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Climate change risk and adaptation for fisher communities in Ghana

Bryony Townhill[1] · **Olivia Harrod**[1] · **Suzanne Painting**[1] · **Emmanuel Acheampong**[2] · **James Bell**[1] · **Benjamin Kofi Nyarko**[2] · **Georg Engelhard**[1]

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Abstract
Artisanal fisheries in Ghana account for more than two-thirds of the country's food fish production and employ or support up to 2 million people. However, many fish stocks are close to collapse through overexploitation, especially stocks such as sardinella that are a staple food for Ghanaians. Climate change is expected to affect the fish themselves as well as fishing activities, increasing the already high risk to fishers' livelihoods and Ghana's food security. Here, we use a climate change risk assessment framework to assess vulnerability of Ghanaian fisheries, considering climate hazards, fish species sensitivity and socio-economic vulnerability of different fisheries sectors and regions. The results show that some of the species that constitute the highest catches in Ghana are highly sensitive to climate change, such as snappers, Congo dentex and groupers. Some species assessed as having low sensitivity to climate change in the region are migratory pelagic fish, including tuna. Species caught by artisanal fleets are typically more sensitive than those captured by semi-industrial and industrial fleets. Regionally, the highest climate risk is found for Volta in the east, and the lowest for the Greater Accra region, along the central part of the coastline. This information can be used to identify, with stakeholders, the climate adaptation actions that are most suitable for the different regions and fisheries sectors. Actions can be tailored to the different aspects of climate risk, helping the country to achieve its aims of restoring fish stocks, safeguarding livelihoods and improving climate resilience for Ghana's artisanal fishers.

Keywords West Africa · Vulnerability · Resilience · Climate action · Artisanal

Introduction

Climate change

Impacts of climate change on marine ecosystems are a global concern due to potential effects on ecosystems as well as on ecosystem services (e.g. nutrient recycling, carbon sequestration, fisheries). These are essential for achieving many of the sustainable development goals (SDGs) targeted by the United Nations: including no poverty (SDG 1), zero hunger and improved nutrition (SDG 2), good health (SDG 3), gender equality (SDG 5), economic growth (SDG 8), conservation of life below water (SDG 14) and peace and justice (SDG 16) (Davies and Riddell 2017; Mugambiwa and Tirivangasi 2017). Climate change studies have demonstrated long-term changes in environmental conditions in many marine ecosystems; compared to past records, the ocean today is warmer, and has a lower pH and dissolved oxygen concentration (Garcia-Soto et al. 2021). In addition, climate change is altering rainfall, regional wind patterns and ocean circulation and is also causing sea-levels to rise (IPCC 2022). These effects have altered marine food web dynamics, from phytoplankton to fish, decreased ocean productivity, resulted in changes to suitable habitats, and led to shifts in the distributions of fish (Lam et al. 2012; Cheung et al. 2010) and other exploited species (Blasiak et al. 2017; IPCC 2022). Targeted species in fisheries are showing shifting patterns of geographic distributions; some have experienced contraction and others continue to fragment. Climate change threatens the well-being of over 3 billion people worldwide who depend on marine and ocean resources for

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✉ Bryony Townhill
bryony.townhill@cefas.gov.uk

[1] International Marine Climate Change Centre, Centre for Environment, Fisheries & Aquaculture Science (Cefas), Pakefield Road, Lowestoft NR33 0HT, UK

[2] Department of Geography and Regional Planning, University of Cape Coast, Cape Coast, Ghana

livelihoods, food and future opportunities (http://www.un.org/sustainabledevelopment/oceans/).

Ghanaian fisheries

The threat posed by global climate change is especially urgent for coastal communities in West Africa, where there is often near-total dependence on marine fisheries for economic development and food security. Fisheries constitute more than 20% of the primary sector (use of natural resources) in West Africa (Belhabib et al. 2015a). By the end of the 2050s, the region is expected to experience as much as 26% drop in annual fish catches, 50% decline in fisheries-related jobs and a total economic loss of US$311 million per annum as a result of global climate change (Lam et al. 2012). The region is also expected to experience as much as one metre of sea-level rise, about 10% higher than the global average, by the end of this century (Serdeczny et al. 2017). This will amplify the exposure of coastal lands and infrastructure to stormy wave action and flooding (Evadzi et al. 2018; Alves et al. 2020). It will also push seawater further inland with adverse effects on brackish water systems (e.g. mangroves, lagoons) that hold shellfish which are mainly exploited by vulnerable populations – women, children and the elderly (Chuku 2019; Davies-Vollum et al. 2019). The combination of these effects, exacerbated by other practices such as mangrove deforestation (Aheto et al. 2016), is expected to increase the vulnerability of artisanal, small-scale fishing communities in West Africa to economic and food insecurity (Lam et al. 2012).

This paper is focused on the climate change risk confronting Ghana's marine fisheries, and the adaptive strategies required to face the challenge. Like other countries in West Africa, Ghana obtains the bulk of its marine fish catches from the Guinea Current Large Marine Ecosystem (GCLME) in the Gulf of Guinea (eastern tropical Atlantic). Fisheries associated with the GCLME contribute, directly and indirectly, to livelihoods for nearly 10% of the population of Ghana (MoFAD 2015). Most fishers are engaged in the artisanal sector (107,518 canoe fishers in 2016; Fig. 1), which is responsible for about 70% of the fisheries production in Ghana (Dovlo et al. 2016; MoFAD 2015) and contributes around 3% of gross domestic product (GDP) (Stark et al. 2019). These artisanal fisheries operate within each of Ghana's four coastal administrative regions, viz. the Western, Central, Greater Accra and Volta Regions (Fig. 2). They currently employ or indirectly support 1.5—2 million people, most of whom have little or no formal education (Lazar et al. 2018), with men typically involved mostly in harvesting and women generally responsible for post-harvest processing, storage and distribution. The total value of the artisanal fisheries, the most important sector locally in terms of employment and catches, reaches about $1 billion a year when multiplier economic effects associated with the value-chain of the industry are considered (Belhabib et al. 2015b).

Fig. 1 Artisanal fishing vessels – wooden canoes typically powered by 1 or 2 outboard engines – laid up on the beach of Biriwa, a small fishing town near Cape Coast, Central Region, Ghana. Photo: James Bell

Ghanaian fish stocks

The reliance on fisheries means that many of the fish stocks serving as the base of Ghana's artisanal fisheries are close to collapse through overexploitation (Cook et al. 2021c). This is largely a product of the significant over-capacity across all fleets operating in the GCLME but notably aggravated by illegal fishing techniques by industrial trawlers owned and operated by Chinese firms, licensed under shell companies run by Ghanaian owners (Stark et al. 2019). These fish stocks, mainly made up of small pelagic species (e.g. sardinella, anchovies) are severely overfished, with fishing mortality rate far in excess of the fishing mortality required for the maximum sustainable yield (F_{MSY}) of the fishery (Lazar et al. 2018). If the stocks collapse, there would be loss of direct employment for more than 200,000 people, leading to a sharp drop in purchasing power and worsening food insecurity (Belhabib et al. 2016), with a strong likelihood to increase conflict between West African countries over shared marine resources (Stark et al. 2019).

Climate change impacts on Ghanaian fisheries

Distinguishing between the effects of climate change and fishing is challenging, yet also essential for identification of measures required to enable fisheries managers and fishing communities to adapt to changes in the environment. Belhabib et al. (2016) observed that climate-induced changes in potential catch and species composition have many similarities to changes induced by over-exploitation, and therefore would have similar repercussions on the economic and social

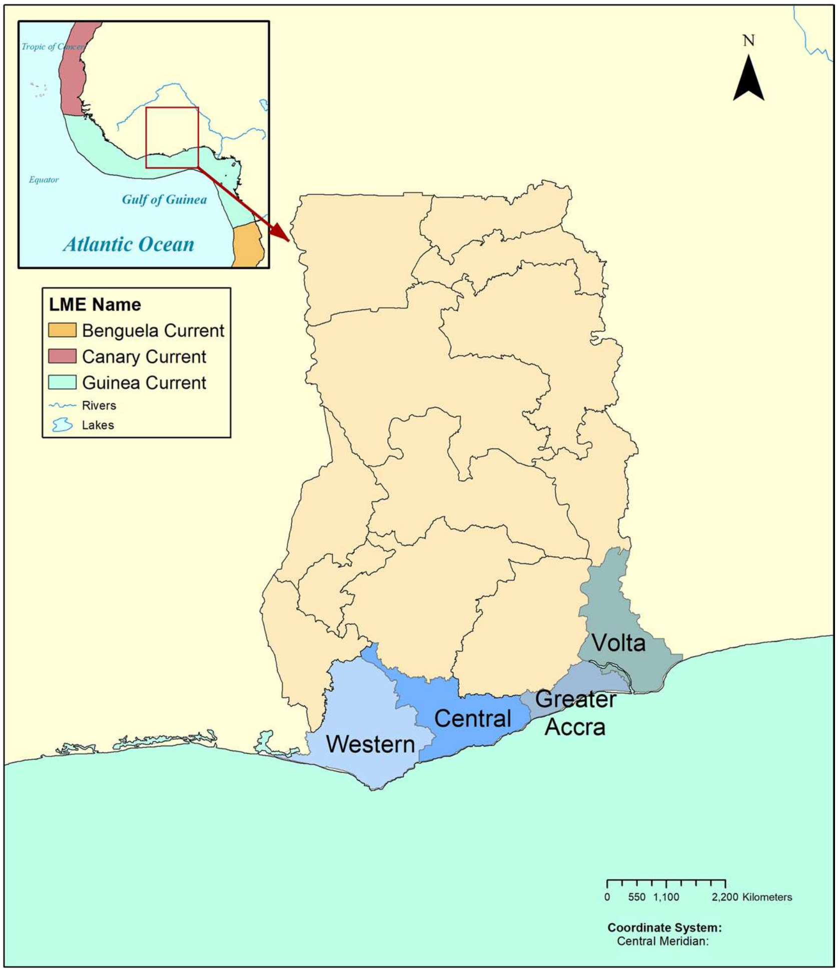


Fig. 2 Map of West Africa showing Large Marine Ecosystems (LME) boundaries (see inset) and the four coastal regions of Ghana used in assessments of climate change risks to fisheries and fishers

performance of fisheries. Many more studies have been done for the West Africa region than for individual countries, but even so, the impacts of climate change in the region are not well studied (Belhabib et al. 2016). In Ghana, a number of studies have investigated environmental factors influencing fisheries using temperature data available from satellites or regional data sets (Cury and Roy 2002; Hardman-Mountford and McGlade 2002; Koranteng and McGlade 2002; Cheung et al 2013). These statistical model approaches are based on identifying links between sea surface temperatures and fish catches. A limited number of modelling studies have predicted climate impacts on fisheries across West Africa, with contradictory results. Modelling by Lam et al. (2012) projected that Ghana's fish landings would decrease by 55% by 2050, whereas Barange et al. (2014) projected an increase in productive potential of 23.9% across the Gulf of Guinea. This shows the difficulties in predicting climate change impacts across different fish stocks at a regional scale and the need for studies specific to certain sectors.

Climate change affects the health and distributions of fish themselves as well as the activities of fishers targeting these (Townhill et al. 2021), leaving fishers' livelihoods and Ghana's food security at high risk. The extent of impacts on fishers and local communities will depend on the adaptive capacity of the communities (Barange et al. 2014) and the resilience of fish stocks in the region. Climate change is likely to exacerbate the problem that most fish stocks are over-exploited (Lindegren et al. 2010), putting further pressures on ecosystem response and resilience (Planque et al. 2010). Previous studies suggest that adaptive capacity is generally low among coastal communities in West Africa, with limited options for alternative livelihoods and adaptation (Belhabib et al. 2016; Lam et al. 2012; Nunoo et al. 2014; Cinner et al. 2008; Okyere et al. 2023), and potentially negative implications for the economy and food security.

Climate change risk assessment

To address some of the gaps in understanding of the impacts of climate change on fisheries in Ghana and how these may impact the fishing communities, we adopt a climate change risk assessment approach, which enables assessment of the sensitivity of different fish species to environmental change and the vulnerability of fishing communities to changes in fish distribution and abundances. The methodology is adapted from the Intergovernmental Panel on Climate Change (IPCC) risk assessment framework, and the approaches of Pinnegar et al. (2019), Hare et al. (2016) and Colburn et al. (2016). This approach can be applied in regions with limited data availability and developed further as more detailed information becomes available.

The purpose of a climate change risk assessment is to consider the degree to which a country or sector is exposed to climate change hazards, the different components of the associated risk, as well as the speed at which it becomes exposed, and how well it can cope. The risk assessment framework laid out in the IPCC Working Group 2 (WGII) Assessment Report 5 (AR5; IPCC 2014) considers how impacts and risks linked to climate change can be managed by supporting decision makers to design and implement adaptation and mitigation options. As such, upon completion of a fisheries risk assessment, the sector is able to compare relative risks and identify the components of the sector that are most in need of support to build adaptive capacity.

Aim of this paper

The overall aim of this study was to assess the risks of climate change to fisheries in Ghana, taking account of climate hazards, sensitivity of different fish species and habitats, and the socio-economic vulnerability of the different fisheries sectors and regions. Breaking down the different components of climate risk for fisheries gives fisheries and environment managers more detailed information with which to prioritise adaptation action. A full dataset of Ghanaian fish catches by fleet and region was not available, and meant that a standard climate risk assessment could not be completed for each region. As such, this work was split to investigate fish species sensitivity, fisheries sector vulnerability, and regional climate risk (with a focus on artisanal fisheries). The specific aims included the identification of:

1. Which of the main Ghanaian fish species are most climate sensitive overall?
2. Which fisheries sectors are most vulnerable, based on catch composition?
3. With regard to their artisanal fishing communities, which regions are more at risk from climate change?

Methods

The IPCC climate risk assessment methodology (IPCC 2014) was adapted to the available fisheries data for Ghana. Owing to the lack of comprehensive fisheries data, the methodology was, in line with the above three aims, broken down into three different aspects of climate risk: (1) fish species sensitivity; (2) fisheries sector vulnerability; and (3) regional artisanal climate risk. The data sources for the assessment are shown in Table 1.

Fish species sensitivity

The assessment included a total of 39 fish and shellfish species, representative of Ghana's fisheries catch. These included several small pelagic species which together comprise a large part of the total catches, including anchovies (Engraulidae), sardinella (*Sardinella aurita* and *S. maderensis*), Cunene horse mackerel (*Trachurus trecae*) and chub mackerel (*Scomber colias*). These mobile species, feeding predominantly in the water column, are typically caught by various nets, particularly artisanal purse seine and beach seines (Cook et al. 2021a, b). While some (e.g. sardinellas) prefer more coastal habitats, others (e.g. anchovy, chub mackerel and horse mackerel) tend to be found in offshore waters. Highly sought after are several large pelagic species (e.g. tuna: especially skipjack *Katsuwonus pelamis* and yellowfin *Thunnus albacares*), generally caught further offshore by industrial vessels using long lines or benthic and pelagic trawl nets. A range of demersal species, which feed predominantly on or near the seabed, are also caught, some of these in coastal waters (e.g. mobile dentex seabream species, and sedentary groupers) or on reefs (e.g. sedentary snappers), although the majority of the demersal species are more widespread across the continental shelf region extending to a depth of 200 m.

For 35 of the assessed species, information on the catches (for 2019) was collated from the FAO's FishStat database (FAO 2021). Four additional species were included which were considered part of species complexes in the 2016 CECAF (Fishery Committee for the Eastern Central Atlantic) catch data, which is based on estimates from fisheries surveys (FAO 2019). These were pink dentex (*Dentex gibbosus),* Canary dentex (*D. canariensis)* and bluespotted seabream *(Pagrus caeruleostictus)*, which are considered part of the 'dentex species complex' along with Angola dentex (*D. angolensis*). Longneck croaker (*Pseudotolithus typus)* was added, considered to be part of the 'croaker species complex' along with Bobo croaker *(P. elongatus)* and cassava croaker (*P. senegalensis)* (Cook et al. 2021b).

To assess each of the selected species' sensitivity to future climate changes, information related to their biological traits (temperature and habitat preferences, etc.) was compiled and a sensitivity score assigned for each of these traits, adapting the approach of Pinnegar et al. (2019) and Hare et al. (2016). Data on temperature tolerances and specificity, overall habitat specificity, population resilience and price were compiled (Table 1), which relate to a species' ability to withstand changes to their environment. A price

Table 1 Data sources for the climate risk assessment

Data	Source
Fish species sensitivity	
Total fish catches, all fleets	2019 Ghana catches from FAO's FishStatJ (FAO 2021)
Temperature tolerances and specificity: Minimum and maximum preferred temperature (°C, as 10th and 90th percentiles of observed temperature ranges: TP10, TP90) Range of preferred temperatures (°C)	Aquamaps (http://www.aquamaps.org)
Habitat specificity: Mobility Habitat Horizontal habitat preference Vertical habitat preference	Fishbase (http://www.fishbase.se) for fish SeaLifeBase (https://sealifebase.ca) for invertebrates
Population resilience: Population doubling time	Fishbase (http://www.fishbase.se) SeaLifeBase (https://sealifebase.ca) For invertebrates
Price: Price category	Fishbase (http://www.fishbase.se) SeaLifeBase (https://sealifebase.ca) For invertebrates
Fisheries sector climate vulnerability	
Fish catches for each sector	2016 catches for specific sectors, as reported by Fishery Committee for the Eastern Central Atlantic (CECAF) catch data (FAO 2019). 2016 is the most recent year with data available for all species. These catch data are estimated from surveys
Regional artisanal climate risk	
Fisheries vulnerability: Percentage of population with food insecurity Proportion of the population who are fishers Number of fishers per canoe Percentage households with additional livelihood other than fishing or farming (only fishing households surveyed)	Ministry of Food and Agriculture (2022) Number of fishers: Ghana Marine Canoe Frame Survey (Dovlo et al. 2016) Total population: 2010 Population and Housing Census (Ghana Statistical Service 2013) Ghana Marine Canoe Frame Survey (Dovlo et al. 2016) USAID/Ghana Sustainable Fisheries Management Project report (Ofori-Dansen et al. 2019)
Hazard: Mean rainfall, mean wind speed	Weatherbase (http://www.weatherbase.com)
Poverty: Poverty rate, poverty gap, severity of poverty	Ghana Poverty Assessment (World Bank 2020)
Inequality: Gini coefficient and Palma Ratio	Poverty Trends in Ghana 2005–2017 (Ghana Statistical Service 2018)
Socio-economic vulnerability: Access to adequate toilet facilities, access to electricity, proportion ill or injured who consult a doctor, school attendance rates (primary, junior and secondary) for males and females	Poverty Trends in Ghana 2005–2017 (Ghana Statistical Service 2018)

score was included to indicate likely levels of targeting by the fisheries, which may make targeted species more vulnerable to pressures such as climate change. For each attribute, a scoring system was allocated between 1 (low sensitivity or high tolerance) and 4 (high sensitivity or low tolerance) as outlined below and in Table 2. These scores were then combined to give an overall fish species sensitivity score.

Tolerance of high temperatures

For each species, information on their temperature preferences was taken from Aquamaps (accessed April 2021). To assess a species' tolerance to high temperatures, the 'maximum preferred temperature' (90th percentile of a species' full temperature range, TP90) was used. A sensitivity score was allocated to each species, based on criteria for TP90 described in Table 2.

Temperature specificity

To assess a species' robustness to variations in temperature conditions, the temperature specificity metric was used (Pinnegar et al. 2019). Species that have a narrower range of temperature conditions are considered more likely to be impacted by increasing temperatures caused by climate change. Other species that have a wider range of temperatures in which they can function normally are less likely to be removed from their preferred temperature range with

Table 2 Definitions of the five species traits that, in combination, comprise overall species sensitivity. When scoring each species trait, four rankings were distinguished, with in all cases rankings 1 and 4 representing low and high climate sensitivity, respectively. Overall species sensitivity was calculated as the average of the five trait scores for each species

Species trait Score	Definition of score
High temperature tolerance	TP90 > 28.2 °C
1. Very high	TP90 between 28.0° and 28.2 °C
2. High	TP90 between 27.5° and 28.0 °C
3. Medium	TP90 < 27.5°
4. Low	
Temperature specificity	Temperature range > 12 °C
1. Low	Temperature range between 8° and 12 °C
2. Medium	Temperature range between 4° and 8 °C
3. High	Temperature range < 4 °C
4. Very high	
Habitat specificity	Oceanic, epipelagic, highly migratory/mobile species; and slope, bathydemersal, mobile species
1. Low	
2. Medium	Coastal/shelf, pelagic/benthopelagic/demersal, mobile species
3. High	
4. Very high	Reef-associated, epipelagic/pelagic/benthopelagic/demersal, mobile species
	Very high Reef-associated, demersal, sedentary species
Population resilience	Estimated minimum population doubling time < 15 months
1. High	Estimated minimum population doubling time 1.4–4.4 years
2. Medium	Estimated minimum population doubling time 4.5–14 years
3. Low	Estimated minimum population doubling time > 15 years
4. Very low	
Price category	Low, as defined in Fishbase
1. Low	Medium, as defined in Fishbase
2. Medium	High, as defined in Fishbase
3. High	Very high, as defined in Fishbase
4. Very high	
Overall species sensitivity	*Average of sensitivity scores < 1.9*
1. Low	*Average of sensitivity scores 2.0–2.4*
2. Medium	*Average of sensitivity scores 2.05–2.9*
3. High	*Average of sensitivity scores > 3.0*
4. Very high	

future predicted warming. Temperature specificity was based on a species' range (T) of preferred temperatures (between 10 and 90th percentile, TP10 and TP90), and was scored based on the temperature specificity criteria described in Table 2.

Habitat specificity

For each species assessed, data related to habitat specificity was taken from FishBase, and in the case of cuttlefish, from SeaLifeBase (accessed April 2021). In particular, 'horizontal habitat preference' was assessed, which includes oceanic (species found widely in the Atlantic Ocean), coastal/shelf (offshore species associated with the continental shelf), and reef-associated (species found close to coral reefs), which was split into two categories depending on whether a species is pelagic (in the water column) or demersal (close to the seabed). 'Vertical habitat preference' was also a consideration, including pelagic, epipelagic (living in the uppermost layers of the water column), benthopelagic (in the water column or near to the seabed), demersal and bathydemersal (close to the seabed at depths below 200 m). In addition to these characteristics, the 'mobility' of a species also affected the overall habitat specificity. Species were scored as highly migratory (ranging over 100 s-1000 s of kilometres), mobile (ranging over 10 s of kilometres), or sedentary (staying within a few kilometres). A habitat specificity score was allocated to each species by combining the mobility, horizontal and vertical habitat preferences, as listed in Table 2 (criteria as in Pinnegar et al. 2019).

Population resilience

Data was used from FishBase (accessed April 2021) to determine a species' population resilience to exploitation and effects of a changing climate. Population resilience scores were allocated based on the estimated minimum amount of time needed for a particular population to double, the specific times of which are listed in Table 2.

Price category

The exact price per pound of species was not publicly available from the Ghana fisheries census, so the more general information on fish price category was used from FishBase (accessed April 2021), which categorises prices as low, medium, high and very high. Species with low, medium, high, and very high mean price score can be seen as increasingly more sensitive to targeted fishing and are therefore considered more vulnerable to other pressures such as climate change. The price category scoring criteria is listed in Table 2.

Overall fish species sensitivity

An overall fish species sensitivity score was then calculated for each of the species assessed, by taking the mean of the scores for temperature tolerance, temperature specificity, habitat specificity, population resilience and price score. As all sensitivity scores ranged between 1 and 4, the overall species sensitivity score was similarly allocated, with a score of 1 indicating low species sensitivity, to a score of 4, indicating a very high species sensitivity (Table 2).

Fisheries sector climate vulnerability

For each of the nine main fisheries sectors in Ghana, overall sector climate vulnerability was assessed. The sectors comprised of five artisanal and four industrial (or semi-industrial) main gear types (see Fig. 3 for an overview, with catches by sector for the 10 most important species by total weight landed; based on Cook et al. 2021a, b, and in line with FAO 2019; FCWC 2021).

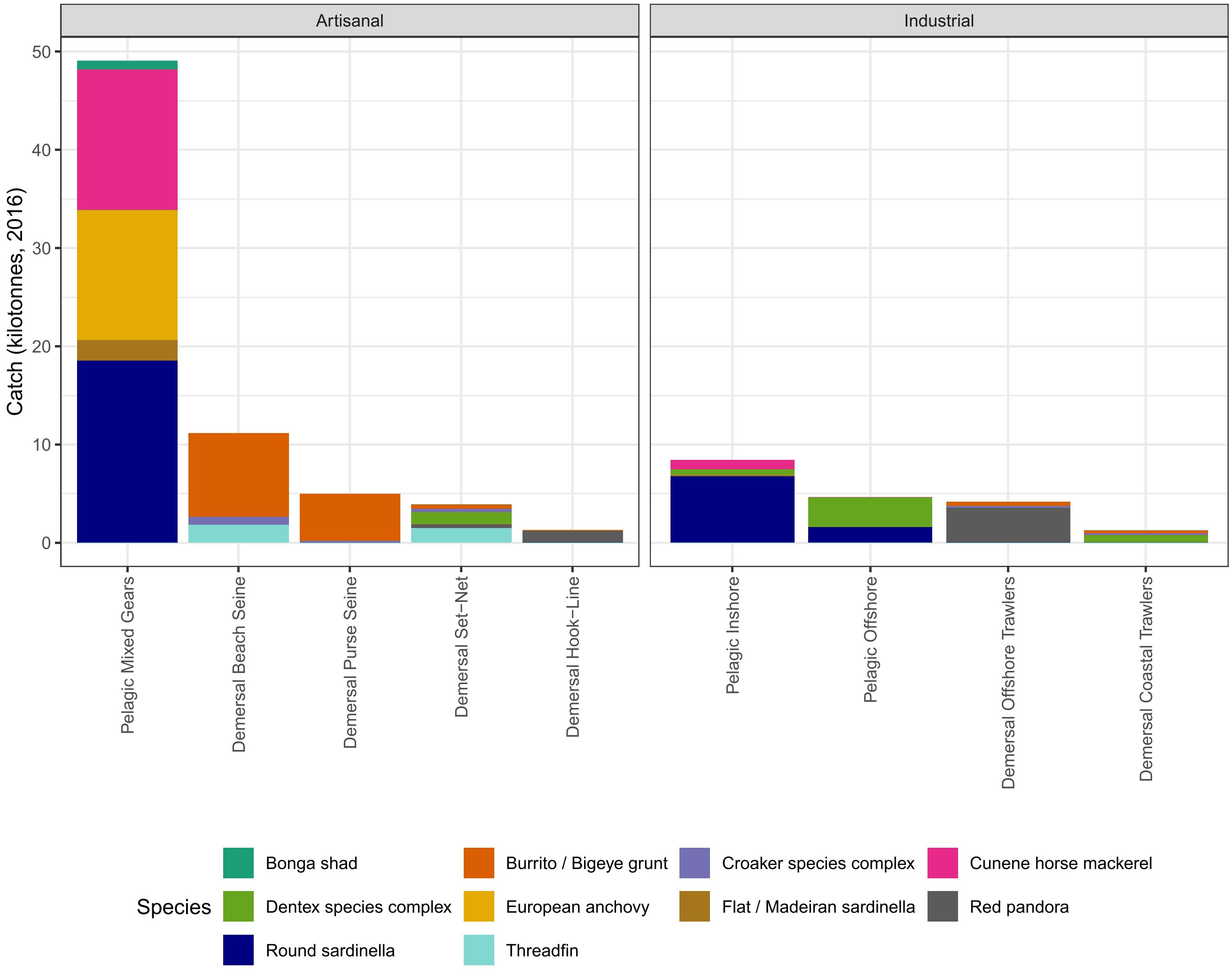


Fig. 3 Ghana artisanal (left) and industrial (right) fisheries: 2016 catches of the ten most important fish species (by quantity of landings) for each of nine main gear types. Colour-coding indicative of species (or species groups)

The artisanal fisheries sectors include: (1) pelagic mixed gears; (2) demersal beach seines; (3) demersal purse seines; (4) demersal set-nets; and (5) demersal hook-lines. The industrial (or semi-industrial) fisheries sectors include: (6) the pelagic inshore fleet; (7) the pelagic offshore fleet; (8) demersal coastal trawlers; and (9) demersal offshore trawlers. For brief characterisations of each of the sectors, see Supplementary Table S1.

For each of the sectors, climate vulnerability was assessed by combining data on the species composition of catches for each sector, with the species sensitivity scores for all species caught as calculated above. CECAF provides estimates for the main fish caught by the main fisheries sectors and gear types in Ghana, with the most up to date being 2016 (FAO 2019). To calculate the overall species sensitivity for each sector, the catch for each species was multiplied by the fish species sensitivity (as calculated above); the product was summed across all species, and then divided by the total catch for that sector:

$$sector\ vulnerability = \sum \frac{(species\ sensitivity \times species\ catch)}{total\ catch}$$

The resulting scores were then normalised across sectors to give a sector vulnerability score, between 0 and 1.

The FAO/CECAF Working Group records species complexes for dentex and croakers, with catch records not broken down by species. In the case of these groups, to calculate the overall species sensitivity the unweighted mean of the species sensitivity scores across the species comprising each complex was calculated. Thus, in the dentex species complex, the mean sensitivity of Canary dentex, pink dentex, Angola dentex and bluespotted seabream was used; and in the croaker species complex, the mean sensitivity across longneck croaker, cassava croaker and bobo croaker was used (Cook et al. 2021b).

Regional artisanal climate risk

Given the very high importance of artisanal fisheries to food security in Ghana, our assessment of climate risk to the country's four coastal regions focuses on their artisanal fisheries. The assessment was based on data on fisheries vulnerability, climate hazard, and social and economic vulnerability. Detailed information was available for artisanal fishers, which make up 98% of fisherfolk (Dovlo et al. 2016), and so were the focus of this assessment. Data were compiled for five main risk components, each consisting of multiple subcomponents, as described below. The final regional artisanal climate risk score was then determined, adapting the approaches of Colburn et al. (2016) and Pinnegar et al. (2019). Data sources are shown in Table 1.

Fisheries vulnerability

For each region, fisheries vulnerability was determined by using data on (1) percentage of population with food insecurity, (2) proportion of the population who are fishers, (3) number of fishers per canoe, and (4) percentage of households with alternative livelihoods, other than fishing or farming (only fishing households surveyed). Although catch data are frequently also included to assess fisheries vulnerability, in this case no such data were available disaggregated by region. For each of the 4 subcomponents included, data were normalised across the four regions, to give a score between 0 and 1. The mean of the scores was then taken to give the fisheries vulnerability of the region.

Climate hazard

The level of hazard for each region was determined using (1) mean rainfall and (2) mean windspeed by region. Wind affects the ability of fishers to go out to sea, and the safety of fishers at sea. High rainfall also contributes to flooding which can cause damage to infrastructure such as roads, houses, markets and schools, fisheries landing and storage sites, particularly in low-lying areas (Effah et al. 2023). For both wind speed and rainfall, data were normalised across the four regions, to give a score between 0 and 1. The mean of the two scores was then taken to give the hazard score for the region.

Socio-economic vulnerability

Socio-economic vulnerability was assessed based on three components: (1) poverty, (2) inequality, and (3) housing, health and education vulnerability. Of these, (1) poverty vulnerability was determined using data on poverty rate, poverty gap and severity of poverty in each region. The poverty gap is the ratio where the mean consumption of the poor falls below the poverty line. Severity of poverty is the inequality in consumption among the people living below the poverty line. The second component, (2) inequality vulnerability was determined using the Gini inequality coefficient and the Palma inequality ratio. The third component, (3) housing, health and education vulnerability, was based on regional data on access to adequate toilet, access to electricity, proportion of ill or injured persons who consult a doctor, and attendance of males and females at primary school, and junior and secondary schools. As above, the data was normalised across regions to give a score between

0 and 1, and these were then averaged to give a score for poverty vulnerability, inequality vulnerability and housing, health and education vulnerability. An average was then taken to give the socio-economic vulnerability score for the region.

Regional artisanal climate risk

For each of Ghana's coastal regions, the overall, regional artisanal climate risk was then calculated, by taking an average of the scores for fisheries vulnerability, hazard, and socio-economic vulnerability.

Results

Fish species sensitivity

Tolerance of high temperatures

The average maximum preferred temperature (TP90), across all 39 species (or species groups) assessed, was 27.8 °C, and the range was 22.9 °C to 28.5 °C (Fig. 4). Three species showed a 'very high' tolerance to high temperatures (TP90 > 28.2 °C), including largehead hairtail, yellowfin, and skipjack tuna. Of these, largehead hairtail demonstrated

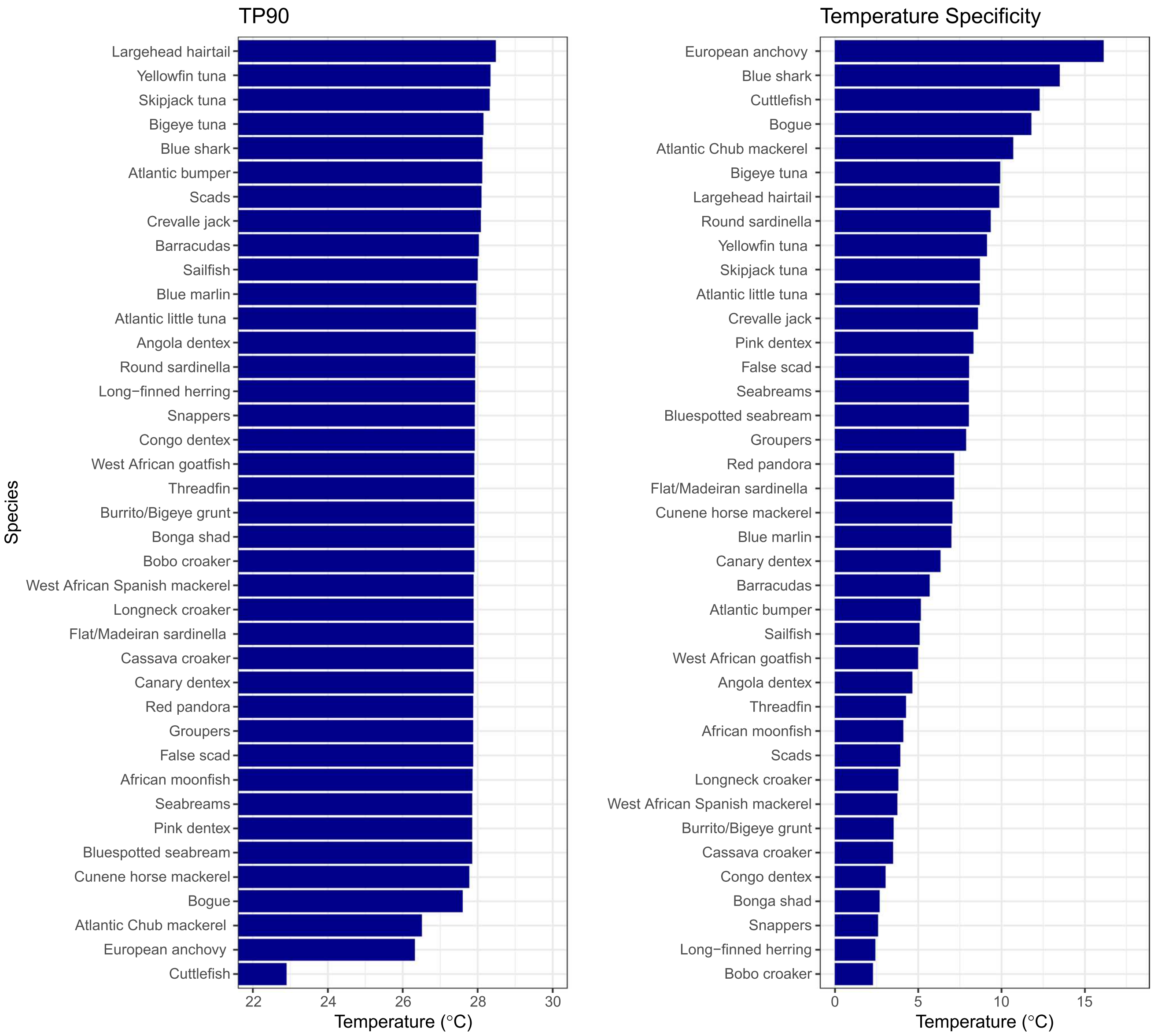


Fig. 4 Maximum preferred temperature (TP90; left) and temperature specificity (range of preferred temperatures; right) of 39 species (or species groups) of significance to fisheries in Ghana. The species are ranked by TP90 (left) or temperature specificity (right), from least thermally sensitive (top) to most thermally sensitive (bottom)

the highest tolerance at 28.5 °C. Seven species showed a TP90 between 28 °C and 28.2 °C, indicating 'high' tolerance of high temperatures; these were all pelagic, and highly migratory or mobile – for example, blue shark and barracudas. The majority of the species assessed had a 'medium' tolerance to high temperatures (TP90 between 27.5 °C and 28 °C). The 26 species in this group consisted mainly of mobile demersal fish, but also some large pelagic species such as Atlantic little tuna and blue marlin. Some of the most economically important fish species in Ghana showed a 'low' tolerance to high temperatures (TP90 < = 27.5 °C), such as Atlantic chub mackerel and European anchovy. Cuttlefish also fell into this category.

Temperature specificity

Three species were categorised as having 'low' temperature specificity (T range > 12 °C)—European anchovy, blue shark, and cuttlefish; the large range of temperatures these species tolerate indicates an ability to adapt to more dramatic temperature variations (Fig. 4). A mix of 13 pelagic and demersal species showed a 'medium' temperature specificity (T range > 8 °C and < 12 °C), including mackerels, tunas and seabreams. Another 13 species showed a 'high' temperature specificity (T range > 4 °C and < 8 °C); these were associated with the continental shelf, coastal areas, and included larger pelagic species such as blue marlin and sailfish. The species identified as having 'very high' temperature specificity (T range < 4 °C) were mostly sedentary demersal species and reef-associated fish, such as croakers and snappers. Full temperature preference data is provided in Supplementary Table S2.

Habitat specificity

Eight of the assessed species were considered oceanic and highly migratory resulting in a 'low' habitat specificity score (Table 3). These species included mostly large pelagic species such as tunas, blue shark and sailfish, but also smaller fish such as Atlantic chub mackerel and European anchovy. The majority of the assessed species belonged to the 'medium' category of habitat specificity, including 21 species of mostly mobile pelagic species and demersal species. One species in this group (Atlantic little tuna) is highly migratory but found mostly within the coastal zone. The five species with a 'high' habitat specificity were either mobile or sedentary, and associated with reefs or the continental shelf, including seabreams and African moonfish. The species identified as having 'very high' habitat specificity were all sedentary demersal fish found on the continental shelf, including snappers, dentex (seabreams), groupers, and West African goatfish (Table 3).

Population resilience

Of the 39 species (or species groups) assessed, five had a 'high' population resilience to fishing (population doubling time of less than 15 months); these included bonga shad, African moonfish, West African goatfish, long-finned herring, and round sardinella. Thirty-one species had a 'medium' resilience (population doubling time 1.4–4.4 years), including both mobile pelagic and sedentary demersal species. Only barracudas and blue shark were characterised by a 'low' population resilience (population doubling time 4.5–14 years), and none of the assessed species were categorised as having 'very low' population resilience (population doubling time > 15 years). Full scoring is found in supplementary materials (Table S3).

Price category

Of the 39 species (or species groups) assessed, only 2 fell into the 'low' price category, including Atlantic bumper and false scad. Twelve species were categorised as having a 'medium' price score, and these featured a variety of pelagic and demersal species. The largest number of species were characterised by a 'high' price score, including bonga shad, which has the highest catches of all species in Ghana (Table 2). Three of the assessed species (or species groups) had a 'very high' price score, indicating the highest sensitivity to fishing and climate change impacts; these were Atlantic chub mackerel, bigeye tuna, and groupers. Full scoring can be found in the supplementary material (Table S3).

Overall species sensitivity

Overall species sensitivity to climate change, based on the mean of the 5 species sensitivity metrics (maximum preferred temperature, temperature specificity, habitat specificity, population resilience, and price category), for Ghana fisheries is displayed in Fig. 5. Species are categorised as small pelagic, large pelagic, or demersal species, and for each group are displayed in order of highest (top) to lowest (bottom) species sensitivity scores. Both the small and large pelagic species had a medium average sensitivity (2.3 and 2.1 respectively), whereas the demersal species on average had a high sensitivity (2.7). Of this group, snappers, Congo dentex and groupers had the highest sensitivity, all scoring 3.2 (very high). The lowest scoring species were skipjack tuna, yellowfin tuna and blue shark, which all scored 1.8 (low).

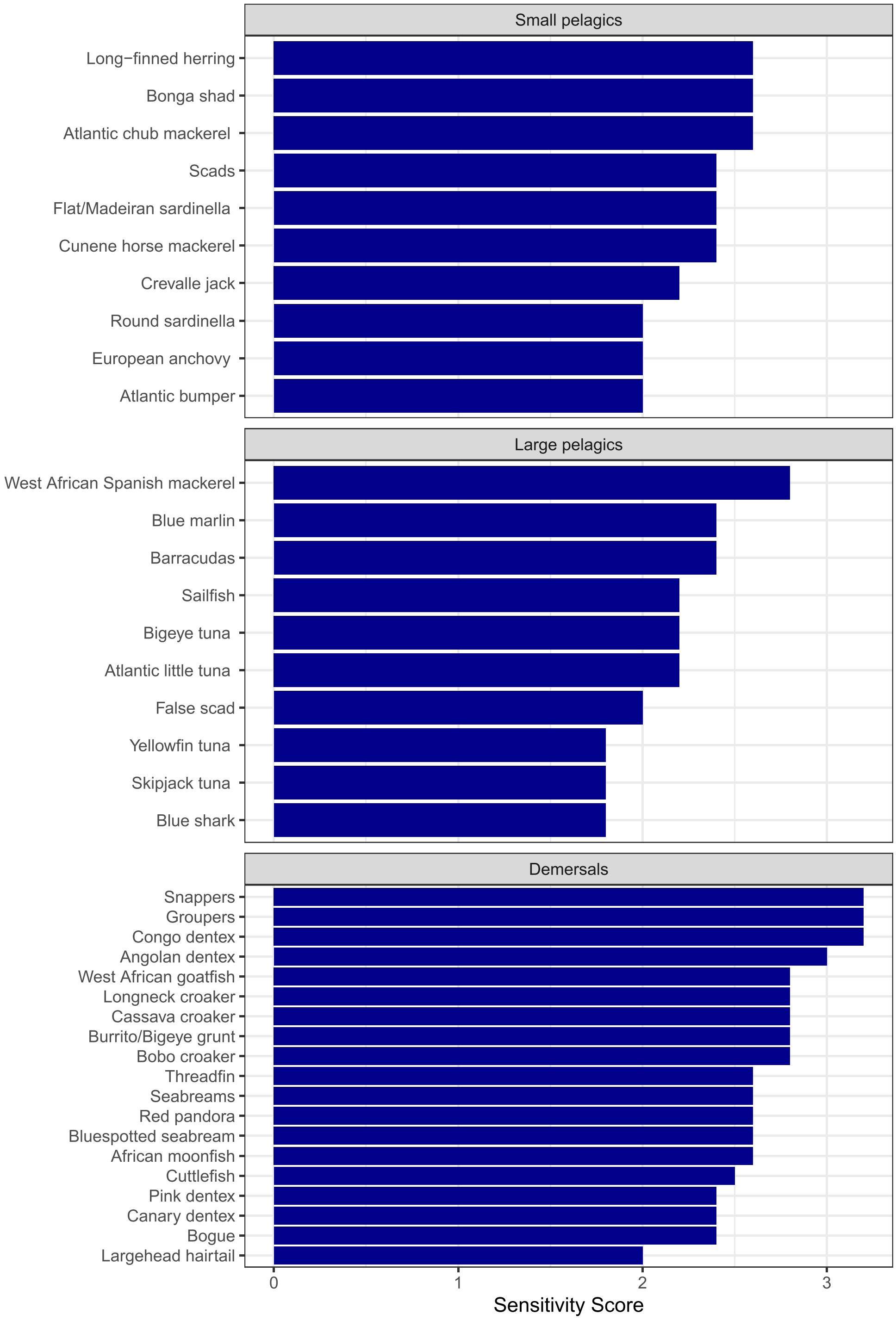
Fisheries sector climate vulnerability

For the nine main fisheries sectors of Ghana, information on catches in 2016 is displayed in Fig. 3, broken down by the ten most important species (or species groups) for Ghana

Table 3 Habitat specificity traits for the species assessed, distinguishing the species groups of small pelagic, large pelagic, and demersal fish. Within each species group, the individual species are ordered here according to the 2019 fisheries catches as an indicator of importance to Ghana fisheries

Scientific name	Common name	2019 catches (tonnes)	Horizontal habitat preference	Vertical habitat preference	Mobility	Overall habitat specificity
Small pelagics						
Engraulis encrasicolus	European anchovy	41,667	Oceanic	Pelagic	Highly migratory	1
Sardinella aurita	Round sardinella	34,582	Coastal	Pelagic	Mobile	2
Chloroscombrus chrysurus	Atlantic bumper	13,565	Shelf	Epipelagic	Mobile	2
Caranx hippos	Crevalle jack	8846	Reef-associated	Pelagic	Mobile	3
Scomber colias	Atlantic chub mackerel	7526	Oceanic	Pelagic	Highly migratory	1
Decapterus spp.	Scads	5861	Shelf	Pelagic	Mobile	2
Sardinella maderensis	Flat or Madeiran sardinella	5529	Coastal	Pelagic	Mobile	2
Trachurus trecae	Cunene horse mackerel	3039	Oceanic	Benthopelagic	Mobile	2
Ilisha africana	Long-finned herring	2909	Coastal	Epipelagic	Mobile	2
Ethmalosa fimbriata	Bonga shad	452	Coastal	Epipelagic	Mobile	2
Large pelagics						
Katsuwonus pelamis	Skipjack tuna	60,179	Oceanic	Epipelagic	Highly migratory	1
Thunnus albacares	Yellowfin tuna	24,864	Oceanic	Epipelagic	Highly migratory	1
Sphyraena spp.	Barracudas	5059	Shelf	Epipelagic	Mobile	2
Caranx rhonchus	False scad	4291	Shelf	Benthopelagic	Mobile	2
Thunnus obesus	Bigeye tuna	2865	Oceanic	Pelagic	Highly migratory	1
Scomberomorus tritor	W. African Spanish mackerel	2098	Coastal	Epipelagic	Mobile	2
Euthynnus alletteratus	Atlantic little tuna	1589	Coastal	Epipelagic	Highly migratory	2
Prionace glauca	Blue shark	414	Oceanic	Pelagic	Highly migratory	1
Istiophorus albicans	Sailfish	391	Oceanic	Epipelagic	Highly migratory	1
Makaira nigricans	Blue marlin	321	Oceanic	Pelagic	Highly migratory	1
Demersals						
Brachydeuterus auritus	Bigeye grunt or burrito	32,814	Coastal	Benthopelagic	Mobile	2
Pagellus belottii	Red pandora	5428	Shelf	Demersal	Mobile	2
Trichiurus lepturus	Largehead hairtail	3280	Coastal	Benthopelagic	Mobile	2
Sparidae spp.	Seabreams	2793	Shelf	Benthopelagic	Sedentary	3
Sepia officinalis hierredda	Cuttlefish	2780	Shelf	Demersal	Mobile	2
Galeoides decadactylus	Threadfin	2642	Shelf	Demersal	Mobile	2
Pseudotolithus elongatus	Bobo croaker	2286	Coastal	Demersal	Mobile	2
Pseudotolithus senegalensis	Cassava croaker	2286	Coastal	Demersal	Mobile	2
Selene dorsalis	African moonfish	1653	Shelf	Demersal	Sedentary	3
Lutjanidae spp.	Snappers	1572	Reef-associated	Demersal	Sedentary	4
Dentex congoensis	Congo dentex	1516	Shelf	Demersal	Sedentary	4
Dentex angolensis	Angolan dentex	1089	Shelf	Demersal	Sedentary	4
Epinephelus spp.	Groupers	877	Coastal	Demersal	Sedentary	4
Pseudupeneus prayensis	West African goatfish	794	Shelf	Demersal	Sedentary	4
Dentex canariensis	Canary dentex	N/A	Coastal	Demersal	Mobile	2
Boops boops	Bogue	N/A	Shelf	Demersal	Mobile	2
Dentex gibbosus	Pink dentex	N/A	Shelf	Benthopelagic	Sedentary	3
Pagrus caeruleostictus	Bluespotted seabream	N/A	Shelf	Benthopelagic	Sedentary	3
Pseudotolithus typus	Longneck croaker	N/A	Shelf	Demersal	Mobile	2

Fig. 5 The overall species sensitivity for the small pelagic (top), large pelagic (centre) and demersal (bottom) species. Within each category, the species are ranked from highest (top) to lowest (bottom) sensitivity score



fisheries (see Supplementary Table S4 for catch data by species and sector). The table highlights the great importance of Ghana's artisanal pelagic sector with the highest catches overall, with the industrial sector having substantially lower catches. Considering climate vulnerability for each sector (Fig. 6) (based on their catch compositions and each species' sensitivity scores), the pelagic sectors were assessed as having lowest vulnerability (5) and the demersal sectors as having generally higher vulnerability, particularly the artisanal demersal purse seiners (score 1.0), the demersal coastal trawlers (score 1.0) and the artisanal demersal beach seiners (score 0.86). These sectors show high vulnerabilities because of their relative reliance on burrito (bigeye grunt), a highly sensitive species. Demersal trawlers were assessed as having a mid-range climate vulnerability, because their main catches are the highly sensitive dentex complex, and

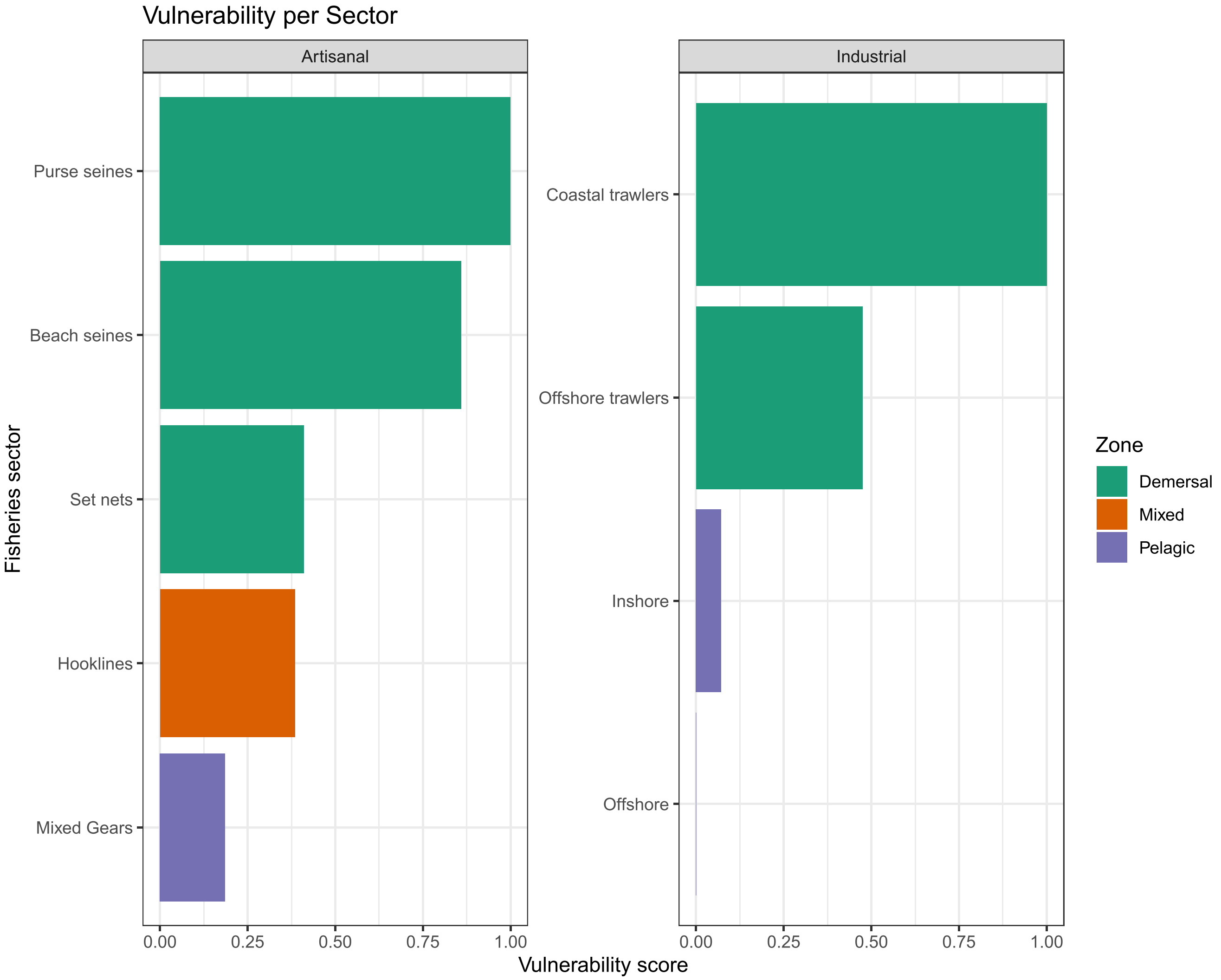


Fig. 6 Climate vulnerability index for each of the nine main fisheries sectors of Ghana, distinguishing artisanal (left) and industrial (right) fisheries

the low sensitivity red pandora. The relatively low vulnerability of the three pelagic sectors (artisanal pelagic, pelagic inshore, and pelagic industrial) was related to their main catches consisting of less sensitive species, such as round sardinella, Cunene horse mackerel and European anchovy.

Regional artisanal climate risk

Among Ghana's four coastal regions, the Volta region in the east was found to have the highest overall climate risk with regards their artisanal fisheries (score 0.66), owing to it having the highest scores for the risk components climate hazard (0.81) and socio-economic vulnerability (0.67) (Fig. 7). The region with lowest overall climate risk was Greater Accra (0.31), associated with the lowest scores for each component (fisheries vulnerability 0.32, hazard 0.28, and socio-economic vulnerability 0.33). Highest fisheries vulnerability was found in the Central region (0.67).

The high climate hazard score for Volta was mainly driven by the high mean wind speed for the region, and the high socio-economic vulnerability score reflects the region's higher poverty and inequality levels than the other three regions (e.g. highest in terms of poverty rate, poverty gap, Gini inequality coefficient and Palma index; least in terms of electricity and toilet access: see Table 4). Volta's fisheries vulnerability was also high, as it had the highest number of fishers per canoe among the regions, and joint-highest (with Central regions) levels of food insecurity (Table 4). Although the Volta region had the highest proportion of fisher households with alternative livelihood income, this was still only a very small proportion of the total (0.4%).

The low regional artisanal climate risk for Greater Accra reflected the low annual mean rainfall, the low poverty rates

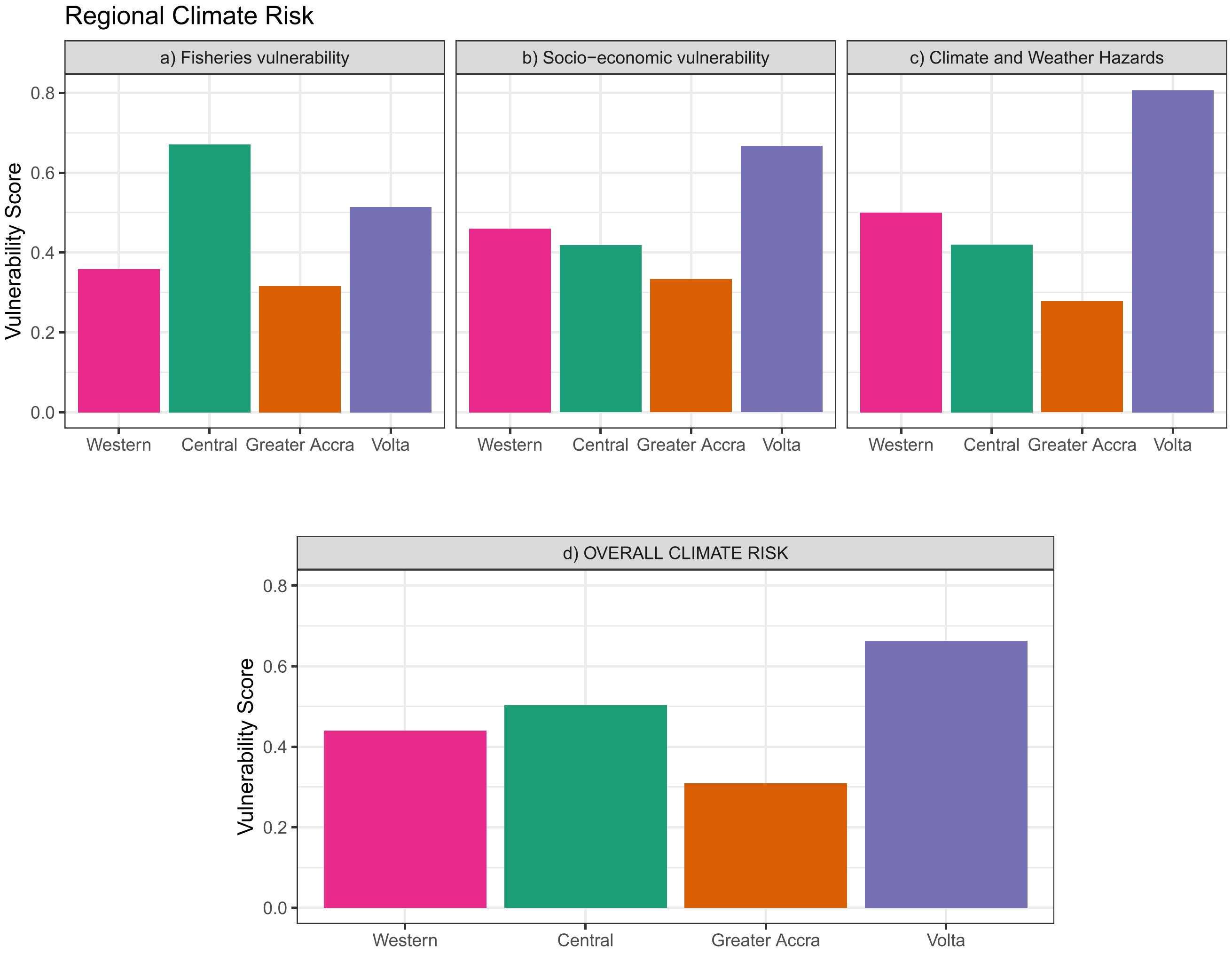


Fig. 7 Risk component scores (a, fisheries vulnerability; b, socio-economic vulnerability; c, climate and weather hazards) for Ghana's four coastal regions; and (d) overall artisanal climate risk for each region

(poverty rate of 2.5%, poverty gap of 0.5, poverty severity of 0.1), and the lowest socio-economic vulnerability (highest access to electricity and toilets, highest levels of doctor consultation; see Table 4).

Discussion

Ghana's climate risk

This study aimed to assess the climate change risk to Ghanaian fisheries, taking into account the fish species caught and the socio-economic vulnerability of the different fisheries sectors and regions. Thirty-nine economically important species (or species groups) for Ghana were assessed based on their biological traits and habitat preferences. The species found to be most sensitive to climate change and fishing pressures were demersal species found on the continental shelf and in coastal areas, especially groupers, snappers and croakers. Their high sensitivity was mainly due to their limited distribution and sedentary characteristics. This contrasts with many pelagic species such as tunas and blue shark, which are much more widely distributed and so able to tolerate a wider range of temperatures and to move out of areas that exceed their environmental tolerances. Similar findings, of greater climate sensitivity in demersal or reef-associated compared to pelagic species, have also been found in the Caribbean (Dominica: Pinnegar et al. 2019), although elsewhere (e.g. Humboldt Current System, South America) pelagic fishes (along with benthic species) were found to be more climate vulnerable (Ramos et al. 2022).

Accordingly, the fisheries sector assessment indicated that those fisheries targeting mainly pelagic species are least sensitive to climate change. Fisheries for species such as round sardinella and European anchovy, which have wide temperature tolerance ranges and migratory behaviour, have

Table 4 Regional artisanal climate risk for the four coastal regions of Ghana, along with the scores for the three main components fisheries vulnerability, climate hazard, and socio-economic vulnerability, as well as the data for 21 different sub-components used to calculate regional artisanal climate risk

Region	Western	Central	Greater Accra	Volta
Regional artisanal climate risk	0.44	0.50	0.31	0.66
Fisheries vulnerability				
Fisheries vulnerability score	0.36	0.67	0.32	0.51
Food insecurity (% of population)	1.00	3.00	1.00	3.00
Fishers (% of population)	0.01	0.02	0.01	0.01
Average number of fishers per canoe	8.31	8.66	9.82	13.99
% fishing households with alternative livelihood (other than fishing or farming)	0.23	0.21	0.10	0.39
Climate hazard				
Hazard score	0.50	0.42	0.28	0.81
Mean annual rainfall (inches)	49.2	44.8	29.8	41.7
Mean wind speed (mph)	3.5	3.8	6.0	8.0
Socio-economic vulnerability				
Socio-economic vulnerability score	0.46	0.42	0.33	0.67
Poverty rate (%)	21.1	13	2.50	37.3
Poverty gap	4.9	3.6	0.5	13.0
Severity of poverty	1.7	1.3	0.1	6.4
Poverty vulnerability score	0.4	0.3	0.0	1.0
Gini inequality coefficient	36	35	35	40
Palma index	1.5	1.6	1.4	1.8
Inequality vulnerability score	0.2	0.2	0.0	1.0
Access to adequate toilet	61	68	86	44
Access to electricity	0.8	0.9	0.9	0.8
Ill or injured who consulted a doctor (%)	23	23	40	21
Junior and secondary school attendance females (%)	31	46	54	33
Junior and secondary school attendance males (%)	37	32	47	31
Primary school attendance females (%)	75	78	88	76
Primary school attendance males (%)	74	84	78	70
Housing, health, education vulnerability score	0.8	0.8	1.0	0.0

low climate sensitivity. Most notably, the assessment indicated the artisanal demersal purse seine and beach seine sectors to be most vulnerable; these sectors are relatively reliant on species such as burrito (big eye grunt) which have high sensitivity, due to specific habitat preferences and low tolerance of high temperatures.

The examination of the artisanal fisheries in the coastal regions found that Volta had the highest climate risk, as a result of highest hazard scores, as well as highest poverty rate scores. Volta also has the highest food insecurity rate, as a result of the relative importance of several highly vulnerable demersal species. Conversely, Greater Accra was the coastal region assessed as having the lowest climate risk, owing to the lowest annual rainfall (associated with flood risk), and the lowest poverty rates among the four assessed regions. The results of these different assessments suggest that overall, the artisanal demersal purse seine and beach seine sectors in the Volta region are the most vulnerable.

The most economically important species for Ghana include small pelagic fish such as round sardinella, Madeiran (or flat) sardinella, Cunene horse mackerel and anchovies, however because of their highly migratory nature, their distribution ranges and movements are transboundary, management at the national level alone is not sufficient for maintaining sustainable stocks (Cobinna 2018). The stocks of these species are considered close to collapse (Cook et al. 2021a, b, c), but this will affect fishers in different regions and sectors differently, and any effort control plans should consider being specific to individual regions, depending on the level of economic development (Cobbina 2018). This emphasises that although these species show low sensitivity to climate change, they are still at very high risk in Ghana from overfishing, and so may not be as resilient to changing environmental conditions as they would otherwise be.

As found here for Ghana, across West Africa, fishers are generally highly vulnerable to climate change, as they are dependent on fish for both food and livelihoods, and because the economies they live in tend to have limited adaptive capacity (Belhabib et al. 2016). Lam et al. (2012) found that the dominance of artisanal fleets in West African fisheries could be a limiting factor in the ability of these communities to adapt to climate-related changes of marine resources or environmental conditions. Similarly, Cinner et al. (2008) and Nunoo et al. (2014) reported that a lack of alternative livelihood options for small scale fishers is one of the leading factors in the continuing trend of stock over-exploitation and therefore decreasing catches. Other factors affecting capacity building in Ghana's fishing communities include low levels of formal education, and a lack of training in fisheries management or planning (Okyere et al. 2023) This is reflected in the present study, with each of the coastal regions examined having high levels of food insecurity, high proportions of the population who are fishers, and high levels of socio-economic vulnerability.

This study is limited by lack of data on some additional factors which affect climate risk. These included region-specific fisheries catches and data on fuel subsidies. Artisanal fishers in Ghana have access to some fuel subsidies (available at approximately 60% of usual market price), but these create regional inequality in the economic viability of fishing activities and have limited effectiveness in safeguarding livelihoods (W. Akpalu, pers. comms.). More detailed fisheries catch data would allow a more in-depth assessment of the different aspects of climate risk to the different sectors within each region, which could then be used in developing adaptation actions and building climate resilience. While this can be done with the assessment completed here, a more detailed analysis would allow for more specific targeting of the different aspects of vulnerability. Collecting more detailed fisheries data and making it available to researchers will allow these, and other studies on sustainable fishing more generally, to take place.

Adaptation and climate resilience

With a range of adaptation measures available for fisheries (FAO 2018), climate change risk assessments, such as this, can be used to identify adaptation actions which are suitable for specific regions or fisheries sectors, targeting specific aspects of climate risk (Townhill et al. 2021). The differences we found in climate risk for each region show that adaptation should be location- and sector-specific, taking into account differences in the socio-economic situation and the species caught. Adaptation must also consider historical and cultural aspects of fisheries, the heavy dependence on fish for food, and diet preferences for certain species (Belhabib et al. 2016).

A possible adaptation to ensuring the sustainability of Ghanaian fisheries could include market diversification (Katikiro and Macusi 2012). The results of the species sensitivity assessment show that some of the least climate sensitive fish species in Ghana are Atlantic bumper, largehead hairtail, bogue, Canary dentex and pink dentex. However, promoting target of least sensitive species, such as skipjack and yellowfin tuna, if necessary allowing additional quota, would allow over-exploited demersal species to recover, increasing the resilience of the fisheries (FAO 2018). It is important that markets diversify away not only from species highly sensitive to climate change, but also away from highly overfished stocks such as sardinellas, anchovy, Bonga shad and Cunene horse mackerel (Cook et al. 2021a, b).

In the past, it was more common for industrial fisheries to make changes to their target species compared with artisanal fisheries (Belhabib et al. 2016). Industrial fisheries, assessed here as less vulnerable than the artisanal and inshore sector, are able to move greater distances, throughout West African waters, and hence can more easily switch target species or adjust to shifting stock distributions. More locally based fleets which use canoes are less flexible in their ability to move to more distant fishing grounds and thus are more vulnerable to range shifts of commercial species, or local depletions of target stocks (Belhabib et al. 2016). Artisanal fleets may instead look to diversify towards a broader 'portfolio' of species to catch, and away from overfished and/or highly climate sensitive species. Without directed interventions to improve stock status, e.g. by fleet rationalisation, or to help retrain fishers or provide new gear, this maintains pressure on highly exploited species and reduces income for fishers in the long term, even without the impact of climate change.

In the present study, there were various aspects of socio-economic vulnerability (referred to as adaptive capacity in the previous IPCC vulnerability framework (IPCC 2001)) scores that came out low across all four regions examined, including poverty, access to education and healthcare. A previous study looked at climate adaptation, adaptive capacity and fisher perceptions of climate change (Freduah 2016), and found that many fishers did not have a good understanding of how climate change may impact their fisheries, and consequently adopted reactive coping strategies rather than planned or proactive adaptation. Educating fishers about climate change is considered vital if they are to adapt to climate change (Katikiro and Macusi 2012). Freduah (2016) stated that low adaptive capacity and lack of understanding of climate change, can hinder effective adaptation and often leads to maladaptation. As such, adaptation measures that increase adaptive capacity are needed.

The artisanal sector of the Ghanaian fleet relies largely on the use of traditional canoes and is most significant in terms of employment (Dovlo et al. 2016). There were estimated to be a total of 11,583 canoes fishing in Ghana in 2016 (Dovlo et al. 2016), considerably higher than the number of canoes needed to sustain the Ghanaian fishery without going beyond the Maximum Sustainable Yield (MSY) – around 9,100 (Environmental Justice Foundation 2020). Therefore, climate adaptation options may involve some fishers seeking alternative, or at least supplementary livelihoods to maintain an income. Potential options could include diversifying to industries such as farming, trading, real estate and transport businesses (Gardner 2016; Environmental Justice Foundation 2020). Future programmes on alternative livelihoods could include education and must be monitored effectively, to ensure fishers do not return to the fishery after a plan has been implemented (Cobbina 2018). Previous research has documented that artisanal fishers in Ghana would consider an alternative livelihood if economically viable options were available. Asiedu & Nunoo (2013) and Anning et al. (2012) reported that over 73% and 62% of fishers surveyed expressed willingness to move away from fishing, and Gardner (2016) found that many fishers already had a supplementary source of income to fishing, particularly farming during seasons of lower fish stocks. Conversely, in a survey by Cobbina (2018), 77.5% were not willing to stop fishing, although the differences may have been due to survey location and availability of other jobs at the time.

In the Western region of Ghana, a climate vulnerability assessment of the Old Akwidaa community was undertaken, using detailed information on the community assets and fishing and non-fishing livelihoods (Effah et al. 2023). In our study, the Western Region showed high scores for the climate and socio-economic vulnerability aspects. By focusing on one area, Effah et al. (2023) could go into more detail about the exposure to climate hazards, and to undertake interviews on fisher perceptions of climate and the state of infrastructure and landing sites, such as roads. They found that the community was particularly at risk from impacts from flooding, particularly artisanal fishing assets, and lacked coping strategies for climate change. The authors also recommended that the community move to higher ground to reduce their risk from flooding, construct climate-proof infrastructure, and seek alternative or diversified livelihoods.

Conclusions

The combined effects of overexploited stocks, climate change pressures and socio-economic vulnerability of artisanal fishers, have huge implications for food security and the economy of Ghana's coastal regions (Belhabib et al. 2016; Effah et al. 2023). On top of this, illegal fishing in Ghana also affects the ability of artisanal fishers to adapt (Yang et al. 2019). These aspects will need tackling alongside each other to ensure that Ghanaian fishers and the communities that rely on them have income and food for the foreseeable future. Barriers to adaptation must also be considered, in order for these to be overcome and ensure that adaptation is effective in the long term (Yang et al. 2019). By understanding the specific aspects of climate risk in different sectors and regions, adaptation actions can be identified which benefit both the people who rely on fisheries for food and livelihoods, and also help ensure the longevity of fish populations in the region.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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