




## Stronger adaptive response among small-scale fishers experiencing greater climate change hazard exposure

Xochitl Édua Elías Ilosvay <sup>1</sup>, Jorge García Molinos <sup>2</sup> & Elena Ojea <sup>1</sup>

Progressive climate-driven environmental changes are threatening the global livelihoods of small-scale fishers, yet how their adaptation responses vary in relation to hazard exposure is poorly understood. We use a systematic review approach to identify a global data set of 301 reported adaptation responses (remaining, adaptive, and transformative) of small-scale fishers to climate change and analyse their spatial agreement with estimated geographical location of global coastal hotspot areas for specific climate change hazards associated to those responses (long-term trends in sea surface temperature, cumulative intensity of marine heatwaves, frequency of tropical storms, and intensity of associated storm surges). Only 37% of responses were found in climate change hotspots. Despite this, our results evidence that fishers are responding more passively in areas with lower exposure levels to abrupt climatic events. The relative proportion of adaptive and transformative responses increase with climate change hazard exposure.

<sup>1</sup>Centro de Investigación Mariña, Universidade de Vigo, Future Oceans Lab, Vigo, Spain. <sup>2</sup>Arctic Research Center, Hokkaido University, Sapporo, Japan.  
email: [xochitl.ilosvay@uvigo.es](mailto:xochitl.ilosvay@uvigo.es)

Small-scale fisheries (SSF) employ over 90% of the world's capture fishers<sup>1</sup>, produce around half of the global catch directly consumed by humans<sup>2</sup>, and provide food and labor opportunities for ~100 million people around the globe<sup>3</sup>. They are also especially vulnerable to the effects of anthropogenic climate change<sup>4,5</sup>. While increasing ocean temperatures are pushing marine species towards colder environments in higher latitudes and deeper waters<sup>6–9</sup>, small-scale fishers struggle to maintain their traditional livelihoods<sup>10,11</sup>. Warming is but one of the many faces of climate change. Progressive environmental trends of ocean acidification, altered rainfall regimes, and more frequent and intense extreme events (e.g., marine heatwaves, cyclones, and storms)<sup>12,13</sup> apply additional pressure on SSF by putting the safety of fishing operations at risk or by damaging infrastructure and housing<sup>14–16</sup>.

Whilst fishers' responses to climate change are increasingly being reported in the literature<sup>17–19</sup>, climate change adaptation responses have been mainly investigated using climate change projections or hypothetical impacts, and existing studies rarely address exposure to compound climate change hazards<sup>20</sup>. Identifying current hotspots of climate change exposure in relation to existing adaptation strategies can shed light on these questions as natural laboratories that lead to the advancement of adaptation science and policy across spatial scales<sup>21,22</sup>.

Recent work suggests that adaptation responses in fisheries cover a range of strategies, from remaining and coping to adapting and transforming<sup>23–25</sup>, and that, among other drivers, the choice of response can be shaped by the magnitude of climate change impacts<sup>26</sup>. Adaptive responses have been defined as changes in existing practices and behaviors allowing the pre-existing social–ecological system to absorb the change, while transformative responses can alter the existing social–ecological system, possibly leading to the creation of a new system<sup>24</sup>. The literature proposes that transformative responses are adopted, for example, as incremental impacts accumulate or after radical ecosystem shifts<sup>26</sup>. However, this novel theoretical foundation is still supported by little empirical evidence on how the nature and characteristics of the hazard can shape adaptive or transformative individual responses<sup>24,27</sup>. Here, we address these research gaps using a systematic review approach<sup>28,29</sup>. From an initial, exhaustive review of 680 scientific papers and technical reports, we select 60 documents that meet our screening criteria from which we extract and categorize (remain, adapt, transform) past and/or current autochthonous responses of small-scale fishers to climate change (see “Methods”). We define “autochthonous responses” as deliberate local adaptations undertaken solely by

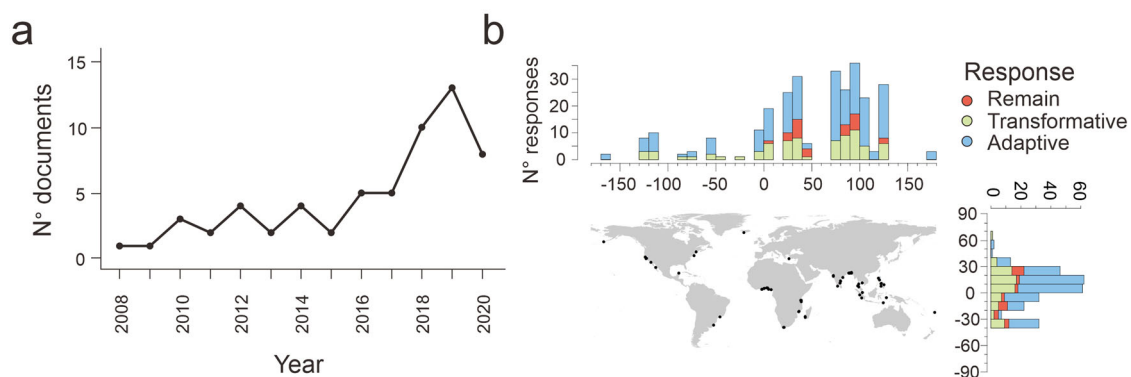
small groups or individuals (i.e., small-scale fishers) exposed to multi-scalar drivers and feedbacks<sup>30,31</sup>. Past literature has primarily focused on large-scale adaptations in high-income counties<sup>32</sup>. However, individual responses are always present, regardless of the presence or absence of top-down adaptation plans or strategies, because individual fishers must adapt to sustain themselves<sup>33</sup>. For this reason, we focus on individual autochthonous responses as they are the first level of response and thus play a defining role in climate change adaptation.

We then analyze the spatial correspondence of these responses by type (remaining, adaptive, and transformative responses) with coastal climate change hazard hotspots. We use the hazards most frequently reported to elicit fishers' responses in the literature (i.e., observed rates of ocean warming and intensity of marine heatwaves, frequency of tropical storm, and associated storm surges) (see “Methods”). This allows us to answer the following questions: (a) which and where are the most prevalent climate change hazards impacting SSF worldwide?; (b) where and what type of in situ responses of small-scale fishers to climate change are being reported in the literature?; and (c) are the adaptations reported in the literature located within climate change hotspots and does that correspondence in any way condition the type of adaptation response?

## Results and discussion

**Climate change impacts and adaptations in the literature.** We extracted 301 reported responses of small-scale fishers to climate change from 60 documents that fulfilled all eligibility criteria between the years 2008 and 2020 (Supplementary Table 1, Supplementary Fig. 1, and Supplementary Data 1). The increasing trend in the number of literature reporting fishers' adaptation over the last decade (Fig. 1a) provides clear evidence that climate-driven change in marine systems is a present reality mediating autochthonous response behavior in small-scale fisheries systems<sup>33</sup>, which is gaining momentum in climate change research.

The reported responses of SSF were mostly attributed to a decrease in marine resources coupled to long-term sea-surface temperature (SST) increase (46%), increasing frequency of tropical storms (19%), coastal floods, and sea surges (11%), and marine heatwaves (MHWs) or events associated to them (e.g., coral bleaching events) (6%) (Supplementary Table 2). Almost half of the hazards were categorized to impact resource availability (48%), whereas only 16% were found to impact solely fishing operations (16%) (i.e., storm frequency, sea surges, disease



**Fig. 1** Number of documents with climate change adaptations and location of small-scale fishers' found in the literature. **a** Number of documents ( $n = 60$ ) reporting small-scale fisheries responses to climate change by year of publication. Literature review conducted on July 2020. **b** Spatial distribution and corresponding latitudinal and longitudinal frequency histograms of the resulting reported responses ( $n = 281$ ) from small-scale fishers to climate change reported in the literature by category. Map was created using ArcMap v10.7.1.

outbreaks, and harmful algal blooms caused by marine heatwaves) (Supplementary Data 2). Climate-driven shifting stocks and catch decrease are considered as two of the greatest threats to current fisheries worldwide and in the future<sup>34,35</sup>. Indeed, most of the existing climate change-related SSF literature focuses on such impacts<sup>36–38</sup>. Yet, fishing operation hazards can reduce the number of “fishable” days, endanger fishers during their fishing operations, and impact fishing operational costs<sup>17,39,40</sup>. It is necessary to emphasize that these results do not imply that hazards impacting fishing operations are not considerably impacting SSF worldwide, but rather that those impacts have not been captured by previous literature. Thirty-five percent of the responses were attributed to both resource availability and fishing operations, suggesting that these two hazards often co-occur simultaneously.

Most of the adaptations were found inside the tropical belt (23.5 degrees north and south of the Equator), particularly in South East Asia, India, and Bangladesh ( $n = 152$ ), followed by Africa ( $n = 91$ ), and Latin America ( $n = 19$ ) (Fig. 1b). United States of America ( $n = 17$ ) and Europe ( $n = 2$ ) were the regions with the lowest number of reported autochthonous SSF adaptations.

### Overlap between adaptations and climate change hotspots.

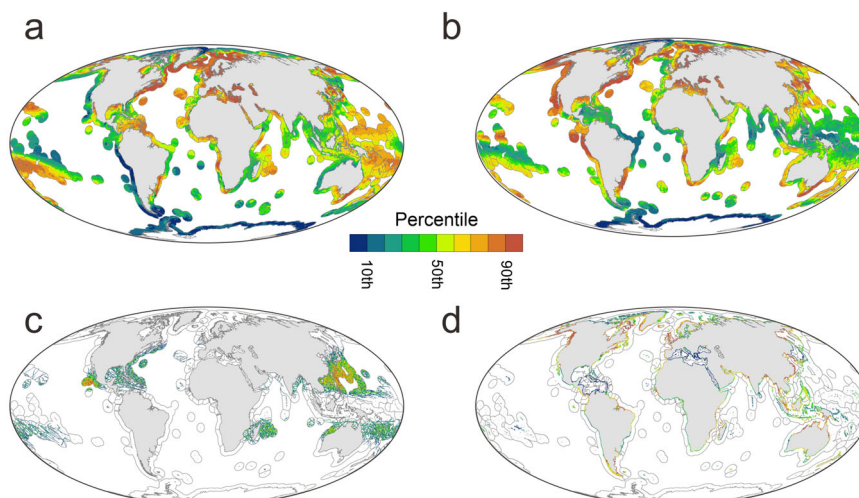
Although most of the reported adaptations were found in the tropics, thus associated to hazards tied to tropical regions, we found that the climate change hotspots (i.e., the 90th percentile hazard exposure regions) concentrated within temperate regions with a few exceptions, such as the North Pacific Coast of South America, the Atlantic Coast of Angola and Namibia, and the South-Eastern coast of Australia (Fig. 2 and Supplementary Fig. 2). Temperate and high-latitude regions also emerge as prominent cumulative hazard exposure areas in which hotspots for single climate change hazards overlap (Fig. 3d). For example, the North East Atlantic Ocean, Arctic region, semi-enclosed seas (such as the Mediterranean, Black Sea, North Sea, and the Baltic Sea), Gulf of California, Atlantic coast of Uruguay and Brazil and South-western coast of Australia were hotspots (90th percentile regions) for both SST warming and MHWs (Fig. 2a, b). The North Sea appears as a hotspot of MHWs and storm surges (Fig. 2b, d and Supplementary Fig. 2).

From 281 responses analyzed, less than half (37%) were located in coastal hazard hotspots (90th percentile). This number more than doubled at the 75th percentile threshold with a total 233 exposed responses (Fig. 3 and Supplementary Data 3 and 4). Although we reduced uncertainties associated to the response locations by applying a 100 km buffer radius, taken as a good compromise distance considering the spatial information available and the distance small-scale fisheries operate from port, inaccuracies in the inferred geographical location of the responses (Supplementary Methods), might have contributed to bias these results to some extent. Importantly, however, results were overall consistent irrespective of the distance from location (see “Methods” and Supplementary Table 3).

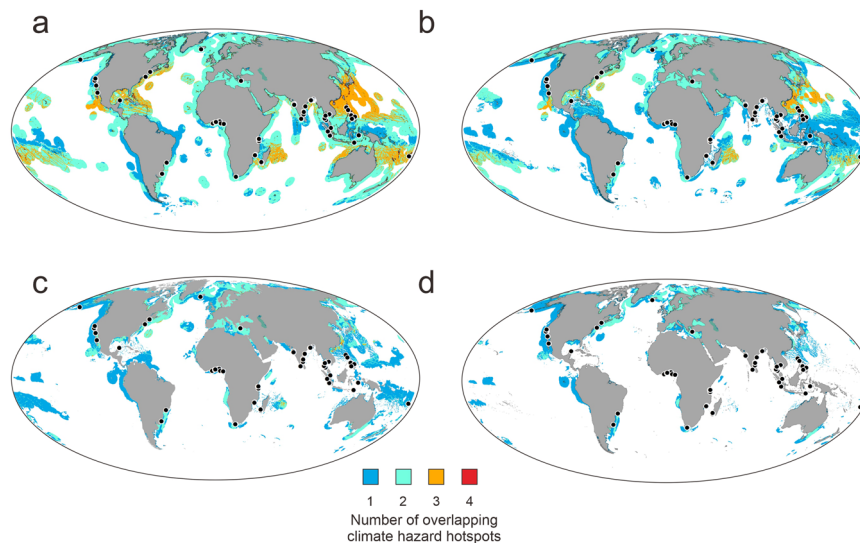
Temperate and high-latitude regions remained exposed to a single or a pair of hazards across exposure thresholds, whereas tropical and subtropical regions often experienced exposure to three or even locally four hazards at lower exposure thresholds (25th and 50th percentiles; Fig. 3a, b). Although exposure to compounded climate change hazards can elicit larger than expected impacts where they interact synergistically even at relatively low magnitudes<sup>41</sup>, this possibility has been scarcely explored for SSF<sup>42</sup> and urgently calls for future research on the subject.

It is also important to note that temperate marine ectotherms have greater thermal tolerance windows than tropical ones, possibly leading to faster poleward migration of tropical species with lower increasing SST rates<sup>43,44</sup>. This is something that may contribute to adaptation being more responsive in the tropics to lower levels of warming compared to temperate regions. This trend may well intensify in the future, as climate change generates a global geographical imbalance of climate-driven expansions and contractions of fishery stocks between tropical and higher latitude regions<sup>45</sup>.

In addition, coastal low-income countries concentrated in tropical regions are not only more vulnerable to climate change because of infrastructure and institutional constraints but are also predicted to experience some of the most devastating impacts of climate change in the future<sup>46–48</sup>. The high vulnerability together with the economic and food security importance of SSF in low-income countries<sup>49,50</sup> might help explain the focus of the climate change adaptation literature in these tropical regions that we



**Fig. 2 Intensity of climate change hazards.** Based on the percentiles associated with each hazard in coastal waters: **a** rate of change in sea-surface temperature (1982–2018), **b** cumulative intensity of marine heatwaves (1982–2018), **c** frequency of tropical storms (1980–2018), and **d** estimates of extreme sea levels associated to storm surges (1974–2014). Color categories associated with deciles with the most extreme (90th) corresponding to coastal hotspots for each of the four hazards (maps with the actual values of the hazards are provided in Supplementary Fig. 2). The maps were created using ArcMap v10.7.1.



**Fig. 3 Spatial overlap of the geographical locations of adaptation responses and climate change hazards.** Correspondence of climate change adaptation responses ( $n = 281$ ) with regions of increasing cumulative exposure to the four climate change hazards (rates of change in sea-surface temperature, cumulative intensity of marine heatwaves, frequency of tropical storms, and intensity of associated storm surges) calculated for their respective (a) 25th, (b) 50th, (c) 75th, and (d) 90th percentiles (the latter representing the climate hazard hotspots). Colors indicate the number of overlapping hazards in a given location. Black dots correspond to the location of the adaptation responses. The maps were created using ArcMap v10.7.1.

observe in our results. On the other hand, the perception of low risk and high adaptive capacity in high-income countries could also have lead research and institutions in these regions to prioritize other issues, such as regulating overfishing or fisheries management<sup>51,52</sup>. This, however, might be changing as the effects of climate change become more evident. Although there are new studies reporting climate change adaptations of small-scale fishers in temperate and Arctic regions<sup>53</sup>, they were not included in this study due to the mismatch with the time scope of our analysis.

**Adaptation types.** The remaining responses were the least frequent, contributing to only 10% of all fishers' responses found in the literature. This evidences that most fishers are actively responding to the impacts of climate change. The most common remaining responses were borrowing money from money lenders or family and friends (29% of remaining responses), reducing household expenses (16%), and sitting and waiting for better weather/marine resource recovery (16%). These types of responses have been attributed in the literature to multiple factors such as individuals not recognizing the threat<sup>54</sup>, fishers attributing the impacts to other local pressures due to existing mental models<sup>55,56</sup>, or fishers not having the resources to respond. However, we found that most remaining responses in our literature review were attributed to capital and knowledge constraints and a sense of powerlessness<sup>39,57–59</sup>.

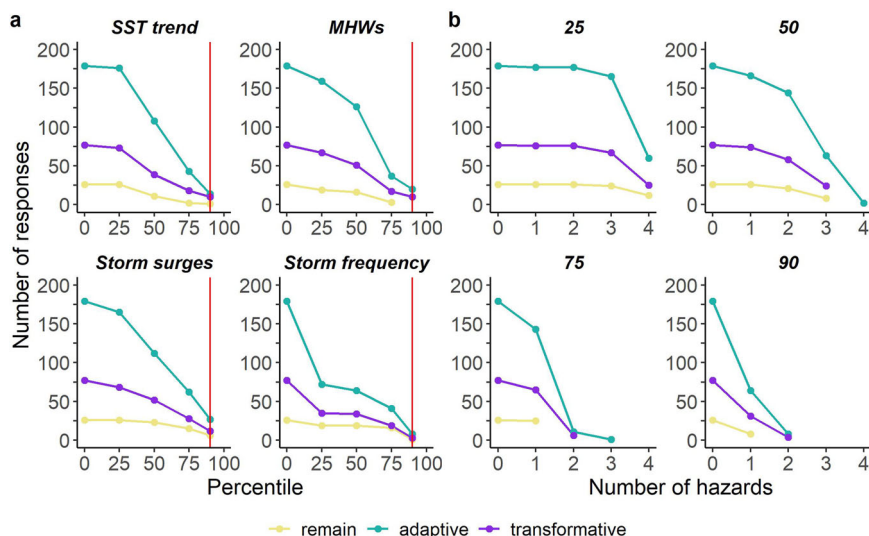
Adaptive responses were the most abundant, comprising 63% of all responses found in the literature review. They comprised a great variety of responses, including change in fishing gear and methods (19% of the adaptive responses), increase in fishing effort (9%), and use of new fishing technology and social networks (each 8%, respectively) as the most frequent ones (Supplementary Data 2). These types of responses are often described as coping mechanisms in the short term and are often viewed as 'maladaptive' because of the high likelihood of exacerbating environmental degradation in the long term through, for example, overfishing or use of inappropriate fishing practices<sup>60</sup>. A great part of the adaptive responses we found in the literature review, such as increasing fishing effort or starting illegal fishing practices, could exacerbate the impacts of climate

change. However, sometimes there was a trade-off between adaptive responses that could heighten the impacts of climate change and adaptive responses that could increase the adaptive capacity of the fishing communities. For example, responses such as changing fishing gear or methods lead fishers to select less selective and more potentially harmful fishing methods<sup>40</sup>, but also provided fishers with more flexibility to adapt to decreasing marine resources helping them transcend their individual limitations to adapt<sup>61,62</sup>. In various documents, we also found that using social networks and creating self-support groups allowed fishers to share increasing expenses<sup>63</sup>, exchange local knowledge and adaptive strategies<sup>15</sup>, and collectively prepare for upcoming storms<sup>64</sup>.

Transformative responses were less abundant than adaptive ones, making 27% of all responses (Supplementary Data 2). The most frequent responses found were diversifying livelihoods, which comprised 49% of transformative responses, and migration (26%). Transformative responses are mainly described as anticipatory, and aim at reducing the root cause of the vulnerability of communities to climate change<sup>24,26</sup>. Alternative livelihoods can enable fishers reduce fishing pressure and their vulnerability to external shocks<sup>65</sup>. However, we found that in some cases fishers opted for farming and livestock as alternative livelihoods, even in locations where droughts were increasingly being observed<sup>40,66</sup>. Migration has also been reported previously as an important adaptation of fishers in West Africa to climate change<sup>67</sup>, and in our literature review, many fishers migrated seasonally to compensate for climate-driven catch losses. However, migrating entailed large monetary investments, did not necessarily ensure them finding a job or better living conditions elsewhere, while outmigration can fracture communities by breaking networks and transforming relationships<sup>40,58</sup>.

**Climate change hazard exposure levels shaping responses.** Differences in the level of hazard exposure can also elicit distinct types of climate change responses, from coping and incremental (adaptive) to transformative adaptations<sup>26</sup>. We found some indication of such relationships between the type of adaptation response, the hazard exposure level, and the cumulative exposure





**Fig. 4 Types of responses of small-scale fishers in relation to climate change exposure.** The responses were categorized following the adaptive–transformative framework of ref. 24. **a** Number of responses found in the literature geographically overlapping regions at four different exposure thresholds (percentiles 25th, 50th, 75th, and 90th) of long-term rate of change in sea-surface temperature (SST) (1982–2018), cumulative intensity of marine heatwaves (MHV) (1982–2018), estimates of extreme sea levels associated to storm surges (1974–2014), and frequency of tropical storms (1980–2018). We used the full set of responses ( $n = 281$ ) that presented coordinates to calculate the number of responses overlapping each hazard exposure level. The number of responses per hazard type per the corresponding threshold is provided in Supplementary Data 2. **b** Number of responses found in regions exposed at least to 1, 2, 3, and 4 cumulative hazards at four exposure levels (percentiles 25th, 50th, 75th, and 90th). Zero equals the total number of responses ( $n = 281$ ). The full set of responses was used for the calculation of responses overlapping each cumulative hazard number using a buffer radius of 100 km. The number of responses of each response type per cumulative hazard number for all exposure levels is provided in Supplementary Data 3. The vertical red line indicates the hotspot threshold (90th percentile).

to hazards. Remaining responses had the lowest relative proportions across all exposure levels and the cumulative number of hazards (Fig. 4). We also found a higher relative proportion of remaining responses in areas with the lowest exposure levels to single hazards (Fig. 4a), and in locations exposed to lower levels of co-occurring hazards (Fig. 4b). Remaining responses were also not present in the highest exposure level (90th percentile) for MHWs and highest co-occurrence of hazards in the higher percentiles (50th, 75th, and 90th). However, they were still found in the highest exposure levels (75th and 90th percentile) of SST rate of change, storm surge intensity, and storm frequency.

Higher levels of exposure were associated with higher proportions of adaptive and transformative responses for all hazards (i.e., the 75th and 90th percentile), albeit no clear differences between the adaptive and transformative responses emerged among the different exposure levels. At the highest exposure thresholds (75th and 90th percentile), there was also no clear difference between adaptive and transformative responses with growing cumulative number of hazards at any of the exposure level (Fig. 4b). Our results follow to some extent the adaptation strategies gradient coupled to increasing hazard level exposure proposed in the literature<sup>26</sup>, but differences among climate change hazards and the lack of clear differences between adaptive and transformative responses may highlight that exposure alone cannot explain fishers' responses to climate change.

Being at the interface between terrestrial and marine systems, coastal communities are also exposed to a wide range of additional climatic hazards, such as flooding or droughts, that may also influence SSF adaptive responses to a changing climate<sup>68</sup>. Various studies also highlight how the socio-economic context, such as the individual adaptive capacity can shape fishers' responses to climate change<sup>22,24,27</sup>. We could not obtain the required information from the original documents identified by our literature review to, for example, include the adaptive capacity domains used in ref. 24 or the social–ecological capital used in ref. 69 in our analysis. Using aggregated capacity

indices from international databases, such as GDP, the GIBNI Index or Institutional compliance, would be possible but potentially inaccurate given that these indices are only available at the country level and, importantly, do not focus specifically on the artisanal fishing activity.

Individual fishers have limited adaptive capacity and our results partly show, for example, the crucial role that the community plays in SFF when facing climate change to exchange knowledge, reduce high costs or as support systems<sup>15,63,64</sup>. However, transformative responses face many barriers for their implementation due to the high monetary, social and political support needed<sup>26</sup>. Fishing communities may also need to access new information, fishing strategies, resource management regimes or alternative livelihoods to face the new challenges arising from climate change. Gianelli et al.<sup>22</sup> confirm this by showing how combining autochthonous adaptations and perceptions of fishers with scientific and institutional effort, benefited the social learning process through adaptive and transformative pathways across levels in a climate change hotspot<sup>22,24,68</sup>.

While, in this study, we focused on adaptation at the individual level, adaptation for building resilience to climate change can also be promoted at a multi-sectoral collective level<sup>70</sup>, for example, by coordinating the autochthonous responses of the fishers and fishing communities with high-level policies and actions to respond to the acute effects of climate change. This is of vital importance as existing fisheries regulations and fisheries policies may limit fishers' flexibility to adapt to climate change<sup>71</sup>. Further research could empirically explore the relationships between hazards, adaptation responses, and the social and institutional context at different levels.

## Conclusion

Local knowledge of SSF-systems still lacks recognition, but our results together with the existing literature analyzing marine systems responses to climate change worldwide<sup>17,18</sup> shed some

light on understanding SSF autochthonous adaptations to climate change. Our results provide evidence that the SSF climate change adaptation literature has mainly focused on tropical regions even though climate change hotspots were mostly found in temperate regions. Despite the importance of this focus, this study highlights the lack of understanding of the responses of SSF in those regions where the impacts of climate change are currently more acute, i.e., climate change hotspots. Disentangling which factors (i.e., levels of exposure to climate change hazards or the socio-economic dynamics in which marine social-ecological systems are embedded<sup>27</sup>) are driving remaining, adaptive, or transformative responses is critical to better comprehend fishers' ability and willingness to respond to these changes in the future<sup>27</sup>. A better understanding of the adaptation strategies and responses that SSF are already implementing in climate change hotspots may facilitate the anticipation and implementation of adaptation strategies, given the climate change projected in the future irrespective of the climate mitigation actions enforced<sup>72,73</sup>.

## Methods

**Literature review.** We followed the methodological framework for systematic reviews provided by the Collaboration for Environmental Evidence<sup>28,29</sup>. Firstly, the inclusion and exclusion criteria were selected using the population (P), exposure (E), comparator (C), and outcome (O) (i.e., PECO) elements following common practice in systematic evidence synthesis<sup>28,29,74,75</sup>. The PECO framework was developed to create clearly-framed research objectives and questions for systematic reviews in the fields of nutrition, environmental and occupational health, to assess the association between exposures and outcomes<sup>75</sup>. For this study, we only considered documents that presented past and/or current small-scale fisheries (SSF) (P) autochthonous responses (O) to ongoing climate change drivers (E) (Supplementary Table 1). Due to the large heterogeneity in fishing operations and vessels that arises from assessing fisheries worldwide<sup>76</sup>, we did not limit SSF to one single definition. Every study that considered their adaptive systems as SSF was included in the analysis. The comparator (C) element was not used during the selection process as it was included later, when comparing the different levels of climate change hazard exposure<sup>28</sup>.

Following ref.<sup>77</sup> guidelines for generating search strings, we first conducted a "naive search" (i.e., a search using keywords that we considered relevant for the aim of this study) using the Scopus citation index. We then used the *litsearchr* R package<sup>77</sup> and the statistics program R version 4.0.2<sup>78</sup> to systematically find keywords and generate a search string which was modified until the "golden rule" was met (i.e., until all studies identified during the "naive search" as containing the information required to answer the research questions appeared in the search results) (Supplementary Note 1 and Supplementary Table 4).

A complementary search was conducted in Google Scholar to account for the large portion of adaptation literature produced by governments, or non-governmental organizations that are mainly available as gray literature ( $n = 150$ )<sup>18,29</sup>.

We then imported the search results into Mendeley reference manager (Supplementary Table 5) and de-duplicated them ( $n = 680$ ). During the title and abstract screening, all records not meeting the selection criteria were excluded (Supplementary Table 1). Records providing only biological information, land-based activities or that were otherwise not related to the research questions were consequently excluded in the title screening ( $n = 242$ ) (see Supplementary Methods). Due to time and workforce constraints, the abstract screening for the resulting set of documents ( $n = 438$ ) was only conducted by the first author. However, a random subsample of 60 documents (>10% of the total sample size as suggested by CEE 2018) was separately screened by each co-author using the established selection criteria to assess the consistency of results. Disagreements (23% of the subsample) were then discussed and the inclusion/exclusion decisions (Supplementary Table 1) revised accordingly and reapplied to the remaining abstracts.

All records resulting from the abstract screening ( $n = 200$ ) were thoroughly assessed. In this study, we only considered existing reported autochthonous adaptation responses of small-scale fishers to ongoing or past climate change drivers. Even though climate change literature is abundant across many regions, we excluded documents that did not meet the selection criteria, and for example, only focused on potential autochthonous adaptations to future impacts<sup>79</sup>, addressed institutional adaptations and/or interventions<sup>80</sup>, or did not explicitly attribute the fishers responses to climate change<sup>81</sup>. This drastically reduced the number of records and regions included in the analysis ( $n = 60$ ) (Supplementary Fig. 3 and Supplementary Data 1 and 4). Literature in French was excluded in this step due to language limitations ( $n = 2$ ). Each fisher's response identified was treated as a single response unit for which we collected the following additional information when available: coordinates, or the name of the location if they were not given (Supplementary Note 2), the climate change hazard identified as motivating the

response, and, if existing, any other stressor related to the response (e.g., overfishing, illegal fishing, price decrease, and change in management strategy). Important information, such as fishers' adaptive capacity or climate change perception, was very scarce, hence, was not possible to collect. In the case of adaptation responses identified from review articles, we used the primary literature source referenced by the authors of the review article for full-text screening (i.e., "snowballing") ( $n = 38$ ). We followed the same exclusion procedure as described above to obtain two new documents with past autochthonous adaptations of SSF (Supplementary Note 2 and Supplementary Fig. 1).

**Climate change adaptations.** First, we coded each response unit into overarching adaptation terms for a better overview. We then classified the fishers autochthonous responses using a modified version of the adaptive-transformative classification used in ref.<sup>24</sup>. This framework allowed us to categorize the responses in an ordered manner without requiring unavailable context and allowed us to test if the adaptation types (proposed by Fedele et al.<sup>26</sup>) change with increasing climate change exposure<sup>26</sup>. For this, we defined our social-ecological systems as a fishing individual interacting with (a) specific marine resource(s) attached to a defined location. Fishers' responses, where the fishers were considered to suffer the economic losses and did not represent an active adaptation response, were classified as remaining responses. Responses that allowed the actor to absorb and/or accommodate to the change without altering the fundamental characteristics and reinforcing the social-ecological systems were considered adaptive; whereas responses truly altering the social-ecological system's properties and allowing fishers to reduce the root causes of vulnerability were considered transformative (Supplementary Data 5).

**Climate change hazards.** We found a total of 23 climate change drivers (i.e., hazards and impacts) documented to elicit responses in the literature review. First, each climate change driver was classified into those related to resource availability and those affecting fishing operations as suggested by Cheung et al.<sup>82</sup> (Supplementary Data 4).

For the exposure analysis, we focused on the most frequent climatic hazards reported in the literature. We first calculated the frequency in which each driver was mentioned, taking into account that each response unit could be attributed to more than one climate change driver. Then, we attributed a climate change hazard to each driver, based on the context provided by each study (if the driver mentioned in the literature was already a hazard, the original hazard was selected) (Supplementary Table 2). For this purpose, climate change hazard was defined as the "occurrence of a [...] human-induced physical 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"<sup>83</sup>. The most frequent (>5% frequency threshold) climate hazards were: rates of change in sea-surface temperature (SST) (46%), frequency of tropical storms (19%), the intensity of storm surges (11%), and cumulative intensity of marine heatwaves (MHWs) (6%), (Supplementary Table 2). We used SST as a proxy for changes in resource availability driven by ocean warming<sup>72</sup>. The decadal oscillation changes were described in the literature as prolonged discrete anomalously warm water events and are known to be one of the of climate change on natural climate variability such as El Niño Southern Oscillation. For this reason, this driver was included in the MHWs hazard<sup>84</sup>.

Sea-surface temperature (SST) trends (°C/year) were calculated as the slope of the linear regression of monthly averaged SST over the period 1982–2018 using the 0.25° daily Optimum Interpolation Sea Surface Temperature (OISST) data set of the National Oceanic and Atmospheric Administration (NOAA)<sup>85</sup>.

Marine heatwave (MHW) average intensity and duration were sourced from the data set provided by the Marine Heatwaves International Working Group<sup>86</sup>. This data set is available globally at 0.25° grid resolution from 1982 to 2018 and have been calculated using OISST AVHRR-only<sup>85</sup> data following<sup>87</sup>. We then calculated the total accumulated intensity (TAI) per grid cell as the sum of the accumulated intensities for all the events that occurred in that cell over the study period (1982–2018), where the accumulated intensity of a single event is defined as the product of its average intensity by its duration.

The storm surge data were obtained from the Global Tide and Surge Reanalysis (GTSR) global data set<sup>88</sup>. The GTSR is provided as 12,000 coastline segments of variable length with associated estimates of extreme sea levels associated to a 1-in-100-year return period calculated for the period 1974–2014<sup>88</sup>. We used these values as our index of exposure for this hazard by directly rasterizing the estimated storm surge levels associated to each coastline segment to our 0.25° working grid resolution.

The frequency of tropical storms data (1980–2018) were obtained from the Best Track Archive for Climate Stewardship (IBTrACS) collected by the NOAA National Climatic Data Center from different Tropical Cyclones Warning Centers and the WMO Regional Specialized Meteorological Centers (RSMCs)<sup>89,90</sup>. First, we unified the reported wind speeds to the common duration of 1-min average by multiplying the maximum sustained wind speeds at 10 m above the surface with different average durations (2-min, 3-min, and 10-min averaging periods) by their corresponding conversion factors (1.03, 1.05 and 1.11 for respectively 2-min, 3-min and 10-min winds)<sup>91</sup>. Only hurricane-category storms as defined by the Saffir-Simpson Hurricane Wind Scale, i.e., storms with a 1-min-average maximum

sustained winds of at least 33 m/s (64 knots), were retained for analysis. The storm frequency was then estimated by dividing the total number of hurricane events in each 0.25° grid cell by the corresponding number of years (29) (Supplementary Table 6).

**Data analysis.** Given small-scale fishing communities are located and develop their activity predominantly in coastal waters, we define our hazard hotspots as those areas comprising coastal cells with values equal or greater than the 90th percentile of the values of all coastal cells for a given climatic hazard. Where the 90th percentile represents those locations having values above the 90% of all locations analyzed per hazard and is often used to identify climate change hotspots<sup>72,92</sup>. We also calculated the quartiles associated to each hazard in the same fashion to contrast SSF responses against a range of different levels of exposure. Coastal cells were globally defined as all cells within exclusive economic zone (EEZ) boundaries<sup>93</sup>.

We defined exposure as the “occurrence of a natural or human-induced physical event 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”<sup>83</sup>. To analyze how the level of exposure to climatic hazards elicits the fishers’ response type (remaining, adaptive, and transformative), we examined the spatial correspondence between the location of each adaptation response with the level of exposure existing in the nearby coastal areas for each exposure threshold (25th (low), 50th (medium), 75th (high), and 90th (hotspot) percentiles) for each individual hazard as well as the aggregated effect of all hazards together at a given threshold level (i.e., cumulative exposure). We counted the number of adaptations (per response type) found inside each exposure threshold and the cumulative number of hazards using 50, 100, 150, 200, 250, and 300 km as buffer radii (Supplementary Table 3 and Supplementary Fig. 4). Taking the spatial constraints of the SSF distance<sup>94,95</sup> we counted the number of adaptations found inside each exposure threshold using 100 km as a buffer radius for the final results (Supplementary Data 2 and 3). The responses for which no location was provided ( $n = 20$ ), were documented but excluded from the hotspot and percentile analysis, resulting in 281 responses (Supplementary Note 2).

## Data availability

The following Supplementary Data that support the findings of this study are available in Zenodo: (a) Supplementary Data 1: Small-scale fishers’ adaptations to climate change database at <https://doi.org/10.5281/zenodo.7097406>; (b) Supplementary Data 2: Classification and frequency of climate change drivers and responses of small-scale fishers at <https://doi.org/10.5281/zenodo.7054437>; (c) Supplementary Data 3: Types of fishers’ adaptations with increasing single hazard exposure at <https://doi.org/10.5281/zenodo.7054459>; (d) Supplementary Data 4: Number of fishers adaptations with the increasing cumulative number of hazards at <https://doi.org/10.5281/zenodo.7054469>; (e) Supplementary Data 5: Literature presenting past climate change small-scale fishers’ adaptations (2008–2020) at <https://doi.org/10.5281/zenodo.7054413>.

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## References

- Kelleher, K. et al. *Hidden Harvest: The Global Contribution of Capture Fisheries* (Worldbank, 2012).
- Pauly, D. & Zeller, D. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nat. Commun.* **7**, 10244 (2016).
- FAO. *The State of World Fisheries and Aquaculture 2018—Meeting the Sustainable Development Goals* (Food and Agriculture Organization, 2018).
- Cheung, W. W. L., Brodeur, R. D., Okey, T. A. & Pauly, D. Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. *Progr. Oceanography* **130**, 19–31 (2015).
- IPCC. Annex II: Glossary [Mach, K.J., S. Planton and C. von Stechow (eds.)], in *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 [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]* (eds Mach, K. J., Planton, S. & von Stechow, C.) 117–130 (IPCC, 2014).
- Pörtner, H. O. & Peck, M. A. Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. *J. Fish Biol.* **77**, 1745–1779 (2010).
- Horta e Costa, B. et al. Tropicalization of fish assemblages in temperate biogeographic transition zones. *Mar. Ecol. Prog. Ser.* **504**, 241–252 (2014).
- Poloczanska, E. S. et al. Responses of marine organisms to climate change across oceans. *Front. Mar. Sci.* **3**, 62 (2016).
- Kumagai, N. H. et al. Ocean currents and herbivory drive macroalgae-to-coral community shift under climate warming. *Proc. Natl Acad. Sci. USA* **115**, 8990–8995 (2018).
- Pecl, G. T. et al. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science* **355**, eaai9214 (2017).
- Young, T. et al. Adaptation strategies of coastal fishing communities as species shift poleward. *ICES J. Mar. Sci.* **76**, 93–103 (2019).
- Pörtner, H. O. et al. *Ocean 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.) 411–484 (Cambridge University Press, 2014).
- Stott, P. A. et al. Attribution of extreme weather and climate-related events: attribution of extreme weather and climate-related events. *WIREs Clim. Change* **7**, 23–41 (2016).
- Iwasaki, S., Razafindrabe, B. H. N. & Shaw, R. Fishery livelihoods and adaptation to climate change: a case study of Chilika lagoon, India. *Mitig. Adapt. Strateg. Glob. Change* **14**, 339–355 (2009).
- Deb, A. K. & Haque, C. E. Livelihood diversification as a climate change coping strategy adopted by small-scale fishers of Bangladesh. in *Climate Change Adaptation, Resilience and Hazards* (eds Filho, W. L. et al.) 345–368 (Springer International Publishing, 2016).
- Lindgren, M. & Brander, K. Adapting fisheries and their management to climate change: a review of concepts, tools, frameworks, and current progress toward implementation. *Rev. Fisheries Sci. Aquaculture* **26**, 400–415 (2018).
- Savo, V., Morton, C. & Lepofsky, D. Impacts of climate change for coastal fishers and implications for fisheries. *Fish Fish* **18**, 877–889 (2017).
- Miller, D. D., Ota, Y., Sumaila, U. R., Cisneros-Montemayor, A. M. & Cheung, W. W. L. Adaptation strategies to climate change in marine systems. *Glob. Change Biol.* **24**, e1–e14 (2017).
- Schlingmann, A. et al. Global patterns of adaptation to climate change by Indigenous Peoples and local communities. A systematic review. *Curr. Opin. Environ. Sustain.* **51**, 55–64 (2021).
- Conway, D. et al. The need for bottom-up assessments of climate risks and adaptation in climate-sensitive regions. *Nat. Clim. Chang.* **9**, 503–511 (2019).
- Pecl, G. T., Hobday, A. J., Frusher, S., Sauer, W. H. H. & Bates, A. E. Ocean warming hotspots provide early warning laboratories for climate change impacts. *Rev. Fish Biol. Fisheries* **24**, 409–413 (2014).
- Gianelli, I., Ortega, L., Pittman, J., Vasconcellos, M. & Defeo, O. Harnessing scientific and local knowledge to face climate change in small-scale fisheries. *Glob. Environ. Change* **68**, 102253 (2021).
- Galappaththi, E. K., Ford, J. D. & Bennett, E. M. A framework for assessing community adaptation to climate change in a fisheries context. *Environ. Sci. Policy* **92**, 17–26 (2019).
- Barnes, M. L. et al. Social determinants of adaptive and transformative responses to climate change. *Nat. Clim. Chang.* **10**, 823–828 (2020).
- 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).
- Fedele, G., Donatti, C. I., Harvey, C. A., Hannah, L. & Hole, D. G. Transformative adaptation to climate change for sustainable social-ecological systems. *Environ. Sci. Policy* **101**, 116–125 (2019).
- Green, K. M. et al. How adaptive capacity shapes the adapt, react, cope response to climate impacts: insights from small-scale fisheries. *Clim. Change* **164**, 15 (2021).
- James, K. L., Randall, N. P. & Haddaway, N. R. A methodology for systematic mapping in environmental sciences. *Environ. Evid.* **5**, 7 (2016).
- CEE 2018. *Guidelines for Authors | Environmental Evidence* <http://www.environmentalevidence.org/information-for-authors> (2018).
- Howard, P. L. Human adaptation to invasive species: a conceptual framework based on a case study meta-synthesis. *Ambio* **48**, 1401–1430 (2019).
- Thornton, T. F., Puri, R. K., Bhagwat, S. & Howard, P. Human adaptation to biodiversity change: an adaptation process approach applied to a case study from southern India. *Ambio* **48**, 1431–1446 (2019).
- Howard, P. Human adaptation to biodiversity change: facing the challenges of global governance without science? Paper presented to the 2009 Amsterdam Conference on the Human Dimensions of Global Environmental Change, 2–4 December (2013).
- Howard, P. L. & Pecl, G. T. Introduction: autochthonous human adaptation to biodiversity change in the Anthropocene. *Ambio* **48**, 1389–1400 (2019).
- Bindoff, N. L. et al. Changing ocean, marine ecosystems, and dependent communities. in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (eds Pörtner, H. O. et al.) 447–587 (2019).
- Golden, C. D. et al. Nutrition: fall in fish catch threatens human health. *Nature* **534**, 317–320 (2016).
- Plagányi, É. Climate change impacts on fisheries. *Science* **363**, 930–931 (2019).
- Papaioannou, E. A. et al. Not all those who wander are lost—responses of fishers’ communities to shifts in the distribution and abundance of fish. *Front. Mar. Sci.* **8**, 669094 (2021).



38. Fogarty, H. E., Cvitanovic, C., Hobday, A. J. & Pecl, G. T. Prepared for change? An assessment of the current state of knowledge to support climate adaptation for Australian fisheries. *Rev. Fish Biol. Fisheries* **29**, 877–894 (2019).
39. Pattinama, E. & Vieldha Ayhuan, V. The role of religion to face climate change: a survival strategy of Christian fishermen families to embody gender perspective and spirituality of GPM's congregation in coastal area of Nusaniwe Subdistrict Ambon City. in *Proceedings of the International Conference on Religion and Public Civilization (ICRPC 2018)* (Atlantis Press, 2019).
40. Esia-Donkoh, K. *Fishing Communities' Adaptation to Climate Change at Komenda-Edina-Eguafo-Abrem Municipality, Ghana* (University for Development Studies, 2017).
41. Simpson, N. P. et al. A framework for complex climate change risk assessment. *One Earth* **4**, 489–501 (2021).
42. Gruber, N., Boyd, P. W., Frölicher, T. L. & Vogt, M. Biogeochemical extremes and compound events in the ocean. *Nature* **600**, 395–407 (2021).
43. Sunday, J. M., Bates, A. E. & Dulvy, N. K. Global analysis of thermal tolerance and latitude in ectotherms. *Proc. R. Soc. B* **278**, 1823–1830 (2011).
44. Chaudhary, C., Richardson, A. J., Schoeman, D. S. & Costello, M. J. Global warming is causing a more pronounced dip in marine species richness around the equator. *Proc. Natl Acad. Sci. USA* **118**, e2015094118 (2021).
45. Pinsky, M. L. et al. Preparing ocean governance for species on the move. *Science* **360**, 1189–1191 (2018).
46. Lam, V. W. Y. et al. Climate change, tropical fisheries and prospects for sustainable development. *Nat. Rev. Earth Environ.* **1**, 440–454 (2020).
47. Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D. & Herrick, S. Climate change impacts on the biophysics and economics of world fisheries. *Nat. Clim. Change* **1**, 449–456 (2011).
48. Allison, E. H. et al. Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fisheries* **10**, 173–196 (2009).
49. Allison, E. H. & Ellis, F. The livelihoods approach and management of small-scale fisheries. *Mar. Policy* **25**, 377–388 (2001).
50. World Bank. *Hidden Harvest: The Global Contribution of Capture Fisheries* (World Bank, 2012).
51. Ford, J. D., Berrang-Ford, L. & Paterson, J. A systematic review of observed climate change adaptation in developed nations: a letter. *Clim. Change* **106**, 327–336 (2011).
52. Edvardsson, I. R., Tingley, D., Conides, A. J., Drakeford, B. & Holm, D. Fishermen's risk perception in four European countries. *Maritime Studies* **139–159** (2011).
53. Schiott, S., Tejnsner, P. & Rysgaard, S. Inuit and local knowledge on the marine ecosystem in Ilulissat Icefjord, Greenland. *Hum. Ecol.* **50**, 167–181 (2022).
54. Hogg, K., Semitiel-García, M., Noguera-Méndez, P., Gray, T. & Young, S. Perceptions of threats facing Cabo de Palos—Islas Hormigas MPA and potential solutions. *Coastal Manag.* **46**, 58–74 (2018).
55. Maltby, K. M., Simpson, S. D. & Turner, R. A. Scepticism and perceived self-efficacy influence fishers' low risk perceptions of climate change. *Clim. Risk Manag.* **31**, 100267 (2021).
56. van Putten, I. E. et al. Empirical evidence for different cognitive effects in explaining the attribution of marine range shifts to climate change. *ICES J. Mar. Sci.* **73**, 1306–1318 (2016).
57. Coulthard, S. Adapting to environmental change in artisanal fisheries—insights from a South Indian Lagoon. *Global Environ. Change* **18**, 479–489 (2008).
58. Gammage, L. C. et al. A case study from the southern Cape linefishery 2: Considering one's options when the fish leave. *South Afr. J. Sci.* **113**, 1–10 (2017).
59. Mozumder, M. M. H., Shamsuzzaman, Md. M., Rashed-Un-Nabi, Md. & Harun-Al-Rashid, A. Socio-economic characteristics and fishing operation activities of the artisanal fishers in the Sundarbans Mangrove Forest, Bangladesh. *Turk. J. Fish. Aquat. Sci.* **18**, 789–799 (2018).
60. Abel, N. et al. Building resilient pathways to transformation when “no one is in charge”: insights from Australia's Murray-Darling Basin. *E&S* **21**, art23 (2016).
61. Aguilera, S. E. et al. Managing small-scale commercial fisheries for adaptive capacity: insights from dynamic social-ecological drivers of change in Monterey bay. *PLoS ONE* **10**, e0118992 (2015).
62. Fregene, B. T. Adaptation strategy by fisher folk to climate change in Ogun State, Nigeria coastal fishing communities: Implications for sustainable artisanal fisheries livelihood. in *Proceedings of the 25th Annual Conference and Fair of the Fisheries Society of Nigeria (FISON)* 327–330 (2010).
63. Franklin, B. S. & Velusamy, M. Vulnerability of marine fishermen to nature-driven stressors. *JCR* **7**, 536–538 (2020).
64. Freduah, G., Fidelman, P. & Smith, T. F. A framework for assessing adaptive capacity to multiple climatic and non-climatic stressors in small-scale fisheries. *Environ. Sci. Policy* **101**, 87–93 (2019).
65. Roscher, M. B. et al. Sustainable development outcomes of livelihood diversification in small-scale fisheries. *Fish Fisheries* **23**, 910–925 (2022).
66. Basu, J. P. Coastal poverty, resource-dependent livelihood, climate change, and adaptation: an empirical study in Indian Coastal Sunderbans. in *Handbook of Research on Climate Change Impact on Health and Environmental Sustainability* (eds. Dinda, S. & Wang, Y.) 441–454 (IGI Global, 2016).
67. Binet, T., Baillieux, R. & Turmine, V. Des migrations de pêcheurs de plus en plus conflictuelles en Afrique de l'Ouest: the migration of fishermen from more and more conflict in West Africa. *Revue Africaine des Affaires Maritimes et des Transports* **5**, 51–68 (2013).
68. Wong, P. P. et al. Coastal systems and low-lying areas. 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.) 360–409 (Cambridge University Press, 2014).
69. Abel, N., Cumming, D. H. M. & Anderies, J. M. Collapse and reorganization in social-ecological systems: questions, some ideas, and policy implications. *E&S* **11**, art17 (2006).
70. Mason, J. G. et al. Attributes of climate resilience in fisheries: from theory to practice. *Fish Fisheries* **23**, 522–544 (2022).
71. Gonzalez-Mon, B. et al. Spatial diversification as a mechanism to adapt to environmental changes in small-scale fisheries. *Environ. Sci. Policy* **116**, 246–257 (2021).
72. Hobday, A. J. & Pecl, G. T. Identification of global marine hotspots: sentinels for change and vanguards for adaptation action. *Rev. Fish Biol. Fisheries* **24**, 415–425 (2014).
73. Pecl, G. T. et al. Autonomous adaptation to climate-driven change in marine biodiversity in a global marine hotspot. *Ambio* **48**, 1498–1515 (2019).
74. Clapton, J., Rutter, D. & Sharif, N. SCIE Systematic mapping guidance. <http://www.scie.org.uk/publications/researchresources/rr03.pdf> (2009).
75. Morgan, R. L., Whaley, P., Thayer, K. A. & Schünemann, H. J. Identifying the PECO: a framework for formulating good questions to explore the association of environmental and other exposures with health outcomes. *Environ. Int.* **121**, 1027–1031 (2018).
76. Smith, H. & Basurto, X. Defining small-scale fisheries and examining the role of science in shaping perceptions of who and what counts: a systematic review. *Front. Mar. Sci.* **6**, 236 (2019).
77. Games, E. M., Stillman, A. N., Tingley, M. W. & Elphick, C. S. An automated approach to identifying search terms for systematic reviews using keyword co-occurrence networks. *Methods Ecol. Evol.* **10**, 1645–1654 (2019).
78. R Core Team. *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, 2020).
79. Bell, J. D. et al. Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. *Mar. Policy* **88**, 303–314 (2018).
80. Lovatelli, A. Technological innovation in mussel seed collection: a response to climate change from fishing communities in southern Chile. *FAO* **33**, 37 (2009).
81. Sievanen, L. How do small-scale fishers adapt to environmental variability? Lessons from Baja California, Sur, Mexico. *Maritime Studies* **13**, 9 (2014).
82. Cheung, W. W. L., Pinnegar, J., Merino, G., Jones, M. C. & Barange, M. Review of climate change impacts on marine fisheries in the UK and Ireland. *Aquatic Conserv. Mar. Freshw. Ecosyst.* **22**, 368–388 (2012).
83. Matthews, J. B. R. et al. Annex VII: glossary. in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Masson-Delmotte, V. et al.) Vol. IPCC 2021 (Cambridge University Press, 2021).
84. Bertrand, A. et al. *El Niño Southern Oscillation (ENSO) Effects on Fisheries and Aquaculture* (FAO, 2020).
85. Huang, B. et al. NOAA 0.25-degree daily optimum interpolation sea surface temperature (OISST), Version 2.1. <https://doi.org/10.25921/RE9P-PT57> (2020).
86. Schlegel, R. W. Marine heatwave tracker. *Marine Heatwave Tracker* <http://www.marineheatwaves.org/tracker.html> (2020).
87. Hobday, A. J. et al. A hierarchical approach to defining marine heatwaves. *Prog. Oceanography* **141**, 227–238 (2016).
88. Muis, S., Verlaan, M., Winsemius, H. C., Aerts, J. C. J. H. & Ward, P. J. A global reanalysis of storm surges and extreme sea levels. *Nat. Commun.* **7**, 11969 (2016).
89. Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J. & Neumann, C. J. The international best track archive for climate stewardship (IBTrACS): unifying tropical cyclone data. *Bull. Amer. Meteor. Soc.* **91**, 363–376 (2010).
90. Knapp, K. R., Diamon, H. J., Kossin, J. P., Kruk, M. C. & Schreck, C. J. International Best Track Archive for Climate Stewardship (IBTrACS) Project, Version 4. <https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C01552> (2018).



91. Harper, B. A., Kepert, J. D. & Ginger, J. D. *Guidelines for Converting Between Various Wind Averaging Periods in Tropical Cyclone Conditions*. Vol. WMO/ TD-No. 1555 (World Meteorological Organization, 2010).
92. Xu, L., Wang, A., Wang, D. & Wang, H. Hot spots of climate extremes in the future. *J. Geophys. Res. Atmos.* **124**, 3035–3049 (2019).
93. Flanders Marine Institute. Marine Regions. <https://www.marineregions.org/disclaimer.php> (2021).
94. Grati, F. et al. Mapping small-scale fisheries through a coordinated participatory strategy. *Fish Fisheries* faf.12644 <https://doi.org/10.1111/faf.12644> (2022).
95. Johnson, A. F. et al. A spatial method to calculate small-scale fisheries effort in data poor scenarios. *PLoS ONE* **12**, e0174064 (2017).

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### Author contributions

X.E.E.I., J.G.M., and E.O. designed the research. X.E.E.I. and J.G.M. performed the research and analyzed the data. X.E.E.I., J.G.M., and E.O. wrote the paper.

### Competing interests

The authors declare no competing interests.

### Additional information

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**Correspondence** and requests for materials should be addressed to Xochitl Édua Elías Ilosvay.

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