.

In this context, the present work aims to provide a better understanding of adaptation processes of seafood-dependent livelihoods to ocean extreme events. We rely on recent global reports and novel scientific literature, together with our experience and expertise as a group working on fisheries adaptation. We propose expanding this research frontier moving on from incremental to transformational change in response to the increasing challenges that these social–ecological systems face. First, we discuss how ocean extreme events cause profound changes in marine (and seafood production) systems, and how this transformational nature is different from that of progressive climate change. Second, we focus on how adaptation science can tackle the challenges embedded in extreme events and shift from an incremental to a transformative response. Finally, we propose a research agenda so that seafood livelihoods can become resilient to the unexpected changes of compound extreme climate-change impacts, including the contribution of this agenda to the United Nations Sustainable Development Goals (SDGs).

The nature of impacts from extreme events

Anthropogenic climate change is affecting the frequency, intensity, and occurrence of multiple types of extreme events in the oceans [21,40]. MHWs, for example, have increased in terms of the number of annual days globally by 54% since 1925 [51]. Estimates indicate that 87% of MHWs are attributable to human-induced global warming, and that future MHWs will be almost 100% if warming exceeds 2ºC [31]. Future MHWs are projected to increase from current centennial events to a one-in-four-day events by 2031–2050 ([68], RCP8.5). Similarly, extreme sea-level events are projected to increase their frequency from centennial to annual by 2040–2080 in most European locations [54] and extreme *El Niño* events are expected to increase over 1.5ºC warming [12].

Climate change is also increasing the likelihood of compound extreme events that can trigger cascading impacts in the ecological and social domains [35,39]. Such impacts include alterations of the ecological structure and functioning of coastal systems, disrupting the provision of ecosystem services such as seafood

production [15,42,62], increase the risks to the ocean-based economy [40], and cause migration and displacement of coastal-dependent communities [1,11]. Existing projections for extreme high temperatures show that targeted marine stocks and fishing employment globally will be negatively affected in more than 80% of coastal countries [15].

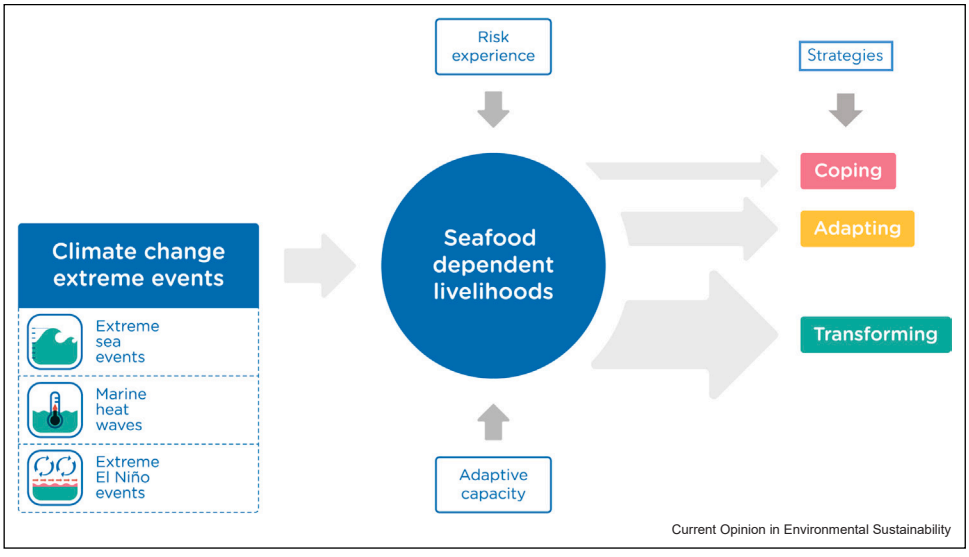
Since extreme events impact fisheries and fishing activity, there are cascade effects through the supply chain [65], including markets and processing up to the consumers [9,20]. Storms and cyclones also have devastating consequences for seafood-dependent livelihoods [43]. In communities that rely on seafood for their dietary needs and livelihoods, such as for many small islands, the failure to adapt the whole seafood system can intensively result into cultural issues, identity an economic loss, risking food security [4,16,36], intensively affecting indigenous communities [61]. These already-existing impacts may be exacerbated by extreme events. For such hazards, the latest IPCC report recognizes the need to move from disaster risk management toward adaptation to extreme events [21,55], opening a novel opportunity for multidisciplinary research on social–ecological system adaptation to extreme events [2,20,62].

Transformational adaptation

To date, fisheries adaptation to climate change has been tackled from the lens of *incremental adaptation* [26,34]. Studies conducted for seafood systems find that adaptation options such as fisheries adaptive management, technological improvements, and international cooperation are largely insufficient to maintain seafood security under the most severe emission scenarios (i.e. RCP8.5) [17,29,30,52]. But extreme events push the climate hazard horizon further as the magnitude of extreme events already exceeds the mean values projected under all scenarios for the end of the century [40].

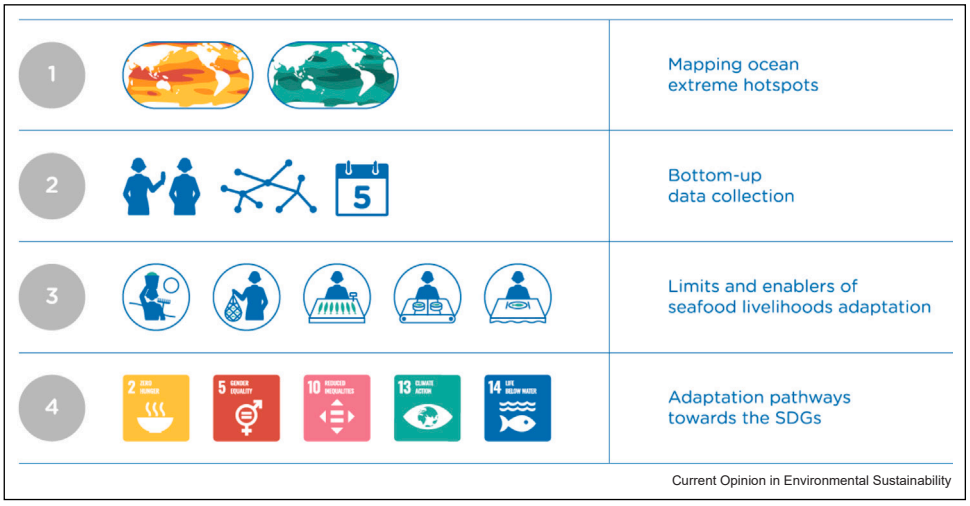
The stream of thought coming from the resilience of social–ecological system thinking understands adaptation to climate change as a process, where systems respond to climate change by using coping, adapting, and transforming strategies [26,33,38] (Figure 2). Transformation of seafood-dependent livelihoods requires a systemic change in the structure and functioning of a community, and many times involves shifting livelihoods, ecosystem services, economic systems, power relationships, and governance agreements [5,10,18,66]. For example, a transformation response at the individual level could include exiting a fishery after an extreme event [59], or shifting consumption toward imported fish [3,46]. Existing theory and evidence points to a transformational change when responding to abrupt change [26,57,59], but transformation can sometimes lead the seafood system to undesirable states. In the context of future climate change, it is crucial to understand 1) what is an adaptation versus a transformation response and 2) identify the risks of maladaptation of both responses [7,66].

Figure 2



Adaptation of seafood-dependent communities to extreme events. Climate-change extreme events include: 1) extreme sea events (weather and sea level), MHWs, and extreme El Niño events. The strategies or responses include coping, adapting (incremental adaptation), and transforming (transformational adaptation).

Figure 3



Priorities for a new research agenda to address seafood-dependent livelihood adaptation to extreme ocean events.

A research agenda for seafood-dependent livelihoods under extreme events

Science is required to support the proposed adaptation to extreme events. We identify four areas for frontier research to understand how seafood-dependent livelihoods can adapt to the single or compounded impacts of climate-change extreme events (Figure 3).

Mapping hotspots of ocean extreme events

So far, studies addressing impacts and adaptation in the seafood sector at the global scale rely on modeled exercises that incorporate projected trends in one or two variables for climate hazards, and rarely combine the effects of several extreme events to see cumulative impacts [15,29,32,45,63]. There is a large opportunity to contribute to the understanding of the impacts of compound extreme events and how these intensive shocks shape seafood- dependent livelihoods' responses [39]. First, the multilayer mapping of observed impacts [12,62] will allow to identify hotspots for single and compound climate hazards, providing a mapping of past exposure. This is crucial to understand how seafood-dependent livelihoods have responded to such extreme impacts and how exposure to past extreme conditions affects the adaptation responses of the seafood systems [67]. In addition to the mapping, adding information on past responses and other shocks can address important research questions. Second, mapping future extreme events under climate scenarios [42,62] will allow to identify hotspots of climate-change impacts on seafood livelihoods that can inform adaptation planning. Future climate-change extreme event hotspots can be combined with studies on the physiological thresholds of exploited species (e.g. [13]) and be linked to the exposure of seafood systems in order to understand the levels of risk and vulnerability of seafood-dependent communities [63]. Some research questions that lie in this frontier are: Do current and future climate-change hazard ocean hotspot areas spatially overlap? Does incorporating extreme events projections change the global impact estimates for the seafood sector? What is the role of past experiences with climate extreme events in adaptation responses? Which livelihood responses are common/specific for incremental and extreme changes?

Bottom-up data collection of adaptation responses

One of the main knowledge gaps today is the lack of empirical evidence on ongoing adaptation responses to exposure to extreme compound events, especially in climate hotspots [67,20]. Another existing gap is that studies are often case-specific and comparability across them is challenging [20,41,47]. To advance in our understanding of the required transformational change, empirical evidence on impacts and adaptations is needed from bottom-up studies that, at the same time, allow for replication and cross-comparison. We recommend research targeted at the local scales where adaptation responses to climate change are generally deployed. This would allow researchers to collect case study realities and systematically compare them across sites. Ideally, such an effort would leverage a comprehensive database of different seafood-dependent livelihoods across the oceans to understand impacts and adaptation to extreme events [56]. This would allow managers to coordinate fisheries responses with current management strategies to ensure that the latter does not hamper fisheries efforts to adapt or identify possible unsustainable fisheries methods emerging. Relevant research questions for this mission are: How much scientific evidence is there on adaptation to extreme events in seafood-dependent

livelihoods? Do the ocean extreme events hotspots match the climate-change adaptation hotspots? Is the empirical evidence targeted at future climate hotspots?

Adaptation barriers and enablers for seafood-dependent livelihoods

Responses to extreme events can lead to maladaptation outcomes when the adaptation process results in a detriment of the systems' sustainability, for example, or when social inequities grow in the seafood system [18,50]. To avoid such outcomes, the identification of barriers and enablers to adaptation and transformation is key. Recent advances on social–ecological resilience suggest that there are a set of key social–ecological domains of adaptive capacity that enable (or not) livelihood responses to climate-change impacts [18,34]. There are examples in the literature on how access to assets, diversification strategies in the activity, and outgoing migration are key drivers of adaptation and transformation responses to extreme events [8,43]. Power relations, sometimes gendered [27], can also shape individual responses to environmental change [18]. A novel approach to adaptive capacity employs social–ecological networks to further explore the structures behind adaptation and transformation responses [5,6,18,59]. For example, existing social networks based on trust and communication among individuals explain adaptation and transformation responses to abrupt change [6,60]. Still, we do not know what causes livelihoods to engage in maladaptation responses as the mechanisms for transformational responses are largely unknown [26,38].

A comprehensive approach that considers the range of barriers and enablers to seafood livelihoods' adaptation is lacking. Power relations and social–ecological networks have been studied in isolation from other domains, such as the market structure and dynamics. The capacity to respond to extreme events is likely to be linked to the flexibility in the production system, the value chain, the strength of market linkages across goods and labor, and market access. The role of market responses to shocks and their relation to social structural changes is poorly understood and needs careful attention. In similar ways, existing rules and management practices can act as barriers and lead to a system collapse. For example, fishing practices and regulations can be constrainers of livelihood adaptation to extreme events in the oceans. While the focus of fisheries management is to adapt to incremental climate change [29], there are additional challenges of increased risk on at-sea operations and of abrupt change in productivity and location or the resources [21]. These challenges may be exacerbated by fixed management systems and institutions. Potential solutions such as ecosystem-based fisheries management and balanced harvesting have not been largely explored in terms of their resilience to extreme events.

To date, we still do not comprehensively understand what adaptive capacity domains are activated to respond to extreme events, nor to specifically explore compound extreme events [39]. Moreover, the adaptive capacity theory has not been explored yet across a system of subsectors (i.e., seafood chain), as opposed to looking at single sectors such as fisheries or agriculture [20]. Relevant research questions identified here are: What shapes seafood- dependent livelihoods responses to extreme events? Do the individual responses facilitate community and governance adaptation and transformation? What are the key social–ecological network configurations and economic factors associated with transforming responses? Which adaptive capacity determinants are associated with maladaptation? How should fisheries management transform to address the challenges of extreme events?

Adaptation pathways toward Sustainable Development Goals and beyond

The world navigates toward a sustainability agenda for 2030, adopted by the United Nations in 2015, that aims to transform the world for the better [49]. The set of overarching SDGs requires profound structural changes in society [58] and deep transformations in policy, economy, technology, and science [49]. As this decade advances, recent scientific reports are raising major concerns about our ability to meet SDGs, illustrating important negative trends in meeting such targets, such as biodiversity loss, livelihood inequalities [58], or climate-change impacts [21,55]. The roadmap for ocean research toward informing SDGs and meeting the 2030 Agenda is highly advanced [10,19,25], but we have seen here that extreme event challenges are largely overlooked for seafood-dependent livelihoods. Despite knowledge on climate-change extreme events causing poverty [20], enhancing food insecurity [7], exacerbating social and gender inequalities [28], and others, a comprehensive understanding of how climate-change extreme events on ocean systems affect the achievement of the SDGs, and guidelines toward overcoming these risks, is not available yet. Besides climate extreme events, economic and social crises are closely interlinked to individual and community responses in the seafood sector. There is an opportunity to use the information on past economic, social, and environmental shocks together with adaptation and transformation responses to extreme events to better design future adaptation pathways [55]. Relevant research questions in this respect are: Are there any adaptation responses that work over the gradient of incremental to extreme impacts? How do climate-driven extreme events compromise

achieving seafood-sustained SDG targets? Does the experience with past economic and social shocks facilitate adaptation to climate extreme events? What transformational responses allow for synergies across SDGs (i.e. gender, industry, and life below water)? How do ocean extreme events constrain climate adaptation pathways?

Final remarks

Here, we argue that climate-change-induced extreme events have been so far left behind in seafood-dependent livelihood adaptation research, and that this oversight can pose important risks for understanding the set of available adaptation responses and implementation pathways that can be promoted. As extreme events push species toward their natural limits in ways not seen before, impacts cascade into seafood-dependent livelihoods facing these sudden changes. We recommend that future research is focused on understanding the impacts and the adaptation to extreme events in the oceans, by exploring transforming strategies that avoid maladaptation outcomes. Our work integrates conventional approaches of hazard and risk management, vulnerability, adaptation, and resilience studies in order to convey the scientific effort into effective transformations in decision-making and practice. Furthermore, research should explore the adaptation process for seafood-related communities and governance systems, and how strategies at the individual level feed in or interact with fisheries management and governance. We believe that a comprehensive approach that considers cumulative hazards that are based on historic extreme events together with socioeconomic shocks with knowledge of the system's adaptive capacity can address the challenges that affect dependent livelihoods.

Data availability

No data were used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Adger WN, Boyd E, Fábos A, Fransen S, Jolivet D, Neville G, De Campos RS, Vijge MJ: **Migration transforms the conditions for the achievement of the Sustainable Development Goals**. *Lancet Planet Health* 2019, **3**:e440-e442.

2. Adger WN, Brown I, Surminski S: **Advances in risk assessment for climate change adaptation policy**. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* (2121) 2018, **376**:20180106.

3. Arthur RI, Skerritt DJ, Schuhbauer A, Ebrahim N, Friend RM, Sumaila UR: **Small-scale fisheries and local food systems: transformations, threats and opportunities**. *Fish Fish* 2022, **23**:109-124.

4. Asche F, Bellemare MF, Roheim C, Smith MD, Tveteras S: **Fair enough? Food security and the international trade of seafood**. *World Dev* 2015, **67**:151-160.

5. Barnes ML, Bodin Ö, Guerrero AM, McAllister RR, Alexander SM, Robins G: **The social structural foundations of adaptation and transformation in social–ecological systems**. *Ecology and Society* (4) 2017, **22**.

6. •• Barnes ML, Wang P, Cinner JE, Graham NA, Guerrero AM, Jasny L, Lau J, Sutcliffe SR, Zamborain-Mason J: **Social determinants of adaptive and transformative responses to climate change**. *Nat Clim Change* 2020, **10**:823-828.
This article empirically illustrates how social ecological network structure within adaptive capacities can shape the responses to impacts in fisheries livelihoods. It proposes a framework for understanding the continuum of coping adapting and transforming livelihoods facing climate change.

7. Bennett NJ, Blythe J, Tyler S, Ban NC: **Communities and change in the anthropocene: understanding social-ecological vulnerability and planning adaptations to multiple interacting exposures**. *Reg Environ Change* 2016, **16**:907-926.

8. Black R, Arnell NW, Adger WN, Thomas D, Geddes A: **Migration, immobility and displacement outcomes following extreme events**. *Environ Sci Policy* 2013, **27**:S32-S43.

9. Botzen WW, Deschenes O, Sanders M: **The economic impacts of natural disasters: a review of models and empirical studies**. *Rev Environ Econ Policy* 2019, **13**:167-188.

10. • Brodie Rudolph T, Ruckelshaus M, Swilling M, Allison EH, Österblom H, Gelcich S, Mbatha P: **A transition to sustainable ocean governance**. *Nat Commun* 2020, **11**:1-14.
While this contributions focuses on transformative ocean governance change, it very well bridges theory with concrete actions and illustrate the way to climate resilient development for the seafood livelihoods and beyond.

11. Buchori I, Pramitasari A, Sugiri A, Maryono M, Basuki Y, Sejati AW: **Adaptation to coastal flooding and inundation: mitigations and migration pattern in Semarang City, Indonesia**. *Ocean Coast Manag* 2018, **163**:445-455, https://doi.org/10.1016/j.ocecoaman.2018.07.017

12. Cai W, Borlace S, Lengaigne M, Van Rensch P, Collins M, Vecchi G, Timmermann A, Santoso A, McPhaden MJ, Wu L: **Increasing frequency of extreme El Niño events due to greenhouse warming**. *Nat Clim Change* 2014, **4**:111-116.

13. Castro-Olivares A, Des M, Olabarria C, deCastro M, Vázquez E, Sousa MC, Gómez-Gesteira M: **Does global warming threaten small-scale bivalve fisheries in NW Spain?** *Mar Environ Res* 2022, **180**:105707, , https://doi.org/10.1016/j.marenvres.2022.105707

14. Challinor AJ, Adger WN, Benton TG, Conway D, Joshi M, Frame D: **Transmission of climate risks across sectors and borders**. *Philos Trans R Soc A: Math Phys Eng Sci* 2018, **376**:20170301.

15. •• Cheung WW, Frölicher TL, Lam VW, Oyinlola MA, Reygondeau G, Sumaila UR, Tai TC, Teh LC, Wabnitz CC: **Marine high temperature extremes amplify the impacts of climate change on fish and fisheries**. *Sci Adv* 2021, **7**:eabh0895.
This study is a comprehensive analysis on the modelled impacts of climate change extreme temperature effects in fisheries productivity and employment at the global level.

16. Cheung WW, Jones MC, Lam VW, D Miller D, Ota Y, Teh L, Sumaila UR: **Transform high seas management to build climate resilience in marine seafood supply**. *Fish Fish* 2017, **18**:254-263.

17. Cheung WW, Reygondeau G, Frölicher TL: **Large benefits to marine fisheries of meeting the 1.5C global warming target**. *Science* 2016, **354**:1591-1594.

18. Cinner JE, Barnes ML: **Social dimensions of resilience in social-ecological systems**. *One Earth* 2019, **1**:51-56.

19. Claudet J, Bopp L, Cheung WWL, Devillers R, Escobar-Briones E, Haugan P, Heymans JJ, *et al*.: **A roadmap for using the UN decade of ocean science for sustainable development in support of science, policy, and action**. *One Earth* (1) 2020, **2**:34-42.

20. Conway D, Nicholls RJ, Brown S, Tebboth MG, Adger WN, Ahmad B, Biemans H, Crick F, Lutz AF, De Campos RS: **The need for bottom-up assessments of climate risks and adaptation in climate-sensitive regions**. *Nat Clim Change* 2019, **9**:503-511.

21. Cooley S, Schoeman D, Bopp L, Boyd P, Donner S, Ito S, Kiessling W, Martinetto P, Ojea E, Racault M-F: **Oceans and coastal ecosystems and their services**. IPCC AR6 WGII. Cambridge University Press; 2022.

22. Costello C, Cao L, Gelcich S, Cisneros-Mata MÁ, Free CM, Froehlich HE, Golden CD, Ishimura G, Maier J, Macadam-Somer I: **The future of food from the sea**. *Nature* 2020, **588**:95-100.

23. •• Cottrell RS, Nash KL, Halpern BS, Remenyi TA, Corney SP, Fleming A, Fulton EA, Hornborg S, Johne A, Watson RA: **Food production shocks across land and sea**. *Nat Sustain* 2019, **2**:130-137.
This paper overviews the range of causes and consequences of shoks to food systems and broadens the focus of our paper by framing the food supply context at the global level together with the other type of shocks (economic, gepolitical, etc). It shows that extreme events are among the two most important shocks to food supply from sea and land.

24. FAO: The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. FAO; 2022, https://doi.org/10.4060/cc0461en

25. FAO: Blue Transformation - Roadmap 2022–2030: A vision for FAO's work on aquatic food systems. FAO; 2022, https://doi.org/10.4060/cc0459en

26. Fedele G, Donatti CI, Harvey CA, Hannah L, Hole DG: **Transformative adaptation to climate change for sustainable social-ecological systems**. *Environ Sci Policy* 2019, **101**:116-125, https://doi.org/10.1016/j.envsci.2019.07.001

27. Frangoudes K, Siri G: **(En) Gendering change in small-scale fisheries and fishing communities in a globalized world**. *Maritime Studies* (2) 2018, **17**:117-124.

28. Frangoudes K, Siri G, Danika K: **Situated transformations of women and gender relations in small-scale fisheries and communities in a globalized world**. *Maritime Studies* (3) 2019, **18**:241-248.

29. Free CM, Cabral RB, Froehlich HE, Battista W, Ojea E, O'Reilly E, Palardy JE, García Molinos J, Siegel KJ, Arnason R: **Expanding ocean food production under climate change**. *Nature* 2022, **605**:490-496.

30. Free CM, Mangin T, Molinos JG, Ojea E, Burden M, Costello C, Gaines SD: **Realistic fisheries management reforms could mitigate the impacts of climate change in most countries**. *PloS one* (3) 2020, **15**:e0224347.

31. Frölicher TL, Fischer EM, Gruber N: **Marine heatwaves under global warming**. *Nature* 2018, **560**:360-364, https://doi.org/10.1038/s41586-018-0383-9

32. Gaines SD, Costello C, Owashi B, Mangin T, Bone J, Molinos JG, Burden M, Dennis H, Halpern BS, Kappel CV: **Improved fisheries management could offset many negative effects of climate change**. *Sci Adv* 2018, **4**:eaao1378.

33. Galappaththi EK, Ford JD, Bennett EM: **A framework for assessing community adaptation to climate change in a fisheries context**. *Environ Sci Policy* 2019, **92**:17-26.

34. Galappaththi EK, Ford JD, Bennett EM, Berkes F: **Climate change and community fisheries in the arctic: a case study from Pangnirtung, Canada**. *J Environ Manag* 2019, **250**:109534.

35. Gallina V, Torresan S, Critto A, Sperotto A, Glade T, Marcomini A: **A review of multi-risk methodologies for natural hazards: consequences and challenges for a climate change impact assessment**. *J Environ Manag* 2016, **168**:123-132.

36. •• Gephart JA, Rovenskaya E, Dieckmann U, Pace ML, Brännström Å: **Vulnerability to shocks in the global seafood trade network**. *Environ Res Lett* 2016, **11**:035008.
This is one of the scarce publications looking beyond fishers to the seafood trade network. It provides some illustration of the cascading effects of shocks to seafood systems.

37. Golden CD, Koehn JZ, Shepon A, Passarelli S, Free CM, Viana DF, Matthey H, Eurich JG, Gephart JA, Fluet-Chouinard E: **Aquatic foods to nourish nations**. *Nature* 2021, **598**:315-320.

38. Green KM, Selgrath JC, Frawley TH, Oestreich WK, Mansfield EJ, Urteaga J, Swanson SS, Santana FN, Green SJ, Naggea J: **How adaptive capacity shapes the Adapt, React, Cope response to climate impacts: insights from small-scale fisheries**. *Clim Change* 2021, **164**:1-22.

39. •• Gruber N, Boyd PW, Frölicher TL, Vogt M: **Biogeochemical extremes and compound events in the ocean**. *Nature* 2021, **600**:395-407.
This is one example of how new model scenarios from CMIP6 can be explored to understand compound effects of climate change extreme events. This constitutes the novel science basis in where to continue exploring the impact pathway towards livelihoods and adaptation.

40. • Harris R, Boyd P, Adrian R, Birkmann J, Cooley S, Donner S, Mauritzen M, Midgley G, Parmesan C, Piepenburg D: **Cross-chapter box EXTREMES: ramifications of climatic extremes for marine, terrestrial, freshwater and polar natural systems**. Cambridge University Press; 2021:22-26.
This cross chapter box from the latest IPCC report shows the existing knowledge on marine extreme events and illustrates the ecological impacts for the cases of the Pacific 'blob' and the Arctic.

41. Hobday AJ, Cochrane K, Downey-Breedt N, Howard J, Aswani S, Byfield V, Duggan G, Duna E, Dutra LXC, Frusher SD, Fulton EA, Gammage L, Gasalla MA, Griffiths C, Guissamulo A, Haward M, Jarre A, Jennings SM, Jordan T, Joyner J, Ramani NK, Shanmugasundaram SLP, Malherbe W, Cisneros KO, Paytan A, Pecl GT, Plagányi ÉE, Popova EE, Razafindrainibe H, Roberts M, Rohit P, Sainulabdeen SS, Sauer W, Valappil ST, Zacharia PU, van Putten EI: **Planning adaptation to climate change in fast-warming marine regions with seafood-dependent coastal communities**. *Rev Fish Biol Fish* 2016, **26**:249-264, https://doi.org/10.1007/s11160-016-9419-0

42. Holbrook NJ, Hernaman V, Koshiba S, Lako J, Kajtar JB, Amosa P, Singh A: **Impacts of marine heatwaves on tropical western and central Pacific Island nations and their communities**. *Glob Planet Change* 2022, **208**:103680.

43. Hossain MA, Ahmed M, Ojea E, Fernandes JA: **Impacts and responses to environmental change in coastal livelihoods of south-west Bangladesh**. *Sci Total Environ* 2018, **637**:954-970.

44. Kleisner KM, Fogarty MJ, McGee S, Barnett A, Fratantoni P, Greene J, Hare JA, Lucey SM, McGuire C, Odell J: **The effects of sub-regional climate velocity on the distribution and spatial extent of marine species assemblages**. *PLoS One* 2016, **11**:e0149220.

45. Lam VW, Allison EH, Bell JD, Blythe J, Cheung WW, Frölicher TL, Gasalla MA, Sumaila UR: **Climate change, tropical fisheries and**

prospects for sustainable development. *Nat Rev Earth Environ* 2020, **1**:440-454.

46. Lam VW, Cheung WW, Swartz W, Sumaila UR: **Climate change impacts on fisheries in West Africa: implications for economic, food and nutritional security**. *Afr J Mar Sci* 2012, **34**:103-117.

47. Lavell A, Oppenheimer M, Diop C, Hess J, Lempert R, Li J, Muir-Wood R, Myeong S, Moser S, Takeuchi K: **Climate change: new dimensions in disaster risk, exposure, vulnerability, and resilience**. Cambridge University Press; 2012:25-64.

48. Matin N, Forrester J, Ensor J: **What is equitable resilience?** *World Dev* 2018, **109**:197-205.

49. Messerli P, Kim EM, Lutz W, Moatti J-P, Richardson K, Saidam M, Smith D, Eloundou-Enyegue P, Foli E, Glassman A: **Expansion of sustainability science needed for the SDGs**. *Nat Sustain* 2019, **2**:892-894.

50. Ojea E, Lester SE, Salgueiro-Otero D: **Adaptation of fishing communities to climate-driven shifts in target species**. *One Earth* (6) 2020, **2**:544-556.

51. Oliver EC, Burrows MT, Donat MG, Sen Gupta A, Alexander LV, Perkins-Kirkpatrick SE, Benthuysen JA, Hobday AJ, Holbrook NJ, Moore PJ: **Projected marine heatwaves in the 21st century and the potential for ecological impact**. *Front Mar Sci* 2019, **6**:734.

52. Oremus KL, Bone J, Costello C, Molinos JG, Lee A, Mangin T, Salzman J: **Governance challenges for tropical nations losing fish species due to climate change**. *Nat Sustain* (4) 2020, **3**:277-280.

53. Pecl GT, Ogier E, Jennings S, van Putten I, Crawford C, Fogarty H, Frusher S, Hobday AJ, Keane J, Lee E: **Autonomous adaptation to climate-driven change in marine biodiversity in a global marine hotspot**. *Ambio* 2019, **48**:1498-1515.

54. Pörtner H, Roberts D, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Nicolai M, Okem A, Petzold J: **IPCC Special Report on the Ocean and Cryosphere in a Changing Climate**. IPCC Intergovernmental Panel on Climate Change; 2019.

55. IPCC, In: [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama, *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2022, Cambridge University Press. Cambridge University Press; Cambridge, UK and New York, NY, USA, 3056, doi:10.1017/9781009325844.

56. Pulver S, Ulibarri N, Sobocinski KL, Alexander SM, Johnson ML, McCord PF, Dell'Angelo J: **Frontiers in socio-environmental research**. *Ecol Soc* (3) 2018, **23**.

57. Rubio I, Hobday AJ, Ojea E: **Skippers' preferred adaptation and transformation responses to catch declines in a large-scale tuna fishery**. *ICES J Mar Sci* 2022, **79**:532-539.

58. Sachs JD, Schmidt-Traub G, Mazzucato M, Messner D, Nakicenovic N, Rockström J: **Six transformations to achieve the sustainable development goals**. *Nat Sustain* 2019, **2**:805-814.

59. Salgueiro-Otero D, Barnes ML, Ojea E: **Transformation in times of climate change: what makes a fisher diversify livelihoods?** *Front Mar Sci* 2022, **1373**.

60. Salgueiro-Otero, *et al.*: **Climate adaptation pathways and the role of social-ecological networks in small-scale fisheries**. *Sci Rep* (1) 2022, **12**:1-13.

61. Schlingmann A, Graham S, Benyei P, Corbera E, Sanesteban IM, Marelle A, Soleymani-Fard R, Reyes-García V: **Global patterns of adaptation to climate change by Indigenous Peoples and local communities. A systematic review**. *Curr Opin Environ Sustain* 2021, **51**:55-64.

62. Smale DA, Wernberg T, Oliver EC, Thomsen M, Harvey BP, Straub SC, Burrows MT, Alexander LV, Benthuysen JA, Donat MG: **Marine heatwaves threaten global biodiversity and the provision of ecosystem services**. *Nat Clim Change* 2019, **9**:306.

63. •• Thiault L, Mora C, Cinner JE, Cheung WW, Graham NA, Januchowski-Hartley FA, Mouillot D, Sumaila UR, Claudet J: **Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries**. *Sci Adv* 2019, **5**:eaaw9976.

This paper applies a vulnerability framework to the global question of food supply under the threats of climate change in agriculture and fisheries. While it does not incorporate extreme events, this framework and exercise can serve as an example to integrate different levels of the impact chain from extreme events to seafood livelihoods in the future.

64. Tidd AN, Rousseau Y, Ojea E, Watson RA, Blanchard JL: **Food security challenged by declining efficiencies of artisanal fishing fleets: a global country-level analysis**. *Glob Food Secur* 2022, **32**:100598, , https://doi.org/10.1016/j.gfs.2021.100598

65. van Putten IE, Farmery AK, Green BS, Hobday AJ, Lim-Camacho L, Norman-López A, Parker RW: **The environmental impact of two Australian rock lobster fishery supply chains under a changing climate**. *J Ind Ecol* 2016, **20**:1384-1398.

66. •• Wilson RS, Herziger A, Hamilton M, Brooks JS: **From incremental to transformative adaptation in individual responses to climate-exacerbated hazards**. *Nat Clim Change* 2020, **10**:200-208.

This is a comprehensive review on empirical studies across sectors that focuses on the drivers of behavioral responses and critically explores the role existing social norms and cultural contexts in shaping those responses. The article clearly differentiates adaptation and transformation responses and highlights the bias in the literature, where efforts have missed targeting collective benefits and are not representative of the diversity of the world's cultures and their related epistemologies and ontologies (i.e. indigenous communities underrepresented).

67. Ilosvay XÉE, Molinos JG, Ojea E: **Stronger adaptive response among small-scale fishers experiencing greater climate change hazard exposure**. *Communications Earth & Environment* (1) 2022, **3**:246.

68. Collins M., M. Sutherland, L. Bouwer, S.-M. Cheong, T. Fr.licher, H. Jacot Des Combes, M. Koll Roxy, I. Losada, K. McInnes, B. Ratter, E. Rivera-Arriaga, R.D. Susanto, D. Swingedouw, and L. Tibig, 2019: Extremes, Abrupt Changes and Managing Risk. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. P.rtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegr.a, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 589–655. https://doi.org/10.1017/9781009157964.008.