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A sustainable blue economy may not be possible in Tanzania without cutting emissions

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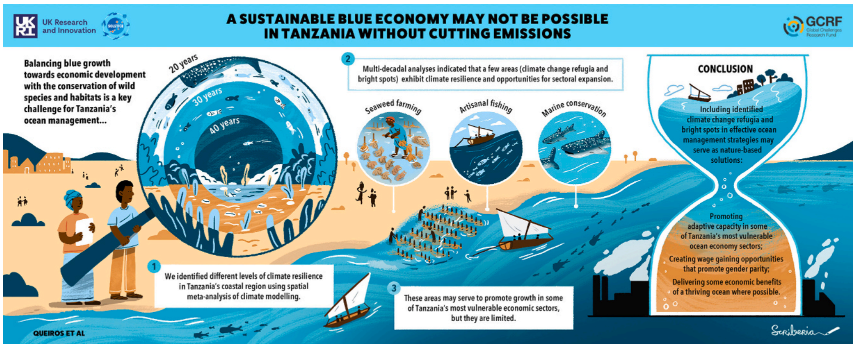
HIGHLIGHTS

- Climate-adaptive marine spatial management is necessary to reduce negative impacts on nature reliant livelihoods.
- We assessed climate-driven risks and opportunities for conservation, artisanal fisheries and seaweed farming across Tanzania.
- Ocean modelling spatial meta-analysis was used to detect the emergence of a climate signal affecting these sectors.
- Participatory mapping assessed how coastal communities may be perceiving climate-driven change in these areas.
- Few areas exhibit climate resilience or opportunities for sectoral growth under higher emissions.
- Climate-smart spatial management may promote adaptation in some of Tanzania's most vulnerable coastal areas.

GRAPHICAL ABSTRACT



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ABSTRACT

Balancing blue growth with the conservation of wild species and habitats is a key challenge for global ocean management. This is exacerbated in Global South nations, such as Tanzania, where climate-driven ocean change requires delicate marine spatial planning (MSP) trade-offs to ensure climate resilience of marine resources relied upon by coastal communities. Here, we identified challenges and opportunities that climate change presents to the near-term spatial management of Tanzania's artisanal fishing sector, marine protected areas and seaweed farming. Specifically, spatial meta-analysis of climate modelling for the region was carried out to estimate the natural distribution of climate resilience in the marine resources that support these socially important sectors. We estimated changes within the next 20 and 40 years, using modelling projections forced under global emissions trajectories, as well as a wealth of GIS and habitat suitability data derived from globally distributed programmes. Multi-decadal analyses indicated that long-term climate change trends and extreme weather present important challenges to the activity of these sectors, locally and regionally. Only in few instances did we identify areas exhibiting climate resilience and opportunities for sectoral expansion. Including these climate change refugia and bright spots in effective ocean management strategies may serve as nature-based solutions: promoting adaptive capacity in some of Tanzania's most vulnerable economic sectors; creating wage-gaining opportunities that promote gender parity; and delivering some economic benefits of a thriving ocean where possible. Without curbs in global emissions, however, a bleak future may emerge for globally valuable biodiversity hosted in Tanzania, and for its coastal communities, despite the expansion of protected areas or curbs in other pressures. Growing a sustainable ocean economy in this part of the Global South remains a substantial challenge without global decarbonization.

1. Introduction

With its Indian Ocean Rim Association (IORA) and Nairobi Convention partners, Tanzania is in the process of developing its Marine Spatial Planning (Ehler, 2021, "MSP"), with various planning processes taking shape across the country. With a coastline spanning over 14,000 km on the western shore of the Indian Ocean, marine-based economic sectors (and associated activities) are a key source of livelihoods for Tanzania's coastal communities and beyond – i.e. it's blue economy (Mwaijande, 2021). Through a strong focus on economic development, social and environmental concerns, and a focus on ecosystem-based management (Ehler and Douvere, 2009), MSP thus offers a potentially important route to deliver on a sustainable Blue Economy for Tanzania's. Specifically, one that delivers on alleviation of poverty; supporting food security; and managing a sustainable marine environment, including through increased participation of women and youth (United Nations, 2015; Mwaijande, 2021). Such challenges are particular salient here, as in other Global South countries. The Tanzanian Government is therefore balancing trade-offs in spatial management needed to deliver on these various goals simultaneously, among others.

The future of marine protected areas (MPAs) in Tanzania is of particular interest to MSP, because of the multi-faceted challenge of addressing community, conservation and wider economic needs (e.g. ecotourism, Albers et al., 2015; Mwanjela and Lokina, 2016). Indeed, there is a strong interest in marine conservation in Tanzania, to protect biodiversity and support wild capture fisheries (Francis and Machumu, 2014). This is reflected in a momentum for the expansion of MPAs (e.g. the proposed Rufiji-Mafia-Kilwa UNESCO Man and Biosphere, NEMC and National MAB Focal Point, 2021). Improved conservation efforts can lead to economic opportunities for adjacent coastal communities, through the creation of alternative MPA-based livelihood opportunities, as well as enhanced revenue for the broader local tourism sector (Burgoyne et al., 2017). However, past examples also exist where the designation of MPAs has been perceived as top-down approach, detrimental to the activity of more traditional local-based, artisanal fisheries and associated coast-based activities, such as processing and selling of catches, and repair of boats and fishing gears (Jiddawi and Ohman, 2002; Mwanjela and Lokina, 2016; Burgoyne et al., 2017). This prioritisation may result from limited understanding of the social and cultural value that local communities place on shared coastal spaces, and can lead to poor outcomes in the efficacy of spatial management, compliance, nature protection and development (Käyhkö et al., 2019). Balancing out the designation of no-take areas with the promotion of alternative MPA-based wage-gaining opportunities for these communities has thus been proposed (Albers et al., 2015). Further to this, megafauna of high value to both effective marine conservation and ecotourism (such as the Coelacanth, several sharks, turtles and marine mammals) often forage in areas also targeted by small scale fisheries in Tanzania (e.g. Ribbink and Roberts, 2006). This presents important spatial management challenges that may affect conservation as well as other development goals (Temple et al., 2018; Said et al., 2020). Lastly, blue growth in Tanzania is also significantly bolstered by seaweed farming. Indeed, the country is an important global producer of red seaweeds in the *Euchema* and *Kappaphycus* genera, which are key sources of commercially valuable carrageenan, used in food industry and cosmetics (Valderrama et al., 2015). Seaweed farming is also seen as a vital sector supporting gender parity in Tanzania, as an activity primarily undertaken by women. In a development context, seaweed farming is thus one of few, vital routes for economic independence for women, and greater participation of women in the blue economy is a key ambition of the 2050 Africa's Maritime Strategy (Fröcklin et al., 2012; Msuya, 2012). The social and economic relevance of the sector has been especially well documented in the Zanzibar archipelago (Msuya, 2013; Charisiadou et al., 2022).

The future of these three economically, socially, and ecologically important sectors unfolds against a backdrop of considerable climate change pressures driven by greenhouse gas emissions, threatening the sustainability of the very resources they rely upon. These pressures include, among others, substantial long-term warming, heatwave pressures and changing wind patterns, posing direct and indirect threat to species and habitats underpinning those sectors (Jacobs et al., 2021; Wilson et al., 2021; Obura et al., 2022). Climate change is also reducing habitat suitable for seaweed farming, and changes in temperature, salinity and light have enhanced susceptibility to disease, mass mortality and reduced crops of cultivated red seaweed species (Msuya, 2017; Largo et al., 2020). As a result, seaweed farming in deeper water is now being explored (Msuya, 2017; Brugere et al., 2020), and this too presents an important spatial management challenge. Excess greenhouse gas emissions thus represent a key factor of risk for the delivery of a sustainable blue economy for Tanzania, despite the country's low global emissions share (United Nations Population Division, 2019).

This study thus aimed to estimate spatial variation in magnitude of climate-driven change of ecosystem components underpinning conservation efforts, artisanal fishing and seaweed farming in Tanzania. We aimed in this way to help inform spatial management strategies for these coastal and marine areas, that may lead to sustainable blue growth despite increasing climate-change pressures. We addressed these challenges by employing the state-of-the-art MSP-specific spatial meta-analysis of climate modelling methods (Queirós et al., 2021). As climate change unfolds heterogeneously across national landscapes (Bindoff et al., 2019), regionally scaled oceanographic processes can lead to the expression of medium-term trends in climate variables that allow for the occurrence of climate-resilient areas, and of areas where localised trends that may not necessarily be consistent with mean long term climate change trends. These two types of sites (climate change refugia and bright spots, respectively) may be harnessed towards the delivery of sustainability goals, and capitalised upon within time-frames that are well fitting to MSP (e.g. a few decades, Queirós et al., 2021), as a time-buying strategy for people and ecosystems. We analysed ocean climate modelling data with the aim of quantifying the potential existence of such sites in Tanzania's exclusive economic zone ("EEZ"), as well as the location of climate sensitive sites. These estimates were then compared with the current distribution of the three sectors, and of other sectors (e.g. diving spots, harbours, etc.) with which they compete for space. We then further assessed, through participatory mapping, whether coastal communities could already perceive climate-driven change in the present. We provide information on potential challenges that may consequently arise for the spatial management of Tanzania's marine resources. We further report on potential opportunities to help support ecosystem adaptation to changing climatic conditions. This assessment was thus co-developed between academics and practitioners involved in marine planning and the three focal maritime sectors in Tanzania, with the ambition to support Tanzania's climate resilience as well as its journey towards sustainability and blue growth.

2. Material and methods

2.1. Tanzania's coastal socio-ecological system

Tanzania's coastline extends 1424 km, from Tanga to Mtwara, on the Western Indian Ocean. It's narrow continental shelf is vastly fringed by coral reefs (in various states of ecological health), with a 200 m depth contour often only a few km from the shore, except off the Zanzibar and Mafia channels, where the shelf extends for >50 km offshore. This narrow shelf is also broken down by important river mouths, such as that of the Ruvu and the Rufiji rivers (Berachi, 2003). As a result, the productive waters of the continental shelf are accessible through daily trips by artisanal fisheries sector boats targeting a large variety of (primarily small pelagic) species, with a high density of >250 landing sites populating the coastline and supporting associated land-based activities (Jiddawi and Ohman, 2002). The artisanal sector is a substantial component of Tanzania's marine fisheries, with most vessels ranging between 3 and 5 m (canoes) or 6 to 15 m (wooden planked boats), which can be powered by paddle, sail, and inboard and outboard engines (Mwaijande, 2021). Overall, the marine fishing sector represents 1.71 % of the national Gross Domestic Product, and employs circa 4 million people (Mwaijande, 2021). Larger commercial vessels operate within Tanzania's rich offshore waters.

Shallow habitats at the centre of MPA designation, such as coral reefs, seagrass beds and mangrove forests, are also the most productive areas of Tanzania seascape and largely support the local artisanal fishing sector, including seafood collection. Artisanal fisheries share space with, and sometimes target, species of value to marine conservation and ecotourism. Those include sharks, rays, octopus and sea turtles (all affected by the health of coral reefs). Species that co-occur in fished areas also include the protected Coelachant *Latimeria chalumnae* and the *Dugong dugong*; and nearshore seagrass beds (Said et al., 2020). Due to the bathymetry of the region, deeper water habitats are also easily accessible at a short distance from the shore (Gates et al., 2021). Deeper waters are exploited by fewer but larger vessels, though it is apparent that these vessels also target shallower onshore waters (Global Fishing Watch, 2016, mean yearly fishing effort (hr/yr); accessed April 2020). Seaweed farms also occur across most of Tanzania's coastline, though the sector is particularly well developed in the Zanzibar archipelago (Msuya, 2013).

2.2. Initial search for modelling datasets for sector-specific analyses

We employed the MSP-specific methods for the spatial meta-analysis of climate modelling data (Queirós et al., 2021). Accordingly, for each activity sector, modelled datasets were sought to best, and as comprehensively as possible, represent the ecosystem components (environmental and/or ecological) underpinning their activity. The author team included experts in each marine sector who provided advice on the species and environmental conditions of interest, guiding the data search. Accordingly, for the conservation sector, species distribution modelling was sought for the species reviewed in Table 1. Furthermore, projections for the distribution of species of interest to the artisanal fishing sector were sought based on expert advice from authors who know the sector well and/or routinely monitor small pelagic species and top predators (tuna and tuna-like species), as well as undertaking small scale catch assessment surveys (Kuguru and Jiddawi, *pers. comm.*). The species of interest to the seaweed farming sector are well described in the literature (e.g. Msuya, 2017). Initial datasets were identified and prepared for analysis, as described below.

2.3. Reviewing climate change evidence and preparing modelling datasets for analysis

Marine ecosystems are highly dynamic so determining whether climate change is a driver of changes in habitat conditions or species distributions requires careful assessment of both temporal mean trends and their variability (Hawkins and Sutton, 2012). The spatial-meta-analysis of modelling data method employed here (Queirós et al., 2021), has been carefully developed to address this aspect of ocean climate change. We therefore reviewed the scientific literature to identify the expected mean climate change-driven trend for each ocean variable or species distribution modelling dataset identified in Section 2.2. To this end, evidence from the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019) was reviewed in detail, and further exchanges with authors with local expertise were carried out to the same end. Trends identified through this review of literature and consultation are documented in Appendices Tables A1–3. In cases when modelling datasets of interest were identified in Section 2.2. but no consistent climate change-driven trend could be established for that specific ecosystem property/species of interest for the Tanzania EEZ, then this modelling dataset was removed from subsequent analyses. For instance, oceanographic current patterns were identified in Section 2.2 as ecosystem properties relevant to the seaweed sector analysis because healthy seaweed require good water movement, and modelling data could be sought for currents. However, no consistent, climate-driven trend could be established for currents via review, so subsequent analyses did not include seawater current modelling data. For all species distribution modelling datasets considered, it was expected that as different species exhibit different degrees of sensitivity to climate change pressures, compensatory mechanisms might take place, at least temporarily, as the more sensitive species perish locally to the benefit of less sensitive species, for which more resource may be made available (Wilson et al., 2021). However, as climate change is projected to decrease both primary and secondary production of the pelagic ecosystem regionally, and as heat waves cause severe bleaching of coral reefs (IPCC, 2019), climate change was reasonably expected to lead to an overall decline in the regional abundance of species assessed here (Appendices Table A2).

2.4. Calculation: Spatial meta-analysis of modelling projections

Once expected mean climate-driven trends had been established for

Table 1
Key taxa of interest to the marine conservation sectorial analysis, and the modelling layers chosen to assess the impact of climate change on their essential habitat.

Taxa	Reason for inclusion (& key species)	Relevant modelling layers
Corals Acropora, Porites, Astreopora, Echinopora, Favia, Favites, Fungia, Galaxea, Goniastrea, Halomitra, Montipora, Platygyra, Pocillopora, Synarea, Acanthastrea, Coscinarea, Cyphastrea, Diploastrea, Echinophyllia, Gardinoseris, Goniopora, Herpolitha, Hydnophora, Leptastrea, Leptoria, Lobophyllia, Merulina, Millepora, Montastrea, Oxypora, Pavona, Physogyra, Pleisiastrea, Podabacia, Psammocora, Seriatopora, Stylophora, Turbinaria (Muhando, 2011).	Corals are major ecosystem component of several Tanzanian MPAs, in recognition of their importance to artisanal fisheries and tourism (Muhando, 2011; Francis and Machumu, 2014).	Bottom layer temperature, bottom layer pH, marine heatwave frequency/ duration, seafloor aragonite saturation, seafloor calcite saturation (IPCC, 2019), seafloor N (as a proxy for eutrophication), wind (as a proxy for storm events) (Muhando, 2011), euphotic depth - light penetration determines depth limits of corals, with few reefs extending below 40 m (EAME, 2004).
Seagrass *Thalassia hemprichii, Thalassodendron ciliatum, Enhalus acoroides, Halophila minor, Halophila ovalis, Halophila stipulacea, Zostera capensis, Cymodocea rotundata, Cymodocea serrulata, Halodule univervis, Halodule wrightii, Syringodium isotifolium, Ruppia maritima* (Gullström et al., 2002; Muhando, 2011)	Seagrass beds are **1)** important nursey habitat for fish **2)** important food resources for protected species (e.g. dugong and sea turtles) **3)** provide ecosystem services such as carbon sequestration, wave attenuation and shoreline protection and N cycling (Muhando, 2011, Amone-Mabuto et al., 2017).	Seafloor N (as a proxy for eutrophication) - eutrophication is often cited as cause for seagrass loss (Gullström et al., 2002). Wind (as a proxy for storm events)- severe storm events can damage seagrass meadows (Amone-Mabuto et al., 2017). Euphotic depth - light penetration determines depth limits of seagrass (EAME, 2004).
Mangroves *Avicennia marina, Bruguiera gymnorrhiza, Ceriops tagal, Heritiera littoralis, Lumnitzera racemosa, Rhizophora mucronata, Sonneratia alba, Xylocarpus granatum, Xylocarpus molluccensis, Pemphis acidula* (Muhando, 2011).	Mangroves provide **1)** important habitat for fish and shellfish (includes nursery habitat) **2)** ecosystem services such as shore protection/wave attenuation, carbon sequestration, sediment and pollution filtering (EAME, 2004, Ellison, 2015, Hamad et al., 2019).	Bottom layer temperature, surface temperature, marine heatwave frequency/ duration (Hamad et al., 2019), surface salinity (increased precipitation and riverine flooding can cause mangrove mortality (Erftemeijer and Hamerlynck, 2005)), wind (as a proxy for storm events) (Muhando, 2011).
Dugong *(Dugong dugon)*	Protected species found in the area. Listed as *Vulnerable* (global assessment) by the IUCN, but thought to be critically endangered in Tanzania although there is no official regional assessment (Muir et al., 2003). The species is probably one of the country's rarest and most threatened mammals. Associated with seagrass meadows (Muhando, 2011).	Given the Dugong's association with seagrass meadows, drivers of seagrass distribution will likely be relevant: Seafloor N (as a proxy for eutrophication) - eutrophication is often cited as cause for seagrass loss (Gullström et al., 2002). Wind (as a proxy for storm events)- severe storm events can damage seagrass meadows (Amone-Mabuto et al., 2017). Euphotic depth - light penetration determines depth limits of seagrass (EAME, 2004).
Green turtle *(Chelonia mydas)*	Protected species found in the Eastern Africa Marine Ecoregion (EAME). Listed as *Endangered* (global assessment) by the IUCN. Associated with seagrass meadows during some life stages (Musick and Limpus, 2017). Nesting beaches in Mafia Island Marine Park (MIMP) (WWF, 2009, Muhando, 2011).	Given the species association with seagrass meadows, drivers of seagrass distribution will likely be relevant: Seafloor N (as a proxy for eutrophication) - eutrophication is often cited as cause for seagrass loss (Gullström et al., 2002). Wind (as a proxy for storm events)- severe storm events can damage seagrass meadows (Amone-Mabuto et al., 2017). Euphotic depth - light penetration determines depth limits of seagrass (EAME, 2004).
Hawksbill turtle *(Eretmochelys imbricata)*	Protected species found in the EAME. Listed as *Critically Endangered* (global assessment) by the IUCN. Associated with coral reefs, seagrass and mangroves during some life stages. Nesting beaches in MIMP (WWF, 2009, Muhando, 2011, Bryceson and Francis, 2014, Musick and Limpus, 2017).	Given the species association with seagrass, corals and mangroves, drivers of distributions of these habitats will likely be relevant. Seagrass: Seafloor N (as a proxy for eutrophication) - eutrophication is often cited as cause for seagrass loss (Gullström et al., 2002). Wind (as a proxy for storm events)- severe storm events can damage seagrass meadows (Amone-Mabuto et al., 2017). Euphotic depth - light penetration determines depth limits of seagrass (EAME, 2004). Corals: Bottom layer temperature, bottom layer pH, marine heatwave frequency/ duration, seafloor aragonite saturation, seafloor calcite saturation (IPCC, 2019), seafloor N (as a proxy for eutrophication), wind (as a proxy for storm events) (Muhando, 2011), euphotic depth - light penetration determines depth limits of corals, with few reefs extending below 40 m (EAME, 2004). Mangroves: Bottom layer temperature, surface temperature, marine heatwave frequency/ duration (Hamad et al., 2019), surface salinity (increased precipitation and riverine flooding can cause mangrove mortality (Erftemeijer and Hamerlynck, 2005)), wind (as a proxy for storm events) (Muhando, 2011).

(*continued on next page*)

Table 1 (*continued*)

Taxa	Reason for inclusion (& key species)	Relevant modelling layers
Olive Ridley turtle *(Lepidochelys olivacea)*	Protected species found in the EAME. Listed as *Vulnerable* (global assessment) by the IUCN (WWF, 2009, Muhando, 2011).	
Loggerhead turtle *(Caretta caretta)*	Protected species found in the EAME. Listed as *Vulnerable* (global assessment) by the IUCN (WWF, 2009, Muhando, 2011).	
Leatherback turtle *(Dermochelys coriacea)*	Protected species found in the EAME. Listed as *Vulnerable* (global assessment) by the IUCN (WWF, 2009, Muhando, 2011).	
Coelocanth *(Latimeria chalumnae)*	Found and often caught in deep water in and around Tanga Coelacanth Marine Park, which is <10 km from Ulenge Island Marine Reserve. Listed as *Critically Endangered* (global assessment) by the IUCN (Muhando, 2011).	Little information available on this species, but possibly bottom layer dissolved oxygen (gill morphology and blood physiology suggests poor O_2 uptake ability, so DO likely to be relevant), bottom layer temperature. A temperature range of 15–20 °C is thought to be optimal for haemoglobin O_2 uptake (Hissmann et al., 2006).
Humphead wrasse (*Cheilinus undulatus*)	One stated reason for MPA designation in the area is to support the sustainability of the reef fisheries. *C. undulatus* is one of the highest-valued reef fish in commercial trade. The humphead wrasse possesses life history characteristics and ecology that makes it particularly vulnerable to fisheries exploitation. They include moderate-late maturation, long lifespan (up to 30 years), and predictable home range and resting sites. Occasionally used as an "umbrella species" for conservation e.g. the conservation of one species protects others due to shared habitat (Graham, Boggs et al. 2014, Weng, Pedersen et al. 2015). Listed as *Endangered* (global assessment) by the IUCN.	Given the association of the Humphead wrasse with coral reefs, drivers of coral distribution are likely to be relevant: Bottom layer temperature, bottom layer pH, marine heatwave frequency/duration, seafloor aragonite saturation, seafloor calcite saturation (IPCC, 2019), seafloor N (as a proxy for eutrophication), wind (as a proxy for storm events) (Muhando, 2011), euphotic depth - light penetration determines depth limits of corals, with few reefs extending below 40 m (EAME, 2004).
Whale shark *(Rhincodon typus)*	Parts of Mafia Island Marine Park are whale shark sighting hotspots (Bryceson and Francis, 2014). Listed as *Vulnerable* (global assessment) by the IUCN.	Surface temperature (Sequeira, Mellin et al. 2014), all primary productivity variables (as a proxy for Chl-a) (Afonso, McGinty and Machete 2014).
Giant black prawn (*Penaeus monodon*)	One stated reason for MPA designation in the area is to support the sustainability of the reef fisheries. Mangroves are an important nursey area for all prawn/shrimp species caught in Tanzania. Adult penaeids are often associated with seagrass meadows (Abdallah 2004, Nagelkerken, Blaber et al. 2008).	Bottom layer temperature, salinity. Temperature and salinity are generally accepted as key predictors of physiological performance in decapod crustaceans - changes in salinity will affect extra-cellular acid-base balance. Larval stages are particularly sensitive to changes in salinity (Whiteley, Scott et al. 2001, Anger 2003, Whiteley, Suckling et al. 2018).[a]
White prawn (*Fenneropenaeus indicus*)	One stated reason for MPA designation in the area is to support the sustainability of the reef fisheries. Mangroves are an important nursey area for all prawn/shrimp species caught in Tanzania. Adult penaeids are often associated with seagrass meadows (Abdallah 2004, Nagelkerken, Blaber et al. 2008).	Bottom layer temperature, salinity. Temperature and salinity generally accepted as key predictors of physiological performance in decapod crustaceans - changes in salinity will affect extra-cellular acid-base balance. Larval stages are particularly sensitive to changes in salinity.[a]
Tiger prawn (*Penaeus semisucatus*)	One stated reason for MPA designation in the area is to support the sustainability of the reef fisheries. Mangroves are an important nursey area for all prawn/shrimp species caught in Tanzania. Adult penaeids are often associated with seagrass meadows (Abdallah 2004, Nagelkerken, Blaber et al. 2008).	Bottom layer temperature, salinity. Temperature and salinity generally accepted as key predictors of physiological performance in decapod crustaceans - changes in salinity will affect extra-cellular acid-base balance. Larval stages are particularly sensitive to changes in salinity (Whiteley, Scott et al. 2001, Anger 2003, Whiteley, Suckling et al. 2018).[a]
Brown shrimp (*Metapenaeus monoceros*)	One stated reason for MPA designation in the area is to support the sustainability of the reef fisheries. Mangroves are an important nursey area for all prawn/shrimp species caught in Tanzania. Adult penaeids are often associated with seagrass meadows (Abdallah 2004, Nagelkerken, Blaber et al. 2008).	Bottom layer temperature salinity. Temperature and salinity generally accepted as key predictors of physiological performance in decapod crustaceans - changes in salinity will affect extra-cellular acid-base balance. Larval stages are particularly sensitive to changes in salinity (Whiteley, Scott et al. 2001, Anger 2003, Whiteley, Suckling et al. 2018).[a]

[a] These references are not specific to the species listed here, but to decapod crustacean species more broadly.

all modelling datasets in our final selection, we undertook three separate sector-specific analyses (marine conservation, artisanal fisheries, and seaweed farming). The spatial meta-analysis algorithm (Queirós et al., 2021) estimates the overall change in the mean of the family of distributions composed of all modelling datasets selected in each analysis in the future period (Section 2.1), relative to the present period, considering also their within dataset variability and across dataset variability. The analysis design employed, for each of the three sectors, thus compared the current state of the marine ecosystem with that in future periods of interest. For these comparisons, we chose temporal horizons that were deemed to be useful to the current development of spatial management mechanisms in Tanzania. Specifically, the overarching political context guiding MSP development is rarely sensitive to more than a few decades; however, the development of climate adaptive policy, with which MSP is necessarily harmonised, may also require the exploration of the longer-term changes (Pınarbaşı et al., 2017). To provide outputs that could inform both aspects of MSP development, we therefore analysed projections for the decade of 2011–2021 to represent the current ecosystem state; and compared these with projections in two mid-term future horizons: 2040–2049 and 2060–2069. Because the purpose of this study is to highlight potential risks and opportunities posed by climate change to the spatial management of Tanzanian waters, all modelling projections analysed were forced using the global greenhouse gas concentration trajectory (i.e. representative concentration pathway, 'RCP', Van Vuuren et al., 2011) RCP 8.5. This scenario has been amply used by the global climate models in the assessments of the Intergovernmental Panel on Climate Change ("IPCC") to represent an upper boundary of plausible future climate change, the historical global emissions rate, and very little or no climate change mitigation (Bindoff et al., 2019; Pedersen et al., 2021). The set of scenarios employed in the models used in the current global assessment of the IPCC combine additional aspects of climate change mitigation and, due to a higher sensitivity of those new generation global climate models to that forcing, a broader spectrum of climate driven futures is now also considered (IPCC, 2021). With emissions in the last decade remaining as the highest on record, and global pledges still falling well behind the Paris Agreement pledges, this analysis design was found to remain relevant at the time of this study (Schwalm et al., 2020; United Nations Environment Programme, 2022).

For each grid cell of the common model domain, a random-effects meta-analysis model was then built, testing (each time) the null hypothesis that change across the ecosystem (described by all modelling layers considered in each analysis, in that grid cell) was zero. Separate analyses were run for each sector (conservation, artisanal fisheries and seaweed farming), emissions scenario and time-frame considered (i.e. 2040s or 2060s). Three outcomes were possible for each analysis, in each grid cell. In the first case, a site was identified as a climate change refuge if the change around the mean was small and/or variability high, suggesting the ecosystem has a high probability of remaining within the bounds of variability observed at present. These are the areas where the ecosystem underpinning each focal sector may be resilient to climate change, and support each sector in a similar way to that in the present time. In the second case, a site was identified as a climate change hotspot, as a result of large change in analysed modelling layers, exceeding present time variability, and consistent with climate change trends for the many datasets considered. These are climate-vulnerable sites, where a climate signal (Queirós et al., 2021) was large within the time-frame of analysis. In the third case, a site was identified as a climate change bright spot, indicating also large change in the ecosystem, beyond present time variability. However, in this case, trends in the modelling datasets considered were predominantly contrary to expected long term climate change trends. These are areas where new opportunities for sustainable blue growth and conservation may emerge, at least in the time-frame of analysis (Queirós et al., 2021). Each category is based on estimation of the confidence interval for the summary effect M, which quantifies change between the two time periods considered in each analysis (present and future), detailed in Queirós et al., 2021. M has a normal distribution: i) a climate change hotspot is identified when M is <0 and its confidence interval does not contain zero; ii) a climate change refuge is identified when M's confidence interval contains 0; and iii) a bright spot is identified when M is >0 and its confidence interval does not contain 0 (Queirós et al., 2021).

All modelling projections analysed employ a 0.25 degree horizontal resolution, as resulting from the setup of the models used to produce them. In the marine conservation analysis, we included biogeochemical modelling projections representing key environmental drivers of the distribution of species identified as underpinning designation of marine protected areas and other marine sites of conservation value in Tanzania (Table 1, Table A1), with some of these species also representing key assets for the ecotourism sector. Habitat suitability modelling datasets for species of interest to conservation value in Table 1 were also available for this analysis, generated by the global Aquamaps initiative (Kaschner et al., 2019). However, the spatial resolution of Aquamaps modelling projections was found to be too coarse (i.e. 1° latitude $\times$ 1° long) to enable an assessment to be made at the much smaller scale at which spatial conservation mechanism have been established within the coastal waters of Tanzania. We therefore elected to compare Aquamaps datasets with the results of the remaining analysis post-hoc, to allow for a greater resolution (of the main analysis). Biogeochemical layers, simulating the key environmental drivers of the distribution of those species of conservation interest, were in turn used, which had been generated by the high-resolution biogeochemical model NEMO-MEDUSA (Nucleus for European Modelling of the Ocean - Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification, Jacobs et al., 2021). This is composed of an ocean general circulation model, NEMO version 3.5 (Madec, 2015), which is coupled to the plankton ecosystem model MEDUSA-2 (Yool et al., 2013). The model's spatial resolution is 0.25 degrees, corresponding to ~;28 km at the equator, and it has 75 vertical layers, which are finer near the surface. The model is surface forced using output from the HadGEM2-ES Earth system model (Jones et al., 2011). In order to reduce computational costs, NEMO-MEDUSA gets its initial conditions from a twin 1° resolution model that is spun up over the period 1860–1975 using the same forcing. The 1975–2005 period is run under historical pCO_2 concentrations and the following period 2006–2099 is run under the IPCC RCP8.5 scenario. Further details of the model setup can be found elsewhere (Yool et al., 2013; Yool et al., 2015). It should be noted that although 0.25 degrees does not fully resolve mesoscale variability, this resolution is higher than that used in the CMIP5 and CMIP6 models, and the model has been validated extensively (Popova et al., 2016) including in the area of analysis in this study (Jacobs et al., 2021). We compared the periods of interest (2011–2021 cf. 2040–2049 and 2060–2069) using decadal annual trends, as well as decadal trends within the North East Monsoon and South East monsoon periods. The former (November to March) is the prevailing fishing season for large, offshore species (Mwaijande, 2021). Data used are detailed in Appendices Table A1.

The artisanal fishing sector analyses were carried out using projections generated by the Dynamic Size-Spectrum Bioclimate Envelope Model ("DBEM", Close et al., 2006; Fernandes et al., 2013) interpolated from the original 0.5 degree resolution for analysis. The SS-DBEM is a well-established multiple species distribution model with a global track record (Fernandes et al., 2016; Fernandes et al., 2017; Bindoff et al., 2019). The analysis focused on 31 species of small pelagic fish that compose the majority of fish harvested by Tanzania's artisanal fishers, the projections for which had been produced specifically for this region (Wilson et al., 2021). We considered in separate analyses projections where: a) the effects of climate change and fishing mortality at Maximum Sustainable Yield had been simulated ("MSY", the maximum biomass that can be taken from that species stock over one year)); or b) the effects of climate change alone had been simulated (i.e. no fishing mortality). This allowed us to compare the effect of climate change (b; the issue at the centre of this study) with those where some fishing pressure is included in addition to climate change (a) but we recognise that fishing pressure in the region may be even higher. See Appendices Table A2 for a list of the modelling datasets included in this analysis. We considered the same decadal comparisons described, without the within monsoon focus, given that the DBEM outputs have an annual resolution.

For the seaweed farming sector analyses, we selected data as in the conservation sector analyses since no species distribution modelling datasets could be sourced for the key species of interest for the sector in

Tanzania, i.e. those in the *Euchema* and *Kappaphycus* genera. Therefore, we based all analyses in known drivers for the distribution of these species. The final list of projections considered is also detailed in Appendices Table A3. We considered the same decadal comparisons described, without the seasonal monsoon focus. Whilst seasonal monsoon analysis would have potentially been informative, the heatwave modelling projections available to this study (a key environmental parameter impacting seaweed distribution) was generated based on annual patterns (Jacobs et al., 2021). These data estimate heat-wave duration, as was calculated based on sea surface temperature data generated by MEDUSA (as described) using a fixed climatology (Jacobs et al., 2021).

2.5. Visualisation and overlay of additional spatial datasets with sectorial interest

A number of additional spatial datasets of interest were also compiled from different sources and used here, to allow us to compare our climate change assessment (2.4) with the current spatial distribution of protected areas (and key habitats and species), seaweed farming sites, and artisanal fishing activity in Tanzania. The distribution of marine protected areas in Tanzania was kindly made available via Tanzania's National Environment Management Council. A number of other datasets were kindly made available to this team by the ZanSea Geonode developers and included in our final maps for different sectors: the distribution of sites under the umbrella of the Ramsar Convention on Wetlands of International Importance(United Nations Educational Scientific and Cultural Organization, 1971), as these are important sites for both biodiversity conservation and the blue economy; a closure area that supports the commercially valuable octopus fishery (*Octopus cyanea*) in the main Zanzibar archipelago island, Unguja; the distribution of key species and habitats based on the review in Table 1 (turtle nesting sites; dugong sightings; opportunistic whale shark sightings); fish landing sites; prawn culture sites; and seaweed culture sites.

We also overlaid onto our analyses outputs estimates of fishing effort based on automatic identification system (AIS) data (that is, for vessels larger than 10 m and thus non-artisanal) derived from Global Fishing Watch, for the period 2016 (accessed March 2020, globalfishingwatch.org).

Projected, present-time native ranges for species of conservation value listed in Table 1 were, then, also retrieved from Aquamaps (Kaschner et al., 2019) and compared with our modelling analyses maps (dugong, coelachanth, octopus, whale shark and humphead wrasse).

2.6. Participatory mapping

Participatory mapping was undertaken with focus groups of key informants (expert fishers and collectors/gleaners) using the methodology detailed in the Appendeces. This work took place in 4 communities on the 3 main islands of the Zanzibar Archipelago, including Wesha in Pemba Island, Nugwi in Unguja/Zanzibar Island, and Bweni and Kilindoni in Mafia Island. This exercise aimed to asses the value that local communities in the Tanzanian coast place on this environment and how this relates to their economic structure. The results from this work were compared with our climate change assessment to determine how large scale climate driven changes in the marine and coastal environment we estimate here by modelling analyses may already be perceived by local communities, and affect their uses of these ecosystems.

3. Results

3.1. Marine conservation analysis

Analyses comparing modelling projections for the present decade with the 2040s (Fig. 1) and 2060s (Fig. 2) suggest that a large climate change signal is likely to emerge in ecosystem attributes driving the distribution of species of conservation value, across the whole Tanzanian coast, under the emissions trajectory RCP8.5. The Kilwa region emerges as the only coastal area harbouring climate refugia in the 2040s (Fig. 1a–d) though this pattern disappears in the analyses contrasting the present decade with the 2060s (Fig. 2). In all marine conservation analyses, the climate signal emerges strongest nearer- than offshore, seemingly affecting areas harbouring marine protected areas and other effective area-based conservation measures, coral reef habitat, Ramsar sites (United Nations Educational Scientific and Cultural Organization, 1971), the Unguja/Zanzibar Island octopus closure site, whale, turtle, humphead wrasse, dugong and coelacanth habitats (Fig. 1). Dive sites, valuable for ecotourism, are also affected. In all analyses, the climate signal is strongest when within monsoon trends are considered (North East Monsoon, Figs. 1c–d and 2c–d; South East Monsoon, Figs. 1e–f and 2e–f) relative to yearly values (Figs. 1a–b and 2a–b), potentially, as a result of within year variability caused by the strong seasonality in ocean conditions. Furthermore, in the 2040s, large areas offshore emerge as potential bright spots of conservation value, potentially affecting species of conservation value with large ranges such as whale shark, even despite the inclusion of heat wave duration projections. However, these areas are less extensive within monsoon periods (Fig. 1c–f), suggesting that any improved habitat conditions may be strongly modified seasonally, and this could be considered alongside any known migration routes for the species (Fig. 1b, c,d). Furthermore, offshore areas classified as bright spots in the 2040s projections (Fig. 1) by and large disappear by the 2060s, especially within monsoon, though some of those remain as potential climate change refuges (Fig. 2). Analysis of the individual modelling layers considered in the 2060s analysis (not shown) suggests that this result emerges not as a reflection of small changes in individual ocean conditions relative to the present decade, but rather as a result of diverging (large) trends in the various ecosystem components considered in the analysis. Specifically: some reflect trends strongly consistent with long-term climate change expectations (e.g. mean sea surface temperature, and heat have duration, increase; surface dissolved oxygen decrease); and some vary in the opposite direction offshore (bottom dissolved oxygen, pH and aragonite and calcite saturation states increase, and offshore seabed temperature decreases). Offshore areas within the east of the EEZ, however, further emerge as potential climate change hotspots within the 2060s under RCP8.5, and there most environmental variables display strong trends consistent with long-term climate change. These hotspots areas (estimated based on decadal comparison of annual values) are also especially large and strong when the analysis is carried out within monsoon periods (Fig. 2c–f).

3.2. Artisanal fisheries analyses

The results from the artisanal, pelagic fisheries analyses are summarised in Fig. 3. Variability in the response of individual target species to climate change drivers (Appendices) seems to be determinant of overall impacts of climate change. Without fishing effort (Fig. 3a), the target community remains largely within the boundaries of present time variability in the 2040s, as some species perish under climate change pressure in the 2040s, but others increase in abundance through compensatory uptake of resources (Wilson et al., 2021). Under these conditions, fishing pressure (simulated at a level seen as moderate relative to what may be actually observed in the region, i.e. MSY) allows for some areas to harbour bright spots for the artisanal pelagic fishing fleet, indicating a substantial increase in species abundances when the community is taken as a whole (Fig. 3b). Those areas occur nearshore, near the RUMAKI proposed Man and Biosphere Reserve, and west of Pemba. However, increase in climate change pressure into the 2060's leads to a reversal of trends in the absence of fishing effort, affecting coastal areas, which now harbour climate change hotspots (Fig. 3c). This is due to an exacerbation of losses in climate-vulnerable species though the cumulative simulated effect of climate change and fishing pressure.

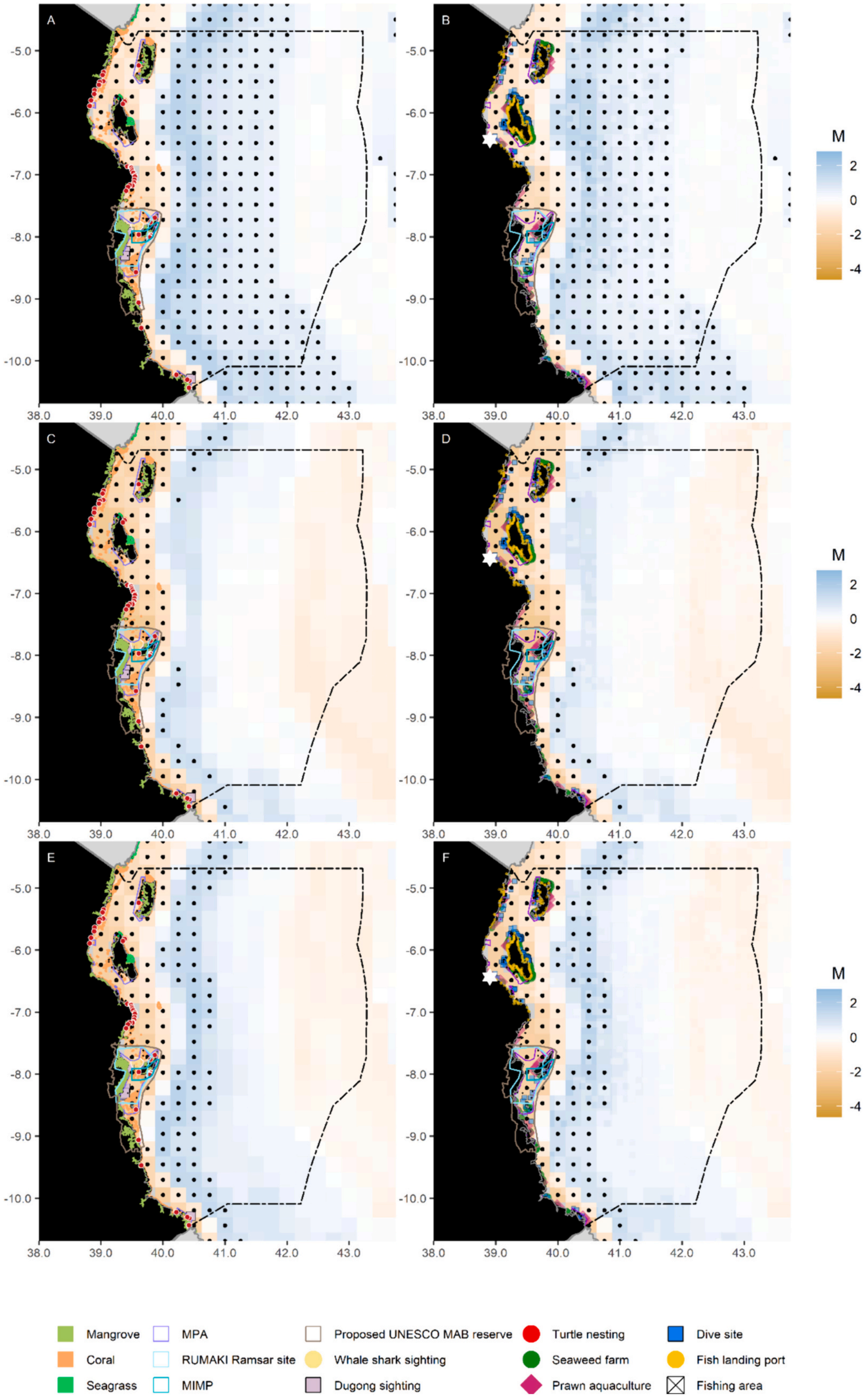

Fig. 1. Climate modelling spatial meta-analysis results for the conservation sector, comparing the present decade (2011–2021) with the 2040s. Background color identifies ecosystem-level trends, which are significant (climate change hotspots ($M < 0$) or bright spots ($M > 0$)) where overlain by black dots; their absence indicating climate change refugia. Top: yearly analysis. Middle: North East Monsoon analysis. Bottom: South East monsoon analysis. A, C, E: GIS data on habitats of conservation value and spatial conservation mechanisms overlain. B, D, F: GIS data on the distribution of spatially managed blue economy sectors and conservation mechanisms is overlain. Map lines delineate study areas and does not necessarily depict accepted national boundaries.

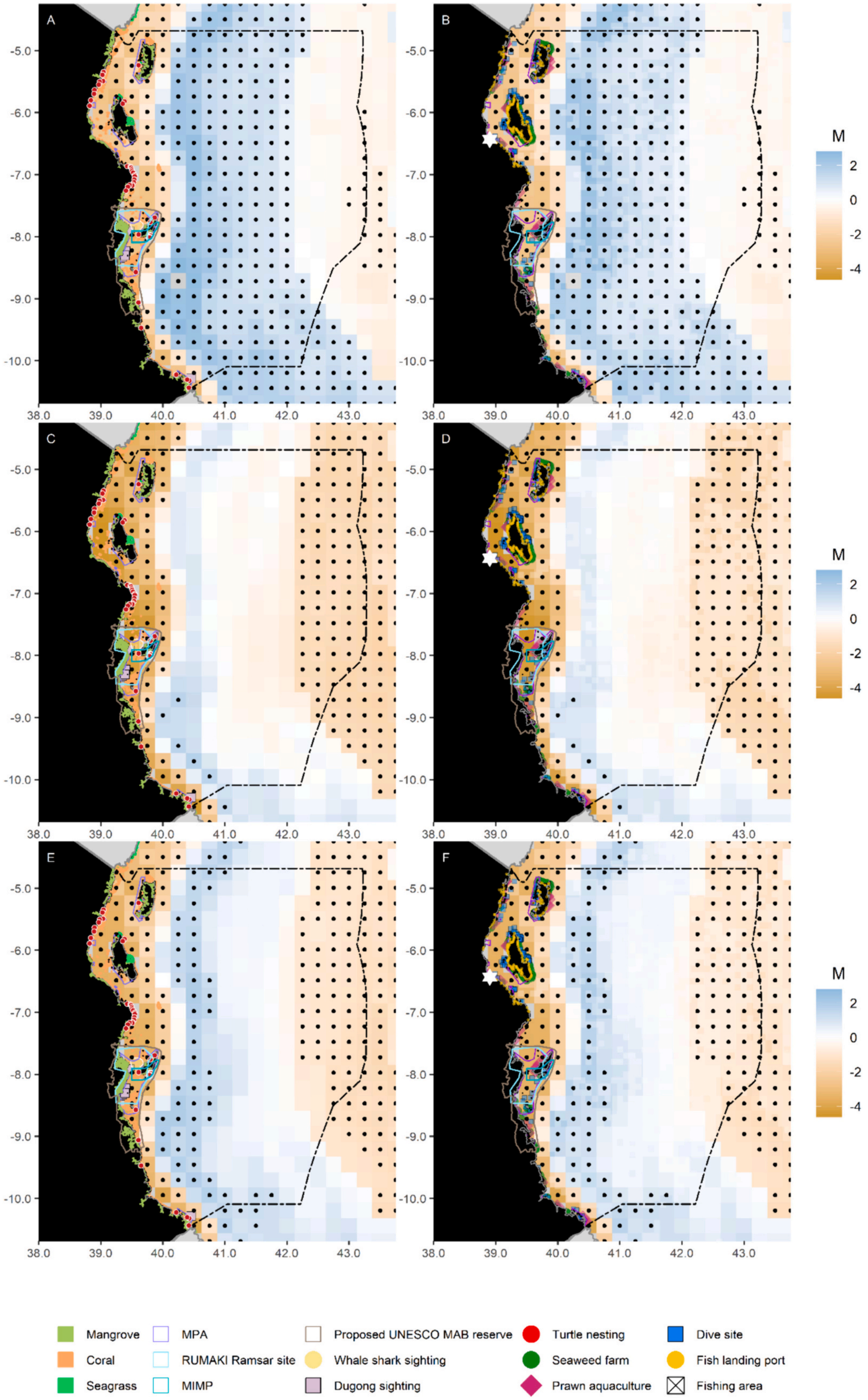

Fig. 2. Climate modelling spatial meta-analysis results for the conservation sector, comparing the present decade (2011–2021) with the 2060s. Background color identifies ecosystem-level trends, which are significant (climate change hotspots ($M < 0$) or bright spots ($M > 0$)) where overlain by black dots; their absence indicating climate change refugia. Top: yearly analysis. Middle: North East Monsoon analysis. Bottom: South East monsoon analysis. A, C, E: GIS data on habitats of conservation value and spatial conservation mechanisms overlain. B, D, F: GIS data on the distribution of spatially managed blue economy sectors overlain. Map lines delineate study areas and does not necessarily depict accepted national boundaries.

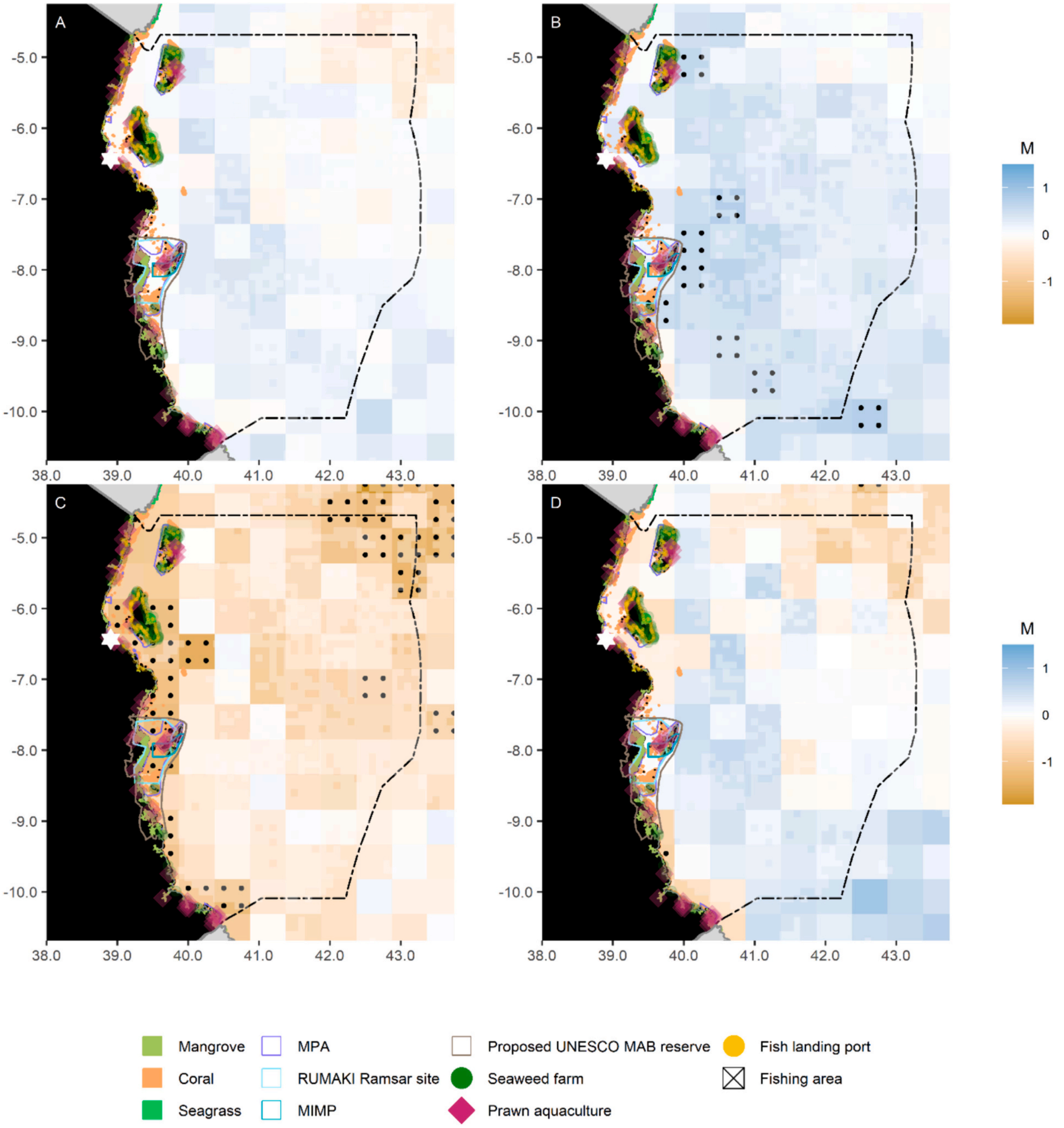

Fig. 3. Climate modelling spatial meta-analysis results for the pelagic, artisanal fishing sector, comparing the present (2011–2021) decade with the 2040s (A,B) and the 2060s (C,D), considering no fishing effort (A,C) or sustainable fishing effort (MSY = 1). Background color identifies the pelagic fished community-level trend, indicating the expression of a climate signal (brown) or a community trend that does not reflect the climate change impacts (blue). These trends are significant where overlain by black dots (please refer to the main text for detail). GIS data overlain indicates the location of key habitats of conservation value and the distribution of spatially managed blue economy sectors. Map lines delineate study areas and does not necessarily depict accepted national boundaries.

These effects impact many areas near landing sites, across the coast, where artisanal fishers would be traditionally involved in daily fishing trips. However, when fishing pressure is simulated (i.e. MSY), the hotspots that emerged in the absence of fishing (Fig. 3c) now become climate change refuges (Fig. 3d). This is because the opposite trends in species abundance, in climate vulnerable cf. resilient species are exacerbated through compensatory mechanisms related to competition for resources (Wilson et al., 2021). That is, as species compete for environmental resources in the modelling simulation under climate change, the effect of simulated fishing mortality appears to affect climate vulnerable species more than climate-resilient species, the latter then being able to access more resource due to the cumulative pressure of climate and fishing on the former. Species that emerge consistently as benefiting from release from competition with climate vulnerable species (that perish) are: the Coryphaenidae common dolphinfish (*Coryphaena hippurus*); Scombridae Kawakawa (*Euthynnus affinis*); Indian mackerel (*Rastrelliger kanagurta*) and narrow-barred Spanish mackerel (*Scomberomorus commersoni*); Carangidae torpedo scad (*Megalaspis cordyla*) and bigeye scad (*Selar crumenophthalmus*); Clupleidae rainbow sardine (*Dussumieria acuta*), goldstripe sardinella (*Sardinella gibbosa*), Indian oil sardine (*Sardinella longiceps*), Kelee shad (*Hilsa kelee*) and Indian pellona (*Pellona ditchela*). Climate change pressure, compounded by fishing effort, may thus lead to a less biodiverse pool of species from which to harvest from under RCP8.5 (albeit a pool potentially able to better withstand climate change), with delicate fisheries management being potentially necessary. Being pelagic, most of these species are not strongly associated with local habitat conditions, but some, such as Kawakawa, Indian mackerel, Narrow-barred Spanish mackerel, Torpedo scad and Bigeye scad, are mobile predators that often hunt in the shallow coral-associated habitats (Osuka et al., 2022). Our results may thus underestimate potentially strong indirect effects of potential loss of their prey communities that could emerge as a result of loss of coral habitat in the region, under the degree of climate change simulated here. Important ecological cascades could thus unfold which our results do not resolve.

3.3. *Seaweed farming analysis*

The trends identified for key environmental drivers of seaweed distribution highlight important climate trends across Tanzania's EEZ in the 2040s, which are exacerbated in the 2060s (Fig. 4), under RCP8.5. Although not harbouring climate change hotspots for seaweed, coastal waters seem vulnerable to climate change ($M < 0$), and this includes key areas where farms are currently located, e.g., in the Unguja/Zanzibar and Mafia Islands. Farms further south along the mainland coast are seemingly located in areas where ecosystem-level climate change effects may be comparatively milder, even under RCP8.5 (Fig. 4).

The modelling data considered in the seaweed farming analysis are presented in table A1 – we included sea surface temperature, heat-wave duration and surface salinity. Other ecosystem properties, such as currents and nutrient levels, are potentially important to seaweed distributions, but were not included in this analysis, although modelling data were available. The reason for their exclusion was that no clear climate-related trends could be established for these variables (methods Section 2.3). The patterns identified in Fig. 4 thus largely reflect changes in the thermal environment and salinity experienced by seaweed. An analysis of these layers individually highlights that whilst mean sea surface temperature and heatwave duration increase substantially across the region in the 2040s, under RCP8.5, modelled salinity also decreases in most areas, contrary to expectation, and this divergence trends across environmental conditions (relative to their expected mean climate trend) potentially explains the overall lack of significant hotspots identified in Fig. 4a (as measured by τ^2, not shown). An analysis of the same layers underpinning the 2060s analysis, highlights that in this case, the reduction in surface salinity is now restricted to the NW of the EEZ, in the Pemba channel, leading to stronger trends emerging elsewhere, relative to the 2040s.

3.4. *Local uses of the environment and climate change*

Beyond modelling analysis, participatory mapping exercises allowed us to explore the perception of ongoing climate-driven changes in the study area. This research took place in four communities, on two of the main islands of the Zanzibar Archipelago, and on mainland Tanzania. The results are illustrated in Fig. 5 and revealed that our focus groups could identify changes in the adjacent marine environments closest to their communities, some of these potentially reflecting on going climate change. The main changes identified, highlighted in all communities, were a reduction in fish abundance and degraded environments. Wesha, on Pemba Island, highlighted key historical fishing grounds that are now "completely depleted of fish", with overfishing being the main driver for this reduction. In a localised area close to an oil refinery, recent oil spills were perceived to be the cause for the death of nearby mangroves. In adjacent sandflats however, overfishing was deemed responsible for reduced prawn catches. In Nungwi, on Unguja Island, rising sea level was perceived to have caused the loss of coastal trees and the subsequent coastal erosion. Participants in the Bweni focus group alone identified coral bleaching, perceived to have been caused by El Niño in 1999. The vast majority of damage to the adjacent reefs, however, was perceived to have been caused by historical dynamite fishing. Loss of seagrass beds in the 1990s, due to "beach seining" and an "explosion" in sea urchin numbers, meant a reduction in fish for species associated with that habitat. Similarly in the south of Mafia, degraded reefs were perceived to have been caused by dynamite fishing in the Kilindoni focus group. Ring nets and small mesh sizes were quoted as the main causes for depleted fish stocks. In areas with increased fish numbers however, the cause was perceived to be spill over from the adjacent Mafia Island Marine Park.

A comparison of the participatory mapping of habitats (Fig. 5, left) and existing observational datasets for these habitats (Figs. 1–2) indicates a good match, confirming the often-held view that coastal communities have a very good grasp of habitat conditions. Importantly, the modelling fishing analyses we undertook suggest that areas in the

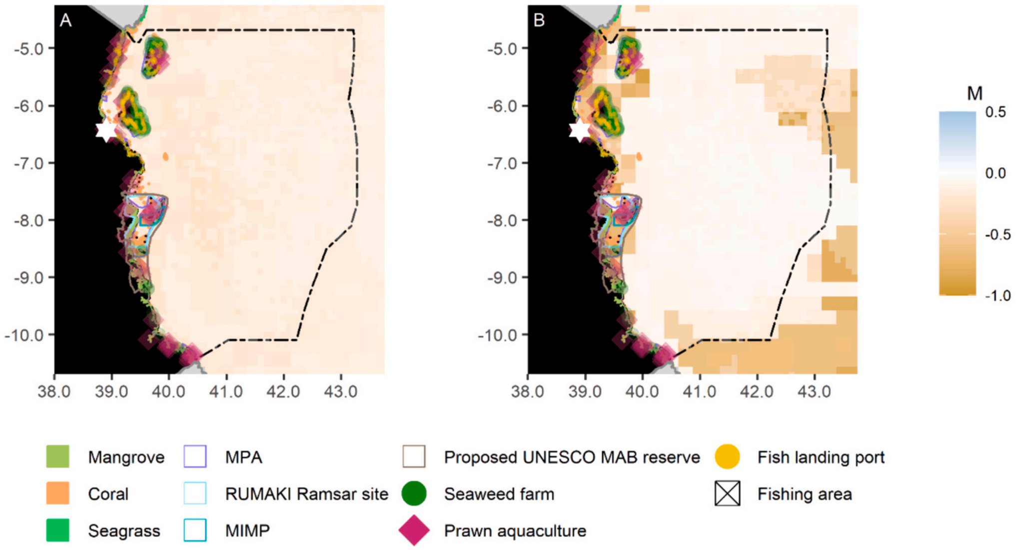

Fig. 4. Climate modelling spatial meta-analysis results for the seaweed farming sector, comparing the present decade (2011–2021) with the 2040s (A) and the 2060s (B). The background color identifies he overall trend in key drivers of seaweed distributions, indicating the expression of a climate signal (brown, everywhere in this plot). or an overall trend that does not reflect the climate change impacts (blue). These trends are significant where overlain by black dots (none in this plot). GIS data overlain indicates the location of key habitats of conservation value and the distribution of spatially managed blue economy sectors. No within monsoon analyses are carried out (please refer to main text). Map lines delineate study areas and does not necessarily depict accepted national boundaries.

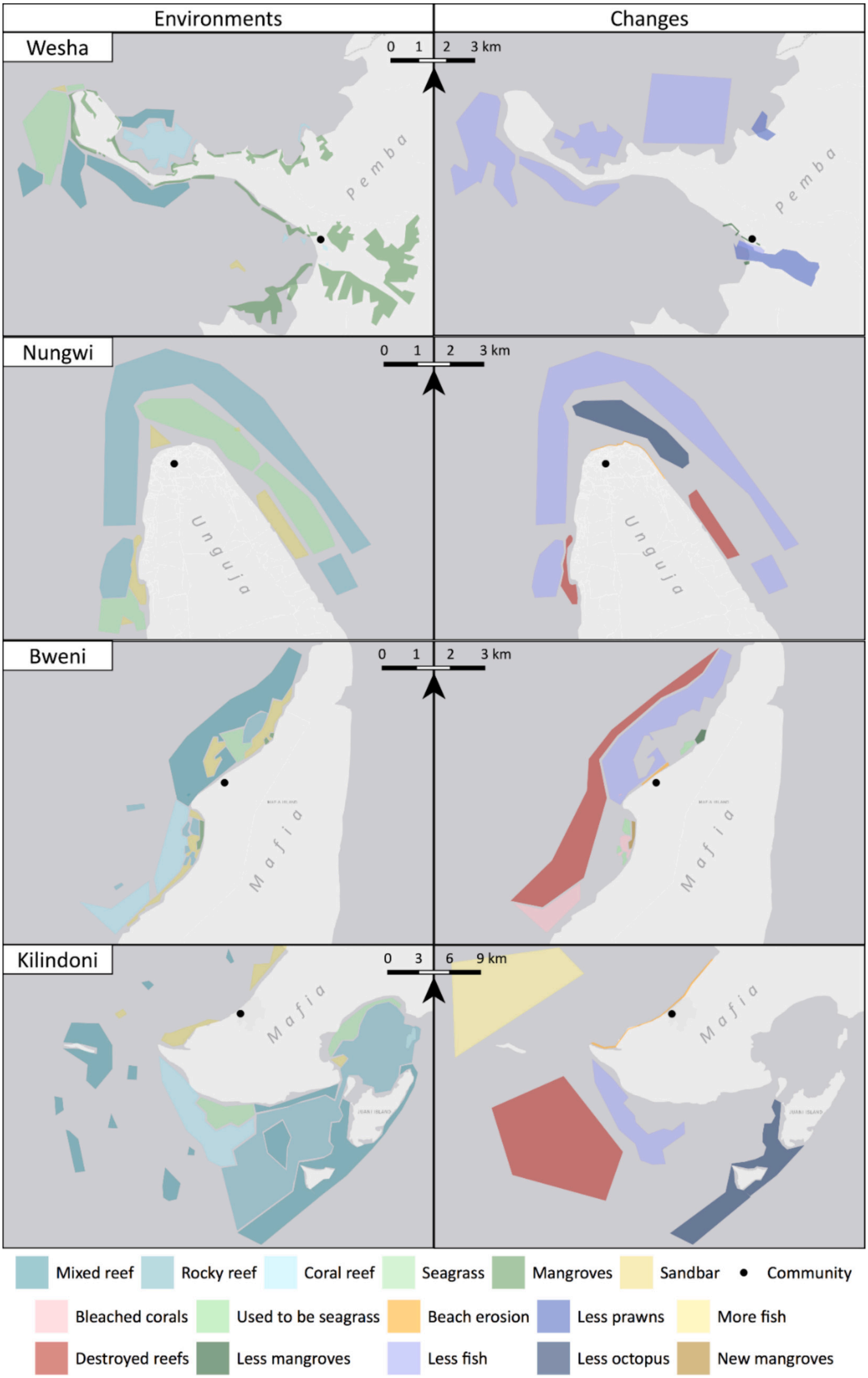

Fig. 5. Participatory mapping undertaken though focus group surveys, in 4 communities across the 3 main islands of Tanzania. Left hand panels indicate key habitat types as identified by communities, and right hand side panels indicate where communities perceive changes in habitat conditions have taken place.

north of Unguja/Zanzibar Island and across Mafia Island, where fishing resource is already perceived to be decreasing, and where fish may have increased recently in the South East of Mafia Island (Fig. 5, right hand side), may be further impacted by strong climate driven trends in the next few decades, under RCP8.5 (Fig. 3). This potential climate-driven loss of fishing resource in these areas, under growing emissions, may thus present important challenges to livelihoods in these communities and may negate the perceived positive effect of the Mafia Island Marine Park on fish communities in future decades. Furthermore, coral reefs currently perceived to have been destroyed by historical dynamite fishing and bleaching in Mafia Island (Fig. 3) may benefit very little from renewed conservation efforts under the new UNESCO MAB reserve in future decades, due to increased, climate-driven change (with climate hotspots identified in the region, under RCP8.5, Figs. 1–2). The same rationale could be expanded to currently deteriorated reefs in northern Unguja/Zanzibar Island (Fig. 5). Growing emissions (represented by RCP 8.5) may thus present existential threats to these ecosystems, affecting coastal communities reliant on them, despite improved environmental management in Tanzania.

4. Discussion

The work presented here was designed to provide information about where current conservation mechanisms, artisanal fisheries and seaweed farming may require more effective approaches to resource management to enable them to adapt to the changing conditions imposed by climate change in Tanzanian waters. Equally, we aimed to identify where the opportunities for maintaining or expanding these sectors may emerge, as regional ecosystems respond to these pressures. Using an upper bound of projected global greenhouse gas emissions for our climate change forcing, we found that growing emissions potentially present a bleak future for coastal areas, where all three sectors are concentrated. Whilst in other areas of the ocean, climate-smart marine spatial management may allow for short- and mid-term resilience of local biodiversity and the blue economy (Queirós et al., 2021; Doxa et al., 2022), our analysis of Tanzanian waters provides a stark example of where this may not be possible, not without global cooperation on decarbonisation. With significant climate change impacts identified in large swaths of coastal areas, where the three focal sectors are concentrated, it is clear that a growing blue economy, based on a thriving ocean that supports biodiversity, and delivers a wide range of valuable ecosystem services that support health and livelihoods, will require a path for global emissions distinct from RCP 8.5.

4.1. Marine conservation

We found that, under RCP8.5, strong effects of climate change could be observed on habitat conditions driving the distribution of key species of high conservation value, from the coast to offshore areas. Coastal areas were found to be particularly vulnerable in the scenario simulated, with climate change hotspots emerging across the vast majority of Tanzania's coastal waters, which host its MPAs as well as high conservation value species such as dugong, coelacanth, and various protected species of prawns and shrimp. Climate change hotspots also emerged across many areas harbouring coral reefs, seagrass, and near turtle nesting sites. Without curbs in global emissions, there is thus substantial threat to globally valuable marine biodiversity that occurs in Tanzania's coastal waters (and neighbouring nations).

Further offshore, patterns of conservation-relevant habitat conditions were more variable over space and time, as a result in some cases, of a marked departure in expected global trends in some ocean variables, in the short- and medium term. Indeed, a short-term improvement of habitat conditions was observed in large areas offshore in the 2040s projections, and, to a smaller degree, further East in the 2060s, likely caused by potential climate-driven changes in circulation and wind patterns, interacting with the complex bathymetry of the region (Jacobs et al., 2021). This result highlights the importance of regional-scaled analysis of climate change trends for ocean management. That is, global mean trends in ocean variables are often more complex and variable at the local and regional scale. This variability, manifested as climate change refugia and "bright spots" (Queirós et al., 2021), can be capitalised upon in the mid-term, if more hospitable conditions for species and habitats emerge (Queirós et al., 2021), at least seasonally (e.g. East of the EEZ, 2060s). The spatial patterns we identified may lead to potentially important effects for large migratory species of global conservation value, such as whale-sharks and five sea turtle species, and their protection should be assessed along the current distribution of their migratory routes. Whale -sharks are also particularly important to the tourism sector, with international divers rushing to these areas, though they are also known to remain in waters closer to shore (Cagua et al., 2015). Improved habitat conditions offshore, at least in the mid-term, may lead to changes in whale-shark foraging habits, but also increase the chances of encounters with large commercial vessels, which were shown here to densely target offshore waters. The potential range shifts of species attractive to ecotourism, along with degradation of coral reefs (Dimopoulos et al., 2019) may also have economic implications for Tanzanian offshore islands. Whilst Tanzania is investing heavily in near shore expansion of MPAs (NEMC and National MAB Focal Point, 2021), protecting those offshore habitats found here to harbour refugia and bright spots from disturbance (e.g. industrial fishing) may therefore also become important, as the region adapts to a changing climate system. Until such a time when global emissions have been markedly reduced, it is uncertain whether restrictions of human activities on these systems though the extension of well-managed, static MPAs will necessarily provide the population and community benefits expected, or inded enhance resilience to climate change (Caughman et al., 2024). However, the evidence uncovered in this study could help identify areas where climate-smart conservation actions could be most successful to support the adaptive potential for at least some of Tanzania's species and habitats of high conservation value (i.e. climate change refugia and hotspots).

4.2. Artisanal fisheries

We found that, under RCP8.5, strong effects of climate change on target species may impact upon vulnerable sections of coastal communities throughout Tanzania, involved in artisanal small pelagic fisheries. Coastal areas north of Unguja/Zanzibar Island (which are deep and upwelling areas) appeared to be more resilient to these impacts. In those areas, we estimated that compensatory mechanisms may lead to overall stability in the targeted fish community, though community structure may change, as more climate resilient species become dominant (i.e. cryptic stability). This estimated response of the target fish community may, thus, provide opportunities for food security and income generation across the northern coast of Tanzania, despite growing emissions. However, these effects were found to depend on the magnitude of climate change experienced at different points along the Tanzania coast, with regions located in or south of Unguja/Zanzibar Island potentially more vulnerable. These effects depended on how far into the future we considered in our analyses, and were found to be modulated by (a moderate level of) fishing effort. In general, the longer into the future we looked under RCP8.5, the more generalised the losses in the fished community became, but fisheries moderated this effect by exacerbating compensatory mechanisms in resource use between climate sensitive and climate resilient species. The impacts of less sustainable fishing levels are reviewed elsewhere (Wilson et al., 2021). Furthermore, our results may be overly optimistic by excluding indirect effects on the small pelagic target community's mobile predator species that may emerge as their coral-reef dependent prey become affected by climate change. Nevertheless, the present analysis strongly suggests that a climate change risk assessment may be necessary to ensure the sustainability of Tanzania's artisanal fishing sector in decades to come, especially in near-shore waters. Coastal communities along the Tanzania coast are sensitive to these changes. For instance, communities who we interviewed reported that increases in fish abundance had been recorded as a result of spill-over from the Mafia Island Marine Park. These effects may be negated by increased climate-driven pressure on target species populations inside the Park, which occurs in an area identified in several of our analyses as a climate change hotspot. However, spatial management mechanisms may also play a role in promoting climate-smart management of this resource. The proposed Rufiji-Mafia-Kilwa UNESCO Man and Biosphere (MAB) site, paired with other UNESCO programmes, provides an opportunity to capitalise on existing tools and knowledge on projecting the impacts of climate change on species targeted by the artisanal fishing sector, as shown here, to support both the sustainability of this resource and coastal communities dependent on fishing. Indeed, with the entry into action of the 2017 Lima Action Plan into the policy landscape of the UNESCO MAB strategy, MAB reserves are expected to explore and test policy strategies that support biodiversity and adaptation to climate change (Pool-Stanvliet and Coetzer, 2020). Promoting awareness about different species sensitivity to climate change within communities exploring the waters of the proposed MAB (which falls within some of the most sensitive areas to climate change identified here) or even establishing and enforcing localised reserve areas to protect breeding or nursery areas for climate resilient species, may thus promote greater climate resilience of the target resource, and of dependent coastal communities. As we only analysed an upper bound of emissions in this study, milder greenhouse gas emissions scenarios should be explored in support of that work.

It is important to note that the spatial scale of our analysis may still mask any potentially significant changes that may occur at even finer scale, and these will be relevant to those in coastal communities fishing off e.g. Unguja/Zanzibar, targeting the coral fringe, a few nm from the shore. It is also important to note that our perspective of sensitivity to climate change in these communities focuses only on changes in their fished resource, and not on additional socio-economic challenges that may promote or hinder adaptation to those changes.

Whilst we focused specifically on resources exploited by Tanzania's artisanal fleet, large, internationally-flagged vessels exploit offshore waters where we found strong, climate-driven changes in habitat conditions, especially at the Eastern edge of the EEZ. Strong changes in habitat conditions offshore, could push large target species in the Scombridae and Coryphaenidea families, as well as Elasmobranchs (Johannesen, 2018) further west, especially during the prime fishing season (North East Monsoon), and with them, large fishing vessels. Whilst most of the EEZ is already fished, this potential displacement of larger vessels closer to shore may lead to increased competition with the artisanal fleet in nearer shore offshore waters, targeted by both sectors of the fleet in future. As these species are also targeted by illegal fishers, a recognised issue in Tanzania, further conflicts may also arise, requiring increased resources to deter Illegal, Underreported and Unregulated (IUU) fishing (already the object of Tanzanian law).

4.3. Seaweed farming

Our analyses suggest that the seaweed farming sector, already experiencing effects of ocean warming at present (Msuya, 2017; Largo et al., 2020), will likely be impacted throughout Tanzania in decades to come, under growing emissions. We found widespread changes across the EEZ consistent with climate change, though no climate change hotspots were observed. Inshore waters appeared to be particularly affected, and this may represent a substantial challenge to the structure of the sector at present, whereby seaweed are grown by women, in shore areas local to their communities. Our modelling suggests that, given the widespread climate-driven trends estimated, lower impacts may be observed offshore, perhaps representing support for current interest in growing seaweed in deeper waters (Msuya et al., 2022). However, given the analyses presented here, without strong curbs in emissions, it is possible that local, shore based farming, currently concentrated in Unguja/Zanzibar Island and Mafia Island may be substantially impacted, exacerbating the challenge of sustainable livelihoods for women, who lead this sector (Msuya, 2012, 2017). The growing interest in the participation of women in Tanzania's blue economy, as also enshrined in the 2050 Africa's Maritime Strategy, may thus be substantially challenged by climate change, requiring support mechanisms to be considered for these communities, for instance, through the inclusion of these communities within the expansion of deeper water seaweed farming (Brugere et al., 2020), and the seaweed processing industry. With production in Zanzibar representing a large proportion of the seaweed farming sector in Africa, these potential impacts represent also broader economic impacts for the region. The growth of deeper water farming may thus represent a substantial route to support the growth of the sector under growing emissions, and management of potential conflicts with other users will be required. Also in this case, marine spatial planning may provide an important route to identify and manage those potential conflicts, through integrated sectorial management strategies and co-location. By-laws coupled with MSP (community- or sector-specific) can also be part of of the solution for such user conflicts since they can be applied in in inshore areas where seaweed is farmed. As with the fishing and conservation sector, similar analyses of modelling projections employing milder greenhouse gas emissions trajectories should be further explored in the development of management strategies.

4.4. Conclusion: Achieving blue growth in Tanzania under growing emissions

Climate-smart marine spatial planning, the effective ecosystem-based management of the ocean under climate change, is a global ambition (Frazão-Santos et al., 2020; Ehler, 2021). Here, we identified small, but potentially important, gains that such strategies could deliver for each of our three focal activity sectors that could be capitalised upon through Marine Spatial Planning, given local and regional variations in the sensitivity of the underpinning ecosystems to climate change. It is important to note that the analyses undertaken here are limited by the resolution of the underlying modelling tools, which whilst skilled, may remain fairly coarse in areas closer to the shore. And yet, the main message that emerges from our analyses is that identified potential sectorial gains may be small without curbing global CO_2 emissions (as expressed by RCP8.5). Tanzania is currently addressing it's own path to net zero through its commitment to the Paris Agreement, and Tanzania's Nationally Determined Contribution target of reducing economy-wide CO_2 emissions by 30–35 % by 2030 (Government of Tanzania, 2021) including the ambition to implement climate-smart approaches that minimise the impacts of climate change on coastal and marine environment as well as fisheries, as explored here. However, with annual emissions several orders of magnitude lower than the top 5 emissions producers China, United States of America, India, Russia and Japan, Tanzania ranks 103rd with a mere 0.03 % of the total global emissions share (United Nations Population Division, 2019). As shown here, growing emissions (depicted by RCP8.5) represent substantial challenges to the sustainability of Tanzania's marine protected species and habitats, its artisanal pelagic fishing sector, and its seaweed farming sector. As such, growing global emissions threaten the growth of Tanzania's blue economy, the delivery of 2050 Africa's Maritime Strategy, as well as the country's commitments to the United Nations 2030 Agenda for Sustainable Development. There is recognised inequality between high emissions producing countries and those that bear the brunt of the impacts of climate change (Mendelsohn et al., 2006). Our analysis supports that this is also the case for Tanzania.

Most countries have now made their national decarbonisation commitments at the 28th United Nations Framework Convention on Climate Change's Conference of Parties (Nationally Determined Contributions), in support of the Paris Agreement (Secretariat of the United Nations

Framework Convention on Climate Change, 2021). Global cooperation on their immediate implementation (Calverley and Anderson, 2022) may be the only path towards a sustainable ocean economy for Global South countries such as Tanzania.

CRediT authorship contribution statement

Ana M. Queirós: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Elizabeth Talbot:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Flower E. Msuya:** Writing – review & editing, Data curation. **Baraka Kuguru:** Writing – review & editing, Formal analysis, Data curation. **Narriman Jiddawi:** Writing – review & editing, Methodology, Funding acquisition, Data curation. **Shigalla Mahongo:** Writing – review & editing, Methodology, Funding acquisition, Data curation, Conceptualization. **Yohana Shaghude:** Writing – review & editing, Methodology, Funding acquisition, Data curation. **Christopher Muhando:** Methodology, Data curation. **Elias Chundu:** Writing – review & editing, Data curation. **Zoe Jacobs:** Writing – review & editing, Funding acquisition, Formal analysis, Data curation. **Sevrine Sailley:** Writing – review & editing, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Elina A. Virtanen:** Writing – review & editing. **Markku Viitasalo:** Writing – review & editing. **Kennedy Osuka:** Writing – review & editing, Data curation. **Shankar Aswani:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Jack Coupland:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Rob Wilson:** Writing – review & editing, Formal analysis, Data curation. **Sarah Taylor:** Writing – review & editing. **Jose A. Fernandes-Salvador:** Writing – review & editing, Formal analysis, Data curation. **Simon Van Gennip:** Writing – review & editing, Formal analysis, Data curation. **Edward Senkondo:** Writing – review & editing. **Modesta Meddard:** Writing – review & editing. **Ekaterina Popova:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Albers, H., Preonas, L., Madrigal, R., Robinson, E.J., Kirama, S., Lokina, R., Turpie, J., Alpizar, F., 2015. Marine Protected Areas in Artisanal fisheries: A Spatial Bio-economic Model Based on Observations in Costa Rica and Tanzania.

Amone-Mabuto, M., Bandeira, S., da Silva, A., 2017. Long-term changes in seagrass coverage and potential links to climate-related factors: the case of Inhambane Bay, southern Mozambique. West. Indian Ocean J. Mar. Sci. 16 (2), 13–25.

Berachi, I.G., 2003. Bioeconomic Analysis of Artisanal Marine Fisheries of Tanzania (Mainland). Universitetet i Tromsø.

Bindoff, N., Cheung, W.W., Kairo, J., Arstegui, J., Guinder, V., Hallberg, R., Hilmi, N., Jiao, N., Karim, M., Levin, L., 2019. Changing Ocean, Marine Ecosystems, and Dependent Communities. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. IPCC (in press).

Brugere, C., Msuya, F.E., Jiddawi, N., Nyonje, B., Maly, R., 2020. Can innovation empower? Reflections on introducing tubular nets to women seaweed farmers in Zanzibar. Gend. Technol. Dev. 24 (1), 89–109.

Bryceson, I., Francis, J., 2014. In: Bryceson, I., Francis, J. (Eds.), Marine Protected Areas (MPAs) in relation to Fisheries Management: Challenges and Experiences from Developing Countries, p. 225. Zanzibar, Tanzania.

Burgoyne, C., Kelso, C., Mearns, K., 2017. The impact of stakeholder relations on the Mnemba island marine conservation area, Zanzibar, Tanzania. Tour. Mar. Environ. 12 (3–4), 239–252.

Cagua, E.F., Cochran, J.E., Rohner, C.A., Prebble, C.E., Sinclair-Taylor, T.H., Pierce, S.J., Berumen, M.L., 2015. Acoustic telemetry reveals cryptic residency of whale sharks. Biol. Lett. 11 (4), 20150092.

Calverley, D., Anderson, K., 2022. Phaseout Pathways for Fossil Fuel Production Within Paris-compliant Carbon Budgets, Tyndall Centre for Climate Change Research, p. 76.

Caughman, A.M., Gaines, S.D., Bradley, D., 2024. Climate change reduces long-term population benefits from no-take marine protected areas through selective pressures on species movement. Glob. Chang. Biol. 30 (3), e17240.

Charisiadou, S., Halling, C., Jiddawi, N., von Schreeb, K., Gullström, M., Larsson, T., Nordlund, L.M., 2022. Coastal aquaculture in Zanzibar, Tanzania. Aquaculture 546, 737331.

Close, C., Cheung, W., Hodgson, S., Lam, V., Watson, R., Pauly, D., 2006. Distribution ranges of commercial fishes and invertebrates. In: Fishes in Databases and Ecosystems. Fisheries Centre Research Reports, 14 (4).

Dimopoulos, D., Queiros, D., Van Zyl, C., 2019. Sinking deeper: the most significant risks impacting the dive tourism industry in the east African marine ecoregion. Ocean Coast. Manag. 181, 104897.

Doxa, A., Almpanidou, V., Katsanevakis, S., Queirós, A.M., Kaschner, K., Garilao, C., Kesner-Reyes, K., Mazaris, A.D., 2022. 4D marine conservation networks: combining 3D prioritization of present and future biodiversity with climatic refugia. Glob. Chang. Biol. 28 (15), 4577–4588.

EAME, 2004. In: Ngusaru, A., Newman, K., Humphrey, S., Goeltenboth, P., Hoyle, D. (Eds.), The Eastern African Marine Ecoregion Biodiversity Conservation Strategic Framework 2004-2005, 54. Dar es Salaam, Tanzania.

Ehler, C.N., 2021. Two decades of progress in marine spatial planning. Mar. Policy 132, 104134.

Ehler, C., Douvere, F., 2009. Marine Spatial Planning: A Step-by-step Approach toward Ecosystem-based Management. UNESCO.

Ellison, J.C., 2015. Vulnerability assessment of mangroves to climate change and sea-level rise impacts. Wetl. Ecol. Manag. 23 (2), 115–137.

Erftemeijer, P.L., Hamerlynck, O., 2005. Die-back of the mangrove *Heritiera littoralis Dryand*, in the Rufiji Delta (Tanzania) following El Nino floods. J. Coast. Res. 228–235.

Fernandes, J.A., Cheung, W.W., Jennings, S., Butenschön, M., Mora, L., Frölicher, T.L., Barange, M., Grant, A., 2013. Modelling the effects of climate change on the distribution and production of marine fishes: accounting for trophic interactions in a dynamic bioclimate envelope model. Glob. Chang. Biol. 19, 2596–2607.

Fernandes, J.A., Kay, S., Hossain, M.A., Ahmed, M., Cheung, W.W., Lazar, A.N., Barange, M., 2016. Projecting marine fish production and catch potential in Bangladesh in the 21st century under long-term environmental change and management scenarios. ICES J. Mar. Sci. 73 (5), 1357–1369.

Fernandes, J.A., Papathanasopoulou, E., Hattam, C., Queirós, A.M., Cheung, W.W.L., Yool, A., Artioli, Y., Pope, E.C., Flynn, K.J., Merino, G., Calosi, P., Beaumont, N., Austen, M.C., Widdicombe, S., Barange, M., 2017. Estimating the ecological, economic and social impacts of ocean acidification and warming on UK fisheries. Fish Fish. 18, 389–411.

Francis, J., Machumu, E., 2014. In: Francis, J., Bryceson, I. (Eds.), "Marine Protected Areas on Mainland Tanzania: What is their Future." Marine Protected Areas (MPAs) in relation to Fisheries Management: Challenges and Experiences from Developing Countries, pp. 153–178.

Frazão-Santos, C., Agardy, T., Andrade, F., Calado, H., Crowder, L.B., Ehler, C.N., García-Morales, S., Gissi, E., Halpern, B.S., Orbach, M.K., 2020. Integrating climate change in ocean planning. Nat. Sustain. 3, 505–516.

Fröcklin, S., de la Torre-Castro, M., Lindström, L., Jiddawi, N.S., Msuya, F.E., 2012. Seaweed mariculture as a development project in Zanzibar, East Africa: a price too high to pay? Aquaculture 356, 30–39.

Gates, A., Durden, J., Richmond, M., Muhando, C., Khamis, Z., Jones, D., 2021. Ecological considerations for marine spatial management in deep-water Tanzania. Ocean Coast. Manag. 210, 105703.

Government of Tanzania, 2021. Nationally Determined Contribution. The Vice President Office of the United Republic of Tanzania.

Gullström, M., de la Torre Castro, M., Bandeira, S., Björk, M., Dahlberg, M., Kautsky, N., Rönnbäck, P., Öhman, M., 2002. Seagrass ecosystems in the Western Indian Ocean. Ambio 31 (7-8), 588–596.

Hamad, H., Mchenga, I., Hamisi, M., 2019. Climate change increasing threats on non-conserved mangroves forests of Micheweni, Zanzibar–Tanzania. Tanzania J. Sci. 45 (3), 527–538.

Hawkins, E., Sutton, R., 2012. Time of emergence of climate signals. Geophys. Res. Lett. 39 (1).

Hissmann, K., Fricke, H., Schauer, J., Ribbink, A.J., Roberts, M., Sink, K., Heemstra, P., 2006. The South African coelacanths - an account of what is known after three submersible expeditions: coelacanth research. S. Afr. J. Sci. 102 (9), 491–500.

IPCC, 2019. In: Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., et al. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. IPCC (in press).

IPCC, 2021. Climate Change 2021 - The Physical Science Basis. Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Jacobs, Z., Yool, A., Jebri, F., Srokosz, M., van Gennip, S., Kelly, S., Roberts, M., Sauer, W., Queirós, A., Osuka, K., 2021. Key climate change stressors of marine ecosystems along the path of the east African coastal current. Ocean Coast. Manag. 208, 105627.

Jiddawi, N.S., Ohman, M.C., 2002. Marine fisheries in Tanzania. Ambio 31 (7–8), 518–527.

Johannesen, T., 2018. Survey of Regional Resources and Ecosystem off South East Africa. Institute of Marine Research, Bergen.

Jones, C., Hughes, J., Bellouin, N., Hardiman, S., Jones, G., Knight, J., Liddicoat, S., O'connor, F., Andres, R.J., Bell, C., 2011. The HadGEM2-ES implementation of CMIP5 centennial simulations. Geosci. Model Dev. 4 (3), 543–570.

Kaschner, K., Kesner-Reyes, K., Garilao, C., Segschneider, J., Rius-Barile, J., Rees, T., Froese, R., 2019. AquaMaps: predicted range maps for aquatic species. Retrieved from. https://www.aquamaps.org.

Käyhkö, N., Khamis, Z.A., Eilola, S., Virtanen, E., Muhammad, M.J., Viitasalo, M., Fagerholm, N., 2019. The role of place-based local knowledge in supporting integrated coastal and marine spatial planning in Zanzibar, Tanzania. Ocean Coast. Manag. 177, 64–75.

Largo, D.B., Msuya, F.E., Menezes, A., 2020. Understanding diseases and control in seaweed farming in Zanzibar. In: FAO Fisheries and Aquaculture Technical Paper (662): 0_1-49.

Madec, G., 2015. NEMO Ocean Engine.

Mendelsohn, R., Dinar, A., Williams, L., 2006. The distributional impact of climate change on rich and poor countries. Environ. Dev. Econ. 11 (2), 159–178.

Msuya, F.E., 2012. A study of working conditions in the Zanzibar seaweed farming industry. In: Women in Informal Employment: Globalizing and Organizing (WIEGO), Cambridge, MA.

Msuya, F.E., 2013. Social and economic dimensions of carrageenan seaweed farming in the United Republic of Tanzania. In: Social and Economic Dimensions of Carrageenan Seaweed Farming. Fisheries and Aquaculture Technical Paper, p. 580.

Msuya, F., 2017. Technological development to help women seaweed farmers cope with the effects of climate change in Zanzibar, Tanzania. World Aquacult. 48 (1), 45–47.

Msuya, F.E., Bolton, J., Pascal, F., Narrain, K., Nyonje, B., Cottier-Cook, E.J., 2022. Seaweed farming in Africa: current status and future potential. J. Appl. Phycol. 34 (2), 985–1005.

Muhando, C.A., 2011. Biophysical Features in the Northern Tanga marine reserves, Tanzania, vi+38. Marine Parks and Reserves Unit, Dar es Salaam, Tanzania.

Muir, C.E., Sallema, A., Abdallah, O., De Luca, D., Davenport, T.R., 2003. The dugong (Dugong dugon) in Tanzania: a national assessment of status, distribution and threat. Wildl. Conserv. Soc. 22.

Musick, J.A., Limpus, C.J., 2017. Habitat Utilization and Migration in Juvenile Sea Turtles. In: The Biology of Sea Turtles. CRC Press, pp. 137–163.

Mwaijande, F., 2021. In: Sparks, D.L. (Ed.), Managing the Blue Economy. A Case Study of Tanzania. The Blue Economy in Sub-Saharan Africa. Working for a Sustainable Future. Routledge, London and New York, pp. 158–179.

Mwanjela, G., Lokina, R., 2016. What does it take to be heard in managing marine protected areas? Insights from Tanzania coastal communities. Afr. J. Econ. Rev. 4 (1), 143–156.

NEMC, National MAB Focal Point, 2021. Briefing Report on UNESCO's Man and Biosphere (MAB) Programme in Tanzania, to be Submitted to the MAB ICC Meeting, Abuja Nigeria 13th–17th Septem- ber 20201. Country report (Tanzania) on MAB Programme, p. 18.

Obura, D., Gudka, M., Samoilys, M., Osuka, K., Mbugua, J., Keith, D.A., Porter, S., Roche, R., van Hooidonk, R., Ahamada, S., 2022. Vulnerability to collapse of coral reef ecosystems in the Western Indian Ocean. Nat. Sustain. 5 (2), 104–113.

Osuka, K.E., Stewart, B.D., Samoilys, M., McClean, C.J., Musembi, P., Yahya, S., Hamad, A.R., Mbugua, J., 2022. Depth and habitat are important drivers of abundance for predatory reef fish off Pemba Island, Tanzania. Mar. Environ. Res. 175, 105587.

Pedersen, J.S.T., Santos, F.D., van Vuuren, D., Gupta, J., Coelho, R.E., Aparício, B.A., Swart, R., 2021. An assessment of the performance of scenarios against historical global emissions for IPCC reports. Glob. Environ. Chang. 66, 102199.

Pınarbaşı, K., Galparsoro, I., Borja, Á., Stelzenmüller, V., Ehler, C.N., Gimpel, A., 2017. Decision support tools in marine spatial planning: present applications, gaps and future perspectives. Mar. Policy 83, 83–91.

Pool-Stanvliet, R., Coetzer, K., 2020. The scientific value of UNESCO biosphere reserves. S. Afr. J. Sci. 116, 1–4.

Popova, E., Yool, A., Byfield, V., Cochrane, K., Coward, A.C., Salim, S.S., Gasalla, M.A., Henson, S.A., Hobday, A.J., Pecl, G.T., 2016. From global to regional and back again: common climate stressors of marine ecosystems relevant for adaptation across five ocean warming hotspots. Glob. Chang. Biol. 22 (6), 2038–2053.

Queirós, A.M., Talbot, E., Beaumont, N.J., Somerfield, P., Kay, S., Pascoe, C., Dedman, S., Fernandes, J., Jütterbrock, A., Miller, P.I., Sailley, S.F., Sará, G., Carr, L.M., Austen, M.C., Widdicombe, S., Rilov, G., Levin, L.A., Hull, S.C., Walmsley, S.F., Aonghusa, C.N., 2021. Bright spots as climate-smart marine spatial planning tools for conservation and blue growth. Glob. Chang. Biol. 27, 5514–5531.

Ribbink, A.J., Roberts, M., 2006. African coelacanth ecosystem programme: an overview of the conference contributions: coelacanth research. S. Afr. J. Sci. 102 (9), 409–415.

Said, S.S., Jiddawi, N., Salmin, Y.N., Cockcroft, V., 2020. Assessment of the status, threats and management of dugongs along coastal waters of Pemba Island, Zanzibar. Assessment 4 (10), 97–106.

Schwalm, C.R., Glendon, S., Duffy, P.B., 2020. RCP8. 5 tracks cumulative CO$_2$ emissions. Proc. Natl. Acad. Sci. 117 (33), 19656–19657.

Secretariat of the United Nations Framework Convention on Climate Change, 2021. Nationally Determined Contributions Under the Paris Agreement, p. 42.

Temple, A.J., Kiszka, J.J., Stead, S.M., Wambiji, N., Brito, A., Poonian, C.N., Amir, O.A., Jiddawi, N., Fennessy, S.T., Pérez-Jorge, S., 2018. Marine megafauna interactions with small-scale fisheries in the southwestern Indian Ocean: a review of status and challenges for research and management. Rev. Fish Biol. Fish. 28 (1), 89–115.

United Nations, 2015. Transforming our World: The 2030 Agenda for Sustainable Development. United Nations, Department of Economic and Social Affairs, New York.

United Nations Educational Scientific and Cultural Organization, 1971. Convention on Wetlands of International Importance Especially as Waterfowl Habitat. Ramsar, p. 7.

United Nations Environment Programme, 2022. Emissions Gap Report 2022: The Closing Window — Climate Crisis Calls for Rapid Transformation of Societies. Nairobi.

United Nations Population Division, 2019. World Population Prospects: The 2019 Revision.

Valderrama, D., Cai, J., Hishamunda, N., Ridler, N., Neish, I.C., Hurtado, A.Q., Msuya, F. E., Krishnan, M., Narayanakumar, R., Kronen, M., 2015. The economics of kappaphycus seaweed cultivation in developing countries: a comparative analysis of farming systems. Aquac. Econ. Manag. 19, 251–277.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., 2011. The representative concentration pathways: an overview. Clim. Change 109 (1–2), 5.

Wilson, R.J., Sailley, S.F., Jacobs, Z.L., Kamau, J., Mgeleka, S., Okemwa, G.M., Omukoto, J.O., Osuka, K.E., Samoilys, M., Sauer, W.S., Silas, M.O., Sululu, J.S., Roberts, M.J., 2021. Large Projected Reductions in Marine Fish Biomass for Kenya and Tanzania in the Absence of Climate Mitigation.

WWF, 2009. The Global Conservation Program. Achievements and lessons learned from 10 years of support for threats-based conservation at a landscape and seascape scale: Eastern African Marine Ecoregion.

Yool, A., Popova, E.E., Anderson, T.R., 2013. MEDUSA-2.0: an intermediate complexity biogeochemical model of the marine carbon cycle for climate change and ocean acidification studies. Geosci. Model Dev. 6 (5), 1767–1811.

Yool, A., Popova, E., Coward, A., 2015. Future change in ocean productivity: is the Arctic the new Atlantic? J. Geophys. Res. Oceans 120 (12), 7771–7790.