A rapid approach to assessing the vulnerability of Mozambican fisheries’ species to climate change

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Abstract

Mozambique is amongst the most vulnerable of Western Indian Ocean (WIO) countries to the impacts of climate change on its marine fisheries. We used rapid assessment methods to evaluate sensitivity, exposure and vulnerability of fisheries species to climate change, appropriate for data-deficient, developing countries in the region. Species were selected based on their importance in industrial and artisanal fisheries’ landings, further prioritized by local experts. Species’ attributes likely to be sensitive to climate change were identified and scored, utilizing life history or biological characteristics. Sea Surface Temperature (SST) was the most prominent climate exposure factor and for which we could confidently predict likely future change. Most species had low or medium overall sensitivity to climate change, with only eight considered highly sensitive. Climate exposure (SST) scores were high off northern Mozambique, while the central and southern regions were generally of medium exposure. Ten species received a High vulnerability score, 14 were Medium, and 16 had a Low vulnerability score. The highly vulnerable species were all fishes, apart from one crustacean; 4 of the 9 were strongly estuarine-associated; the most vulnerable species was the parrotfish Scarus ghobban. This is the first attempt to use a rapid, semi-quantitative, specialist- and trait-based vulnerability assessment of the anticipated effect of climate change on marine fisheries species in the WIO. Challenges experienced were data paucity, limited resources, the large study area, and the complex oceanography of the region. However, a simple methodology was developed, derived from efforts elsewhere, and which can be used to undertake similar assessments for other WIO countries. Raised awareness of climate change among small-scale fishing communities is a necessity, combined with adaptation by promoting fisheries co-management. Also required is support from government to ensure that people can be flexible to change.
Introduction

Along with a host of other impacts, climate change poses a threat to marine species, and thus is a risk to food security, particularly in developing countries. Coastal developing countries are particularly dependent on marine resources as a source of nutrition and income [1], and Mozambique is no exception [2]. However, several studies have shown that the country is amongst the most vulnerable to the impacts of climate change on its marine fisheries, the most recent that of Blasiak et al. [3]. These authors placed Mozambique as 7th most vulnerable (of 147 globally), based on the country’s exposure to climate change impacts, its sensitivity to changes in productive capacity caused by climate change, and its adaptive capacity to deal with climate change. The Indian Ocean is warming fast [4–6] and the regime winds which influence productivity, and thus fisheries, have also changed in the last 40 years [7]. Yet, conflictingly, small-scale fishing, which contributes by far the most to fisheries landings in Mozambique, is increasing [2,8]. This is likely a function of increasing reliance on small-scale fisheries for food, not only because of increases in coastal population, but as a substitute when conditions for agriculture are unfavourable [9–11]. Several major crops are predicted to have decreased yields in the region [12–14], and declining trends in agricultural production in Mozambique [15], some as a consequence of warming [16], mean the increased pressure on small-scale fisheries is likely to be sustained. In this regard, [17] have recently identified villages where coastal community are highly vulnerable to climate change-induced food insecurity. Furthermore, while small-scale fisheries are important for food security, industrial fishing accounts for almost 60% of catch value [18], so potential impacts of climate change on revenue also need to be anticipated. It is thus important for decision-makers to be informed about possible scenarios and to prepare accordingly.

To date, initiatives which identified Mozambique fisheries as vulnerable have been generalized global or regional-scale assessments [e.g. 19–22], and none have attempted an assessment of climate change impacts on fisheries species based on their biology or life history. [23] undertook an empirical quantification of the impacts, though only based on projected fisheries catches of a single tuna species, *Katsuwonus pelamis*. To provide background and context, [2] conducted a review of the Mozambican industrial (including semi-industrial) and artisanal (small-scale) fisheries with the objective of planning for climate change resilience. They clearly outlined the status of, and key challenges faced by, fisheries, including climate change, and presented a number of recommendations on the way forward. One of these was to conduct a vulnerability assessment of key fisheries species to climate change to inform fisheries managers and assist with planning for climate change. This, together with increasing sea surface temperature off Mozambique [24], the rate of which is escalating [25], and the recognition that this could threaten its marine and coastal fisheries [26], provided the initial motivation, background and rationale for the current study. This paper is part of a suite of papers (see “Under publication” in References) on climate change and marine food security in Mozambique.

A detailed vulnerability assessment based on a comprehensive information base, as undertaken elsewhere [e.g. 27–29], was not feasible in Mozambique, where data, financial and human resources are limited. Consequently, we set out to identify and validate a rapid assessment methodology that would provide a defensible and robust platform to evaluate the sensitivity, exposure and vulnerability of identified fisheries species to climate change, and which would also be appropriate for data-deficient, developing countries in the region. Following [30,31] were amongst the first to develop a methodology for the rapid assessment of sensitivity to climate change of a broad range of fisheries species based on their behaviour, habitat usage and life-history traits. This formed the basis for subsequent assessments which also included a climate exposure component, with the rationale that the product of a species’ sensitivity and

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its exposure to climate change provides a measure of its vulnerability [29,32–35]. Notably, until the recent effort by [36] in the Pacific, assessments have hitherto been conducted on species from cool- and warm-temperate regions, and, apart from [37] in South Africa, we are not aware of any such rapid assessments that have been undertaken for marine fisheries species in Africa or the western Indian Ocean.

The objectives were as follows:

- Identify and prioritize key species from artisanal and industrial fisheries.
- Develop a methodology to conduct rapid sensitivity assessments of important artisanal and industrial species to climate change. This methodology should be effective, appropriate and robust enough to give dependable climate sensitivity scores for use by fisheries managers in data-poor developing countries.
- Conduct a sensitivity/exposure/vulnerability assessment of important artisanal and industrial species to climate change.
- Use the results to identify key fishery species likely to be most impacted by climate change, and elucidate the key drivers behind this vulnerability.
- Provide recommendations on how the outcomes can be used as a basis for developing a methodology for rapid vulnerability assessments for Mozambique and the WIO and ultimately as a tool for fisheries managers to promote climate change resilience.

As elaborated in the methods, predicted climate change is here considered to be embodied by changes in seas surface temperature. For simplicity, artisanal here includes small-scale and subsistence; industrial includes semi-industrial.

Materials and methods

Note that no permits were required for this study as no field work was required.

Study area

Most of the main species occurring in industrial and artisanal fisheries in Mozambique are distributed along most of, if not the entire, coastline [2,38,39], and occur in shelf and/or offshore waters, so the study area was defined as the coastline to the EEZ. Recognition was given to the biogeographic regions which underlie the division of the country into three fisheries management zones corresponding to the three ecoregions (Zone A (North 10°- 16°S), Zone B (Centre or Sofala Bank 16° - 21°S), Zone C (South 21°- 26°S); [2]).

Selection of key species

The initial list of important species was based on their importance in landings of industrial and artisanal fisheries [2]. These were further prioritized for climate vulnerability assessment during a workshopping process, taking cognisance of the relative importance of species for food security and revenue. Prioritization was based on workshop participants’ knowledge of the importance of the species to fisheries catches, incorporating diverse taxonomic groups, and acknowledging their distribution across management zones and habitats, while eliminating closely-related, co-occurring species if it was felt that one of the species was sufficiently representative. For example, although the prawns Penaeus indicus and Metapenaeus monoceros are both very important to industrial and artisanal fisheries in Zone C, their distribution and general biology (and hence their attributes for sensitivity to climate change) were considered
sufficiently similar to only include the former species. This process culminated in a list of 40 prioritized species.

**Sensitivity**
The general approach was that of a risk assessment, based on [30,31,33], and references therein, and modified to be achievable in the Mozambique context. A range of attributes was identified, utilizing life history or biological characteristics that are likely to be sensitive to climate change, also taking cognisance of the likelihood that sufficient information on the attributes would be available for the selected species in order to be able to assign scores. The attributes were grouped into one of three broad categories–abundance, dispersal and phenology.

**Abundance**
Species that are more abundant are considered less sensitive or vulnerable to climate change because their greater numbers increase the likelihood of survival of part of the population—thereby increasing chances of recruitment to the fishery. Abundance is a function of productivity, in turn being influenced by:

- Fecundity: highly fecund species should be more resilient to climate change due to enhanced reproductive output
- Recruitment: species which have irregular recruitment are more sensitive as there is greater likelihood of recruitment failure with changing environmental conditions
- Average age at maturity: determines generation time, and consequently reproductive output. Late maturing species are more sensitive to climate change than species which reproduce earlier
- Generalist/specialist: generalists have fewer specific needs so they should be less sensitive to changes in availability of habitat and food due to climate change
- Status of stock: stocks with large biomasses are more resilient to climate change. Implicit in this is that there is higher genetic diversity which confers greater adaptability
- Other Stressors: stocks that are exposed to other stressors (e.g., habitat degradation, invasive species, disease, pollution, hypoxia] will be more sensitive to climate change

**Dispersal**
The more widely dispersed a species, the greater its ability to change its distribution if exposed to climate change, hence it will have lower sensitivity. Dispersal is influenced by:

- Larval duration: species with longer larval duration will disperse further, so they are more likely to be able to take advantage of a wider distribution of habitats and hence are more resilient to climate change
- Post-larval mobility: less mobile species are more sensitive to climate change than species with higher mobility which are more able to avoid environmental changes
- Physiological tolerance: latitudinal range is a proxy for tolerance of environmental conditions—species with a narrow range are more dependent on specific environmental conditions, and hence are more sensitive
Phenology

Climate change may affect seasonal patterns in environmental variables such as salinity, temperature, currents and freshwater flow, and, if events in a species’ lifecycle such as spawning and/or migration are cued by the changes in these variables, then alteration of the patterns may disrupt these events. These species will be more sensitive to climate change than species for which timing of events is related to variables such as day length or moon phase.

- Environmental cues for spawning or migration: species will be more sensitive if they are reliant on cues which could be affected by climate change
- Temporal mismatches of events: species with a longer spawning season are less sensitive as there is greater opportunity for larvae to encounter favourable conditions, promoting survival
- Migration: species which migrate (seasonally or for spawning) are more sensitive because of their reliance on different habitats at different times to complete their life cycle

The attributes are listed in Table 1, as well as the criteria for scoring Low, Medium and High sensitivity.

Exposure

Climate exposure factors are climate variables that could affect species viability. Five climate factors were initially considered, based on their likely influence on the species attributes, and the potential availability of data and modelled trends for Mozambique. However, considerable difficulty was experienced in obtaining plausible predictions of their future trends (see Discussion], hence, most of the exposure factors which have been elsewhere incorporated in climate change vulnerability studies by other workers [e.g. 29,33] could not be

Table 1. Attributes, criteria and categories used to assess level of sensitivity of each species to climate change [after 31,33].

<table>
<thead>
<tr>
<th>Category</th>
<th>Attribute</th>
<th>Low sensitivity (1)</th>
<th>Medium (2)</th>
<th>High sensitivity (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abundance</td>
<td>1. Fecundity</td>
<td>&gt;20,000 eggs/oocytes per year</td>
<td>100–20,000 eggs/oocytes per year</td>
<td>&lt;100 eggs/oocytes per year</td>
</tr>
<tr>
<td></td>
<td>2. Recruitment</td>
<td>Consistent recruitment every 1–2 years</td>
<td>Occasional and variable recruitment</td>
<td>Highly episodic recruitment</td>
</tr>
<tr>
<td></td>
<td>3. Average age at maturity</td>
<td>≤2 years</td>
<td>2–10 years</td>
<td>&gt;10 years</td>
</tr>
<tr>
<td></td>
<td>4. Generalist vs. specialist</td>
<td>Reliance on neither habitat nor prey</td>
<td>Reliance on either habitat or prey</td>
<td>Reliance on both habitat and prey; or extreme reliance on one</td>
</tr>
<tr>
<td></td>
<td>5. Status of Stock</td>
<td>Robust</td>
<td>Uncertain or vulnerable</td>
<td>Threatened or depleted</td>
</tr>
<tr>
<td></td>
<td>6. Other Stressors (excluding fishing)</td>
<td>Stock is experiencing one other stressor</td>
<td>Stock is experiencing no more than two known stressors</td>
<td>Stock is experiencing three or more known stressors</td>
</tr>
<tr>
<td>Distribution</td>
<td>7. Larval duration</td>
<td>&gt;8 weeks/2 months</td>
<td>2–8 weeks</td>
<td>&lt;2 weeks or no larval stage</td>
</tr>
<tr>
<td></td>
<td>8. Post-larval mobility</td>
<td>&gt;1,000 km</td>
<td>10–1,000 km</td>
<td>&lt;10 km</td>
</tr>
<tr>
<td></td>
<td>9. Physiological tolerance</td>
<td>&gt;20˚ latitude</td>
<td>10–20˚ latitude</td>
<td>&lt;10˚ latitude</td>
</tr>
<tr>
<td>Phenology</td>
<td>10. Environmental cues for spawning or migration</td>
<td>No apparent correlation with environmental variables</td>
<td>Weak correlation with environmental variables</td>
<td>Strong correlation with environmental variables</td>
</tr>
<tr>
<td></td>
<td>11. Temporal mismatches of events</td>
<td>Continuous duration; &gt;4 months</td>
<td>Wide duration; 2–4 months</td>
<td>Brief duration; &lt;2 months</td>
</tr>
<tr>
<td></td>
<td>12. Migration</td>
<td>Very little / virtually no migration</td>
<td>Migration is common for some of the population</td>
<td>Migration is common for most of the population</td>
</tr>
</tbody>
</table>
included here. Further reasons for exclusion of 4 of the 5 initially considered factors are given below:

1. Sea surface temperature (SST)
2. Surface air temperature—used as a proxy by Hare et al. [2016] to determine exposure of estuarine-associated species to water temperatures in estuaries—not included here because it did not distinguish estuarine versus non-estuarine areas.
3. Coastal precipitation—not included because it does not reflect catchment inputs to estuaries; also, because river flow into the ocean is strongly mediated by upstream dams.
4. Ocean currents—not included because linear projection would not give reliable information, owing to the complex, highly energetic and chaotic nature of the oceanography off Mozambique [40–43].
5. Chlorophyll—a proxy for primary productivity; not included because of inability to distinguish chlorophyll due to the presence of coloured dissolved organic matter [44], particularly on the wide, turbid Sofala Bank in Zone B.

Expert-based scoring

Sensitivity. This study used a simplified approach adapted from [31,33] that was considered appropriate for the data and expertise available. Initially, a single expert (AJRQ] undertook a desktop review of the literature to score (1—Low, 2—Medium, 3—High] sensitivity attributes for each species. These scores were reviewed by a second expert (STF] and thereafter a five-day workshop was held, attended by all authors, and a final consensus score was agreed upon for each species. The voluminous individual species’ tables with consensus scores and supporting rationale are available on request. Where data were lacking leading to uncertainty when assigning scores, a higher sensitivity score was used, being a conservative approach. Note that the scores imply neither negative nor positive impacts of climate change, only a measure of sensitivity. Data quality scores based on the criteria in Table 2 were simultaneously assigned for each species, to provide a measure of confidence in overall sensitivity scores. An average of the 12 attribute scores was used to obtain an overall score for each species, and quartiles were used to convert these averages to final sensitivity scores of between 1 and 3.

Exposure. Scoring of exposure comprised two components: (1] climate exposure, which was scored first to spatially determine the extent to which climate change was expected to occur; and (2] species exposure, for which scores were assigned based on spatial occurrence of species and the extent to which they could experience the anticipated exposure.

Table 2. Data quality scoring criteria for attributes [after 33].

<table>
<thead>
<tr>
<th>Data quality score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Adequate Data. The score is based on data which have been observed, modelled or measured, from a reputable source.</td>
</tr>
<tr>
<td>2</td>
<td>Limited Data. The score is based on data which are more uncertain, being based on related or similar species, or come from outside the study area, or the source may be less reliable.</td>
</tr>
<tr>
<td>1</td>
<td>Expert Judgment. The score reflects the judgment of the specialists and is based on their general knowledge of the species, or other related species, and their relative role in the ecosystem.</td>
</tr>
<tr>
<td>0</td>
<td>No Data. No information available to score. Very little known about the species or related species and there is no basis for forming an expert opinion.</td>
</tr>
</tbody>
</table>
Expected climate exposure was based on a linear trend of sea surface temperature (SST) derived from the AVHRR (https://coastwatch.pfeg.noaa.gov/erddap/griddap/nciPH53sstn1day.html, accessed in October 2022) level 3 product of 30 years from 1991 to 2020 (hereafter designated as “past”) and linearly projected to 30 years into the future from 2021 to 2050 (hereafter designated as “future”). The historical SST (1991–2020) was initially deseasonalized before obtaining the linear trend since seasonality can potentially skew the trend. The linear trend was obtained using the nonparametric Theil-Sen estimator as opposed to the parametric least-squares regression as it is resistant to outliers and doesn’t draw from any probability distribution, hence it is more robust [45]. The seasonality was then added back to the deseasonalized linear projection into the future (2021–2050).

Exposure to mean climate conditions (EM) was then computed following [33], whereby the historical SST trend was subtracted from the future SST trend projection, divided by standard deviation of the SST over the historical period. Scores were assigned in grid blocks by considering the EM distribution in the lower 25th percentile (1 — Low) and the upper 25th percentile (3 — High), whilst the data between the lower and upper 25th percentiles were 2 — Medium. The SST climate exposure scores were then mapped over the Mozambican EEZ using ArcGIS.

Species exposure was determined by considering the distribution of the juvenile/adult and egg/larval phases of each species within the three management zones (A-North, B-Central, C-South), in the context of the climate exposure (SST) scores per grid block i.e. species exposure was determined by the overlap of the species’ spatial distribution, also recognizing in which management zone most catches were taken, and spatial differences in the extent of the projected change in SST. Species’ depth of occurrence (as juveniles/adults and egg/larvae) was also considered when scoring. Consensus scores were jointly assigned by all authors in a workshop; scores were 1 — Low, 2 — Medium, 3 — High N/A was used if the species did not occur in that management zone, and 0 if the climate exposure was not deemed to have an effect because of the species’ depth of occurrence. Hypothetical examples are given in Table 3 of how contrasting scores were resolved to produce egg/larval and juvenile/adult scores; overall scores were assigned conservatively, e.g., a score of 1 for larvae and 2 for juvenile/adult produced an overall score of 2; scores of 1 and 3 produced an overall score of 2.

**Results**

The 40 selected species were diverse (28 bony fishes, 9 crustaceans, 3 molluscs) and came from 25 families, with clupeids, lutjanids, scombrids and palinurids contributing the most species.

Table 3. Hypothetical species exposure scores, with derived scores for eggs/larvae and juvenile/adult, as well as overall.

<table>
<thead>
<tr>
<th>Species</th>
<th>Eggs/Larvae</th>
<th>Juvenile/Adult</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Management zone</td>
<td></td>
<td>Management zone</td>
</tr>
<tr>
<td>a</td>
<td>A 2 2 2</td>
<td>A N/A 0 0 0</td>
<td>1</td>
</tr>
<tr>
<td>b</td>
<td>3 3 2</td>
<td>1 1 0</td>
<td>1 2</td>
</tr>
<tr>
<td>c</td>
<td>3 2 1</td>
<td>2 3 2</td>
<td>2 2</td>
</tr>
<tr>
<td>d</td>
<td>0 0 1</td>
<td>2 1 3</td>
<td>2 2</td>
</tr>
<tr>
<td>e</td>
<td>3 2 2</td>
<td>2 1 1</td>
<td>1 2</td>
</tr>
<tr>
<td>f</td>
<td>N/A 3 3</td>
<td>2 2 2</td>
<td>2 3</td>
</tr>
</tbody>
</table>

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A diverse variety of fishing gear types ($n = 10$) were represented, and both fisheries sectors were equitably represented, with 13 species considered predominantly Industrial, 15 predominantly Artisanal, while 12 occurred frequently in catches by both sectors. The diversity of species (reflected by their known frequency of occurrence in catches per management zone)

### Table 4. List of 40 prioritized fisheries species

<table>
<thead>
<tr>
<th>Family</th>
<th>Species</th>
<th>Gear</th>
<th>Sector</th>
<th>Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sergestidae</td>
<td>Acetes erythraeus</td>
<td>Chicocota, seine</td>
<td>Artisanal</td>
<td>A,B</td>
</tr>
<tr>
<td>Clupeidae</td>
<td>Amblygaster sirm</td>
<td>Seine, gillnet</td>
<td>Artisanal</td>
<td>A,C</td>
</tr>
<tr>
<td>Geryonidae</td>
<td>Chaceon macphersoni</td>
<td>Trawl, trap</td>
<td>Industrial</td>
<td>B,C</td>
</tr>
<tr>
<td>Sparidae</td>
<td>Cheimerius nufar</td>
<td>Line</td>
<td>Industrial</td>
<td>C</td>
</tr>
<tr>
<td>Sparidae</td>
<td>Chrysolephus puniceus</td>
<td>Line</td>
<td>Industrial</td>
<td>C</td>
</tr>
<tr>
<td>Carangidae</td>
<td>Decapterus russelli</td>
<td>Seine, gillnet, trawl</td>
<td>Industrial, Artisanal</td>
<td>A,C</td>
</tr>
<tr>
<td>Serranidae</td>
<td>Epinephelus albomarginatus</td>
<td>Line</td>
<td>Industrial</td>
<td>A,B</td>
</tr>
<tr>
<td>Lutjanidae</td>
<td>Etelis carbunculus</td>
<td>Line</td>
<td>Industrial</td>
<td>A</td>
</tr>
<tr>
<td>Scombridae</td>
<td>Euthynus affinis</td>
<td>Line</td>
<td>Industrial, Artisanal</td>
<td>A,B,C</td>
</tr>
<tr>
<td>Solenoceridae</td>
<td>Haliporoides triarthrus</td>
<td>Gillnet, beach seine</td>
<td>Industrial</td>
<td>B,C</td>
</tr>
<tr>
<td>Clupeidae</td>
<td>Hilsa kelee*</td>
<td>Seine, gillnet</td>
<td>Artisanal</td>
<td>B,C</td>
</tr>
<tr>
<td>Sciaenidae</td>
<td>Johnius dorsalis*</td>
<td>Gillnet, seine, trawl</td>
<td>Industrial, Artisanal</td>
<td>B,C</td>
</tr>
<tr>
<td>Scaridae</td>
<td>Leptoscarus vaigiensis</td>
<td>Traps, seine, line</td>
<td>Artisanal</td>
<td>A,C</td>
</tr>
<tr>
<td>Lethrinidae</td>
<td>Lethrinus lentjan</td>
<td>Line, seine, trawl</td>
<td>Artisanal</td>
<td>A,C</td>
</tr>
<tr>
<td>Lethrinidae</td>
<td>Lethrinus nebulosus</td>
<td>Line, trap</td>
<td>Artisanal</td>
<td>A,C</td>
</tr>
<tr>
<td>Lutjanidae</td>
<td>Lutjanus sanguineus</td>
<td>Line</td>
<td>Industrial</td>
<td>A,B</td>
</tr>
<tr>
<td>Veneridae</td>
<td>Meretrix meretrix</td>
<td>Hand</td>
<td>Artisanal</td>
<td>C</td>
</tr>
<tr>
<td>Nephropidae</td>
<td>Metaneophrops mozambicus</td>
<td>Trawl</td>
<td>Industrial</td>
<td>B,C</td>
</tr>
<tr>
<td>Octopodidae</td>
<td>Octopus cyanea</td>
<td>Spear</td>
<td>Industrial, Artisanal</td>
<td>A,C</td>
</tr>
<tr>
<td>Sciaenidae</td>
<td>Otolithes ruber</td>
<td>Line, seine, gillnet, trawl</td>
<td>Industrial, Artisanal</td>
<td>B,C</td>
</tr>
<tr>
<td>Palinuridae</td>
<td>Paladinus delagoae</td>
<td>Trawl</td>
<td>Industrial</td>
<td>B,C</td>
</tr>
<tr>
<td>Palinuridae</td>
<td>Paladinus homarus</td>
<td>Diving</td>
<td>Artisanal</td>
<td>C</td>
</tr>
<tr>
<td>Palinuridae</td>
<td>Paladinus ornatus</td>
<td>Diving</td>
<td>Artisanal</td>
<td>A,C</td>
</tr>
<tr>
<td>Penaeidae</td>
<td>Penaeus indicus*</td>
<td>Trawl, seine, gillnet</td>
<td>Industrial, Artisanal</td>
<td>A,B,C</td>
</tr>
<tr>
<td>Sparidae</td>
<td>Polysteganus spp</td>
<td>Line</td>
<td>Industrial</td>
<td>C,B</td>
</tr>
<tr>
<td>Haemulidae</td>
<td>Pomadasys kaakan*</td>
<td>Line, seine</td>
<td>Artisanal</td>
<td>B,C</td>
</tr>
<tr>
<td>Haemulidae</td>
<td>Pomadasys maculatum</td>
<td>Line, seine, trawl</td>
<td>Industrial, Artisanal</td>
<td>B,C</td>
</tr>
<tr>
<td>Lutjanidae</td>
<td>Pristipomoides filamentosus</td>
<td>Line</td>
<td>Industrial</td>
<td>A</td>
</tr>
<tr>
<td>Clupeidae</td>
<td>Sardinella albella</td>
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<td>Artisanal</td>
<td>B</td>
</tr>
<tr>
<td>Scaridae</td>
<td>Scarus ghobban</td>
<td>Traps, spear</td>
<td>Artisanal</td>
<td>A,C</td>
</tr>
<tr>
<td>Scombridae</td>
<td>Scomberomorus commerson</td>
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<td>Industrial, Artisanal</td>
<td>B</td>
</tr>
<tr>
<td>Portunidae</td>
<td>Scylla serrata*</td>
<td>Hand, traps</td>
<td>Artisanal</td>
<td>B</td>
</tr>
<tr>
<td>Siganidae</td>
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<td>Trap, gillnet, seine</td>
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<td>A,C</td>
</tr>
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</tr>
<tr>
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<td>B,C</td>
</tr>
<tr>
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<td>A,B,C</td>
</tr>
<tr>
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<td>B,C</td>
</tr>
<tr>
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<td>Upeneus vittatus</td>
<td>Seine, trawl</td>
<td>Industrial, Artisanal</td>
<td>A</td>
</tr>
<tr>
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<td>Uroteuthis duvauceli</td>
<td>Trawl, seine</td>
<td>Industrial, Artisanal</td>
<td>A,C</td>
</tr>
<tr>
<td>Xiphidae</td>
<td>Xiphas gladas</td>
<td>Line</td>
<td>Industrial</td>
<td>A,B,C</td>
</tr>
</tbody>
</table>

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was highest in Zone C (30 species], with 22 in Zone B and 21 in Zone A; most species featured in catches in more than one Zone.

**Sensitivity**

The individual attribute sensitivity scores assigned by workshop participants for each species are available online (https://doi.org/10.17882/98744); an example is provided in Supplementary Information (S1 Appendix), and the ranked list (based on means of the 12 attribute scores and derived High, Medium and Low sensitivity categories based on quartiles) is shown in Fig 1. Species with low or medium overall sensitivity were in the majority, with only eight (20%) considered highly sensitive. The mean sensitivity scores ranged between 1.42 and 2.25, with a median value of 1.75. By attribute type, High species sensitivity was more prominent for Migration and Other stressors, while there was mostly Low species sensitivity to Recruitment, Physiological tolerance, Fecundity and Temporal mismatch attributes, and mostly Medium sensitivity to Dispersal, Mobility, Stock status and Phenology (S1 Fig). Sensitivity scores as a function of species’ broad habitat associations (soft/reef substrate, pelagic/demersal) were examined but no patterns were observed, other than for estuarine dependency—four of the six estuarine-dependent species were amongst the eight highly sensitive species. The majority (23/40, 58%) of scores were based on limited data for the species concerned, with only 13/40 (33%) species being deemed to have adequate data; scores for four species were assigned on the basis of general knowledge or related species information.

**Climate exposure**

Exposure scores were high off northern Mozambique (Fig 2), with two small areas also with high scores in the southern region, surrounded by medium and low scores. The central and southern area were generally medium exposure, although some low exposure areas were apparent in Beira Bay on the southern Sofala Bank and in the Delagoa Bight eddy region in the south, centred at 26°S, 34°E. There was also a relatively large area offshore in the southern region of the country with low exposure.

**Species exposure**

Fig 3 shows that six (15%) of species are expected to be highly exposed to climate change (greatly increased SST), 30 (75%) species with medium exposure, 3 (8%) with low exposure, and 1 species (*Metanephrops mozambicus*) has no exposure (see Discussion for explanation). High species exposure scores are a function of the expected extent to which the species will experience the High climate exposure seen in Zone A (Fig 2) i.e. if the species occurs in Zone A and another zone (as eggs/larvae and juveniles/adults), it will be highly exposed; whereas if it occurs along the whole coast, even if it is highly exposed in Zone A, the ameliorating effects of lower climate exposure in Zone B and C reduce it to Medium exposure. More than half of the species either did not occur in Zone A, or mainly occurred in Zone A and C, and therefore could not have a high exposure score.

**Vulnerability**

The sensitivity x exposure matrix (Fig 4) shows that 10 species (25%) received a High vulnerability score, 14 were Medium, and 16 had a Low vulnerability score. Although *M. mozambicus* technically scored zero vulnerability owing to its zero score for species exposure, it is included in Low for convenience. The highly vulnerable species were all fishes, apart from one crustacean, the prawn *Penaeus indicus*; 4 of the 9 were strongly estuarine-associated; the most
vulnerable species was the parrotfish *Scarus ghobban*. Of the 10 most vulnerable species, 8 are only caught by artisanal fishers; 2 species feature in both artisanal and industrial sectors. Of the Low vulnerability species, 2 are caught by artisanal fishers only, whereas 8 are caught by Industrial fishers only; 6 species occur in catches by both sectors.
Discussion

This is the first attempt to use a rapid, semi-quantitative, specialist- and trait-based vulnerability assessment of the anticipated effect of climate change on fisheries species in the Western Indian Ocean (WIO). Challenges experienced were data paucity, limited resources (people,
Fig 3. Ranked species exposure scores. High (red), Medium (orange) and Low (green). Note: Metanephrops mozambicus = 0: No exposure because eggs and juveniles/adults occur too deep for exposure to SST. *estuarine-dependent.

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funds], the large area (>16˚ latitude, a coastline of >2 500km), and the complex oceanography of the region. These challenges occur throughout the WIO region, as does the heavy reliance of coastal populations on marine resources and the threat of climate change to fisheries. Notably, a recent global review identified Mozambique as the 5th most compromised African country in terms of a combination of climate change impacts and response capacity regarding marine capture fisheries [46]. We developed a relatively simple methodology, based on efforts elsewhere by more-resourced workers, and which can be used to undertake similar assessments for other countries in the region. The methodology can be used to highlight species which are likely to be particularly affected, to guide future monitoring and research, and thereby assist decision-makers.

There have been very few empirical efforts in the WIO to link population biomass and distribution models to climate models and to project the effect of climate change on marine fisheries species. [23] undertook projections for the tuna Katsuwonus pelamis, while [47] undertook multi-species projections for Kenya and Tanzania; these approaches were not possible for Mozambique because of the lack of resources and the large number of highly diverse species from numerous habitats. When faced with similar issues, other workers have used rapid sensitivity and/or vulnerability assessments, such as in south-east Australia [31], north-east America [33], south-western South Africa [37], Portugal [29], and the central Pacific islands [36]. The approach is a refinement of an ecological risk assessment, with vulnerability of species to climate change being assessed following the Intergovernmental Panel for Climate Change [48] which determines vulnerability as a function of species exposure to changing environmental variables and their sensitivity to environmental change. While the vulnerability determined by [48] also includes adaptive capacity to environmental change, the sensitivity attributes used herein include species resilience—ability to survive and recover from an

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**Fig 4. Matrix of species sensitivity x species exposure scores.** *estuarine-dependent.*

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impact; and adaptive capacity—ability to mitigate impacts by virtue of their ability to move away (dispersal) and/or to switch diet (if they are a generalist). Exposure measures the predicted environmental change that the species is expected to encounter within its distribution, reflecting the overlap between species distribution and the magnitude and spatial distribution of the environmental change [32].

For selection of attributes, we largely followed the approach of [31], who adapted abundance attributes from an ecological risk assessment for the effects of fishing [49] and included attributes in categories on distribution and phenology. Several of the abundance traits are also used for fisheries risk assessments in data-poor situations (e.g. Productivity Susceptibility Analyses), and for extinction risk assessments (IUCN Red List), so their utility is well established. However, we included two additional abundance attributes (stock status and stressors apart from fishing), also included by [33], because we considered them influential on sensitivity. In contrast, we excluded the [33] attribute on ocean acidification as there is too much uncertainty regarding its impacts [50], particularly for Mozambican fisheries species. Overall, the 12 final attributes we used corresponded closely to those of [31,33], as well as [29,36,37]. The biological trait-based attributes essentially reflect the ability of the species to withstand climate change by virtue of the resilience conferred on them by the traits. While most of these studies used a system of individual specialist voting tallies when scoring attributes, we preferred workshop consensus [also adopted by [27] when finalizing attribute scores, following initial scoring by two of the specialists.

We depart considerably from the other studies which calculated scores for several climate exposure factors, with only one factor for Mozambique, SST, being assessed. While cognizant that possible changes in precipitation, ocean currents, oxygen and primary productivity will affect species, none of these were calculable with reasonable confidence in their projection models for the area. When we evaluated/validated the available global Coupled Model Intercomparison Project Phase 6 (CMIP6) models for the Western Indian Ocean by comparing with past observations derived from AVHRR, they deviated significantly from the main observed features; for instance, there was no predicted heating in the north in the models (S2 Appendix, S2 Fig). Ocean acidification was also considered, but there are inadequate data for Mozambique, and impacts of changes in this factor are equivocal [50]. [33] also noted the limitations of global climate models in resolving the importance of regional-scale oceanography and estuaries. Although the use of SST alone may be questioned when considering climate change vulnerability of marine fisheries species, there is voluminous literature demonstrating SST to be the primary factor when assessing climate change impacts on marine ecosystems, either directly or indirectly via changes in precipitation, ocean circulation, oxygen and primary productivity [19,51–54]. Notably, in their national climate change adaptation and mitigation strategy, the Ministry for Coordination of Environmental Affairs in Mozambique (MICOA) considered SST to be the most influential factor on fisheries.

The list of ca. 70 important fisheries species identified by [2] was here reduced to a final prioritized list of 40. Their considerable taxonomic diversity is reflected in the variety of gears with which they are caught. The vast majority of species are from shelf (i.e. shallower) habitats where they are caught by both artisanal and industrial fisheries; the eight slope (crustacean) and oceanic (tuna, billfish) species from deeper water are only caught by the industrial sector. The life history or biological characteristics attributes of most (80%) species were considered to have low or medium sensitivity to climate change. It is noteworthy that, of the six strongly estuarine-dependent species, four had the highest average scores of the eight highly sensitive species. The high scores were due to specialists considering them highly sensitive to impacts on their migration and phenological cues for spawning, and also due to the compounding impacts of other stressors, such as pollution, freshwater inputs, habitat loss and alien species.
This is notwithstanding that juveniles of estuarine-dependent species are often highly tolerant of extreme temperatures in estuaries during their estuarine-dependent life-stage [55]. The majority (68%) of species had low/medium data confidence scores, which is concerning given that these are prioritized fisheries species, pointing to the need for increased research.

The high exposure SST scores in northern Mozambique can be related to the warming pool region around Kenya, Tanzania and Northern Mozambique [4,25,56]. Moreover, the region has been identified as one of the most rapidly warming of the world’s oceans [4]. Conversely, central and southern Mozambique are warming more slowly than the north [25], corroborating the medium to low climate exposure scores there. Further, previous studies described cool water lenses on the southern Sofala Bank [57,58], as well as cool cyclonic eddies in the Delagoa Bight in southern Mozambique [59]. Another study describes the upwelling cell and quasi-permanent cyclonic eddy off Angoche, with upwelling uplifting deep cold water to the surface [60], which explains the localised moderate exposure SST in this region around 16˚S.

Sensitivity and exposure combined to produce 10 species which the workshop specialists considered highly vulnerable to climate change in Mozambique. The most vulnerable, *Scarus ghobban*, is a habitat specialist, preferring seagrasses and coral reefs. This, combined with its exposure to the projected high SST increases in Zone A where its preferred habitats predominate, means it is particularly vulnerable. The other species which were highly vulnerable in our study were small pelagic fishes (3), small-medium coral/seagrass-associated fishes (4), a medium-sized soft-substrate estuarine-dependent fish, and an estuarine-dependent prawn. All 10 species feature prominently in artisanal catches, while the prawn, *P. indicus*, is also extremely important to the industrial trawl sector. Several of the highly vulnerable species contribute substantially to artisanal catches, e.g. *Hilsa kelee* and *Thryssa vitrirostris* [61]. Six of the 10 species had high sensitivity scores, mostly accounted for by high sensitivity to impacts on their migration and phenological cues for spawning, their being specialists regarding habitat and/or prey, and also due to the compounding impacts of other stressors, such as pollution. Five of the species had high exposure scores, driven by the occurrence of all life history phases in Zone A. While these species also occurred in Zone C, where SST increases are not projected to be as high, their high exposure scores in Zone A, in combination with medium sensitivity scores from Zone C, were sufficient to render them highly vulnerable.

Of the 16 low vulnerability species, 14 commonly feature in industrial catches, although only 8 are targets; 8 species feature in artisanal catches, although most of these are not as commonly caught as the high vulnerability species. Only one species, the langoustine *Metanephrops mozambicus*, was not considered to be vulnerable to climate change in the form of increased SST, as a consequence of its living at depth (>300m) at all stages of its lifecycle. This deep-water (300-500m) species is exceptional because it is the only one with benthic larvae; the adults are also benthic and brood the eggs [62], and therefore the effects of increased SST on this deep-water species can be discounted, i.e., it is not expected to experience warming. Most of the heat in the ocean is rapidly dispersed in the upper surface layers and the rate of warming decreases with depth, confirmed by [63] who showed that deeper waters below about 200 m in the WIO are homogeneously cool, even in northern Mozambique where the surface waters are extremely warm.

There is only one other rapid vulnerability assessment study suitable for comparative purposes; other studies examined very different species from temperate habitats. Albeit using a far wider suite of exposure factors, [36] scored *S. ghobban* as low vulnerability in the Pacific islands but conceded that their approach of assigning medium sensitivity scores when information was uncertain/lacking could have led to misleadingly low vulnerability scores for their coral reef fishes. Of the other four species common to our two studies, we concurred with low vulnerability for yellowfin tuna *Thunnus albacares*, while the two deep-water snappers,
*Pristipomoides filamentosus* and *Etelis carbunculus*, which we had scored medium and low respectively, were scored the opposite by [36]; the estuarine crab *Scylla serrata* they considered low compared to our medium score.

**Conclusions and recommendations**

There is widespread concurrence that climate change is occurring and at an increasing rate, and one of the most widespread manifestations of this in marine systems is increased SST [64]. While studies in the region on impacts to fauna are limited, there have been reported changes in species distributions [65] and predicted declines in abundance of several species, particularly in equatorward distributions [47]. The results of our relative vulnerability assessment of a suite of species important to fisheries in Mozambique identifies those which are likely to be particularly affected in this country. While our assessment was challenged by a very large study area, a complex oceanographic context, a considerable number of very taxonomically diverse species, and a marked lack of human, financial and data resources, a defensible list of climate change vulnerability scores for fisheries species was produced, to once again draw decision-makers’ attention to the issue. It is perhaps unsurprising, since most Mozambican marine catches are made by artisanal fishers, that most of the highly vulnerable species are caught by this sector. Finally, with regard to our modification of existing methodologies primarily designed for temperate waters with robust human, data and financial resources, we believe our simplified but defensible approach will provide an effective template and methodology for conducting similar rapid vulnerability assessments in data- and resource-poor countries facing similar challenges in the WIO region.

What can decision-makers do to prepare fishers in Mozambique? Several earlier initiatives have provided recommendations, including the observation that substantial changes to management may not be necessary, but that there is a need for more effective implementation of both existing and proposed arrangements [2,21]. Over 10 years ago, the National Climate Change Adaptation and Mitigation Strategy noted the need to raise awareness of climate change among small-scale fishing communities, combined with adaptation, by promoting local participatory fisheries co-management [26]. There also needs to be ongoing support from government, by ensuring that people can access assets when needed, enabling them to be flexible to change—for example, by using alternative fishing grounds, techniques or species [66]. Notwithstanding that aquaculture can also be vulnerable to climate change, it can supply fish to local markets by providing alternatives if traditionally fished resources are less available. Mozambique has yet to realize its aquaculture potential, though there are recent efforts to revitalize this [67]. There is thus a need for a combination of local and national initiatives; community-level solutions to resolve fisheries issues are known to be preferred by fishing communities in nearby Kenya [68], so efforts to address climate change impacts on fisheries will require buy-in by communities, as well as an overarching national strategy. This will require improved coordination and integration of initiatives, and information sharing by stakeholders.

For the highly vulnerable reef-associated species (two lethrinids and two scarids), appropriate Marine Protected Areas (MPAs) will provide harvest refugia, with prospective benefits to fished populations in neighbouring areas; in contrast, benefits of MPAs to the three highly vulnerable small pelagic fishes (engraulids and clupeids] is not unequivocal [69]. However, two of these small pelagic fishes are estuarine-dependent, and, together with the similarly-dependent penaeid prawn and the haemulid, will benefit from conservation measures in this habitat by means of spatial protection, regeneration of mangroves and/or ensuring adequate freshwater flow. It is therefore noteworthy that the national strategy and action plan for MPA expansion
is being implemented, and the Council of Ministers decided in 2021 that Mozambique will have 10–12% of its EEZ protected by 2030 [70]. However, MPAs on their own are not a panacea. Even if they coincide with climate refugia, which have been identified in northern Mozambique [71], there is a need for lower fishing effort if MPA climate refugia are to function [72]. As these authors note, high fish biomass is key to minimizing the negative effects of climate change.

Future research could involve the identification of climate refugia for vulnerable species, matched with socio-economic studies in such refugia, to provide information on effective management options to sustain viable populations. Basic biological studies are still required for many of the important fisheries’ species. Mozambique’s complex oceanography also requires research, to improve the forecasting abilities of climate prediction models.

Supporting information

S1 Fig. No. of species per sensitivity score category and per attribute type. (TIF)

S2 Fig. Theil-Sen linear trend (22 years) comparison between satellite data (AVHRR) (a) and CMIP 6 model data (b). Coastline and land mask used are from the global database in the public domain (https://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html; Terms of use: GNU Lesser General Public License v3.0 - GNU Project - Free Software Foundation). (TIF)

S1 Appendix. Example of sensitivity scoring table: Chrysoblephus puniceus. CONFIDENCE 3. Note that all Tables and the list of references are available at https://doi.org/10.17882/98744. (DOCX)

S2 Appendix. Predicted future trend in SST. (DOCX)

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References


