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Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries

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ABSTRACT

Coral reefs support the livelihood of millions of people especially those engaged in marine fisheries activities. Coral reefs are highly vulnerable to climate change induced stresses that have led to substantial coral mortality over large spatial scales. Such climate change impacts have the potential to lead to declines in marine fish production and compromise the livelihoods of fisheries dependent communities. Yet few studies have examined social vulnerability in the context of changes specific to coral reef ecosystems. In this paper, we examine three dimensions of vulnerability (exposure, sensitivity, and adaptive capacity) of 29 coastal communities across five western Indian Ocean countries to the impacts of coral bleaching on fishery returns. A key contribution is the development of a novel, network-based approach to examining sensitivity to changes in the fishery that incorporates linkages between fishery and non-fishery occupations. We find that key sources of vulnerability differ considerably within and between the five countries. Our approach allows the visualization of how these dimensions of vulnerability differ from site to site, providing important insights into the types of nuanced policy interventions that may help to reduce vulnerability at a specific location. To complement this, we develop framework of policy actions thought to reduce different aspects of vulnerability at varying spatial and temporal scales. Although our results are specific to reef fisheries impacts from coral bleaching, this approach provides a framework for other types of threats and different social-ecological systems more broadly.

1. Introduction

Millions of people depend on coral reefs for their income and livelihoods. For example, the Great Barrier Reef alone contributes over $5 billion annually to Australia's economy (Access Economics, 2005). Coral reefs are particularly important for fisheries, tourism, and coastal protection, but also have high aesthetic values and some reefs have spiritual values (Cinner and Aswani, 2007; Hicks et al., 2009). Climate change is considered a key threat to coral reefs (Hughes et al., 2003) and to marine fisheries (Allison et al., 2009; Cheung et al., 2010). Climate-related events, such as increased sea surface temperatures (which can cause corals to bleach and die), can have profound impacts on coral reef ecosystems and the people that depend on them. To illustrate, in 1998, coral bleaching at an unprecedented scale caused widespread coral mortality across most of the western Indian Ocean, altering the goods and services provided by these reefs (Graham et al., 2007; Pratchett et al., 2008). Further east, in the central Indo-Pacific, Indonesia is expected to experience the most severe climate-related declines in total marine fisheries of any nation, with projected reductions of over 20% by 2055 (Cheung et al., 2010). Resource users may also have to adapt the ways that they use coral reefs in response to management measures that aim to make coral reefs more resilient to the impacts of climate change (for example, the creation of marine reserves that prohibit fishing). Thus, questions of critical importance to resource managers, stakeholders, and scientists

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alike are how reef-dependant societies are being affected by, and what capacity they have to adapt to, climate change impacts.

Research on social vulnerability to disasters, global environmental change, famine, and poverty has a long history in social science disciplines such as human geography (Adger, 1999, 2006; Cutter, 1996; Kelly and Adger, 2000), yet few studies have examined social vulnerability in the context of changes specific to coral reef ecosystems (Adger, 2003; Marshall and Marshall, 2007; McClanahan et al., 2008a). Although definitions can vary, vulnerability is generally considered to be the degree to which a system is susceptible to, and unable to cope with, the adverse effects of a chronic or stochastic disturbance (Adger, 2006; Cutter, 1996). Vulnerability to environmental change varies across spatial and temporal scales, and for different people within society (for example, the poor or migrants are often considered more vulnerable, Bene, 2009). In the context of reef-dependant societies, understanding the potential impacts of climate change and society's capacity to adapt to these changes requires analyzing the combination of conditions (economic, environmental and social) that contribute to vulnerability, and characterizing locations and segments of society that are most vulnerable.

Several different research frameworks have been developed to examine how vulnerable societies are to environmental change (Adger and Vincent, 2005; Bene, 2009; Brooks et al., 2005; Cutter, 1996; Yohe and Tol, 2002). These typically measure three key dimensions of vulnerability: (1) exposure; (2) sensitivity; and (3) adaptive capacity (Adger, 2000, 2006; Adger and Vincent, 2005; Allison et al., 2009; Gallopin, 2006; Kelly and Adger, 2000; Quentin Grafton, 2010; Smit and Wandel, 2006). Exposure is the degree to which a system is stressed by climatic events and environmental conditions such as the magnitude, frequency, and duration of a climatic event such as coral bleaching or a cyclone (Adger, 2006; Cutter, 1996). Exposure, in the context of coral reefs, varies depending on factors such as oceanographic conditions, prevailing winds, and latitude, which increase the likelihood of being impacted by events such as cyclones or coral bleaching (Maina et al., 2008). Sensitivity, in the context of environmental change, is the state of susceptibility to harm from perturbations or long-term trends (Adger, 2006). Sensitivity can be affected by levels of dependence on natural resources and the technologies used to harvest resources. Adaptive capacity is a latent characteristic that reflects peoples' ability to anticipate and respond to changes, and to minimize, cope with, and recover from the consequences of change (Adger and Vincent, 2005; Gallopin, 2006). Adaptive capacity refers specifically to the preconditions that enable adaptation to change (Nelson et al., 2007). People with low adaptive capacity, such as those who feel they have no alternative livelihoods, may be unable to adapt to changes in the flow of ecosystem goods and services brought about by climate change, or unwilling to take advantage of the opportunities created by change.

Here, we operationalize each of these dimensions of vulnerability to temperature-induced changes in fisheries for 29 coastal communities across five western Indian Ocean countries. This paper builds on previous work that has developed measures for exposure and adaptive capacity (Cinner et al., 2009a; McClanahan et al., 2008a, 2009) by integrating these with a novel measure of sensitivity to build a more holistic perspective of vulnerability. A number of studies have shown that failure to reflect local contextual conditions can lead to policy interventions that undermine the resilience of coastal communities (Bunce et al., 2010; McClanahan et al., 2008a). Consequently, our discussion focuses on how managers, donors, and other policy makers can consider policy actions at different spatial and temporal scales to reduce different aspects of the vulnerability of coastal communities to key impacts of temperature induced climate change on reef fisheries.

2. Methods

2.1. Study sites

Socioeconomic data were collected from 42 coastal communities grouped into 29 sites spanning Kenya, Tanzania, Seychelles, Mauritius, and Madagascar between 2005 and 2006 (Fig. 1). Sites were selected within countries to provide a spectrum of social and environmental conditions (Cinner et al., 2009c). This type of purposive sampling of communities is an appropriate strategy for exploratory studies such as this (Agrawal, 2001), although inferences from the data are constrained by the non-random selection of study sites. For each site we obtained data on: (1) exposure, based on remote sensing data from an Indian Ocean scale stress model (Maina et al., 2008); (2) sensitivity; and (3) adaptive capacity, based on socioeconomic surveys previously reported in (McClanahan et al., 2008a, 2009).

2.2. Exposure

Past coral bleaching data and associated oceanographic conditions across the sites were used to produce a predictive model of coral susceptibility to thermal stress and associated coral bleaching throughout the western Indian Ocean region (Fig. 1) (Maina et al., 2008). The model is derived from six ocean climate variables: sea surface temperature, photosynthetically active radiation [PAR], ultraviolet radiation [UV], chlorophyll, surface currents, and wind velocity. The model utilized in situ coral bleaching data for 216 sites collected between 1998 and 2005 (www.reefbase.org) and field surveys of 91 sites in 2005 to correlate the above environmental factors with bleaching intensity at these specific sites and times (Maina et al., 2008). Environmental data that were significantly correlated with bleaching were used in a GIS fuzzy logic process and Spatial Principal Component Analysis (SPCA) to yield susceptibility maps. These were then synthesized into a single exposure map by summing seven principal components weighted by their relative contribution. The model was tested using coral mortality across 1998 ENSO, for 16-reef locations in the Western Indian Ocean and found a reasonable fit (r^2 = 0.27 and 0.50 when removing two outliers, Maina et al., 2008). Interpretation of the exposure variable is such that higher scores

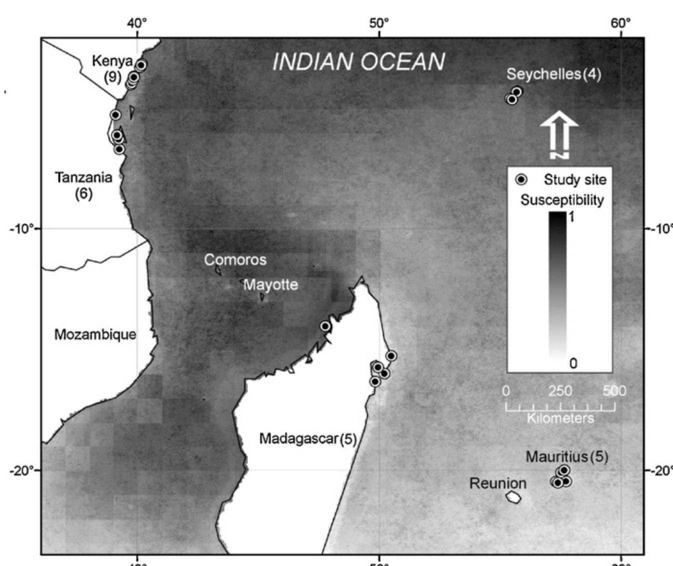

Fig. 1. Map of study sites and their level of exposure to coral bleaching. Darker ocean areas have a higher level of exposure.
Adapted from Maina et al. (2008) and McClanahan et al. (2009).

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are indicative of predicted higher temperature-associated coral mortality. Importantly, although temperature-associated coral mortality events are pulse disturbances, associated impacts on reef fisheries and the livelihoods of communities that depend on them, can take years to decades (Graham et al., 2008; Pratchett et al., 2008; Wilson et al., 2006). This is due to two processes; firstly the reduction in small size classes of target reef fish species typically occurs when the reef structural complexity of dead corals erodes, which occurs several years after the live coral itself has dies, and secondly, the loss of smaller cohorts of target reef fishery species takes some time to lead to a collapse of associated adult stocks (i.e. there are fewer small cohorts to recruit into fishery size classes) (Graham et al., 2007).

2.3. Sensitivity

Consistent with other studies and protocols, we develop a metric of sensitivity based on the level of dependence on fisheries (Allison et al., 2009; Marshall et al., 2010). This indicator was developed based on surveys of 1564 household in 29 sites previously described in McClanahan et al. (2008a). Sampling of households within communities was based on a systematic sampling design. We conducted between 23 and 143 household surveys per site, depending on the population of the communities and the available time to conduct interviews per site. In sites with a low density of fishers in the general population, additional systematic surveys were conducted from the population of fishers.

To develop the sensitivity metric, we asked respondents to list all livelihood activities that bring in food or income to the household and rank them in order of importance. Occupations were grouped into the following categories: fishing, selling marine products, tourism, farming, cash crops, gleaning, salaried employment, the informal sector, other, and 'none' (see Cinner and Bodin, 2010 for details). To better understand sensitivity to the impacts of temperature events on fisheries, we considered fishing and fish trading together as the 'fisheries' sector and all other categories as the 'non-fisheries' sector. This grouping has parallels in agricultural economics where activities are classified as 'farm' and 'non-farm' (Barrett et al., 2001). We purposely grouped gleaning (i.e. hand collecting marine organisms) as a non-fisheries activity because the connections between high-temperature events and abundance of the marine invertebrates targeted in gleaning is not well established. Our metric of sensitivity incorporates the proportion of households engaged in fisheries, whether these households also engage in non-fisheries occupations (what we call 'linkages' between sectors), and the directionality of these linkages (i.e. whether respondents ranked fisheries as more important than, say, agriculture) (Eq. (1)):

$$S = \frac{F}{F + NF} \times \frac{N}{F + NF} \times \frac{(r_{fn}/2) + 1}{r_{fn} + r_{nf} + 1} \qquad (1)$$

where S = sensitivity, F = number of households relying on fishery-related occupations, NF = number of households relying on non-fishery-related occupation, N = number of households, r_{fn} = the number of times fisheries related occupations were ranked higher than non-fishing occupations (normalized by the number of households), r_{nf} = the number of times non-fisheries related occupations were ranked higher than fishery occupations (normalized by the number of households). The first term in Eq. (1) captures the ratio of fishery to non-fishery related occupations. The second term captures the extent to which households dependent on fisheries also engage in non-fishery livelihood activities. This term decreases the level of sensitivity when many households are engaged in both occupational categories. The third term captures the directionally of linkages between fisheries and non-fisheries such that communities were more sensitive when households engaged in fisheries and non-fisheries occupations consistently ranked the fisheries sector as more important than other livelihood activities. Using this composite metric, we were able to capture some previously unexplored aspects of sensitivity, although we acknowledge that sensitivity and occupational dependency can have a number of social and psychological dimensions that we are not able to cover here (Marshall, 2010; Marshall and Marshall, 2007). Additional description of our metric can be found in Appendix A.

2.4. Social adaptive capacity index

Here, we employed the social adaptive capacity index developed in McClanahan et al. (2008a). Based on both the household surveys described above and key informant interviews, we derived eight indicators of adaptive capacity. These were: (1) recognition of causal agents impacting marine resources (measured by content organizing responses to open-ended questions about what could impact the number of fish in the sea); (2) capacity to anticipate change and to develop strategies to respond (measured by content organizing responses to open ended questions relating to a hypothetical 50% decline in fish catch); (3) occupational mobility (indicated as whether the respondent changed jobs in the past five years and preferred their current occupation); (4) occupational multiplicity (the total number of person-jobs in the household); (5) social capital (measured as the total number of community groups the respondent belonged to); (6) material assets (a material style of life indicator measured by factor analyzing whether respondents had 15 material possessions such as vehicle, electricity and the type of walls, roof, and floor): (7) technology (measured as the diversity of fishing gears used); and (8) infrastructure (measured by factor analyzing 20 infrastructure items such as hard top road, medical clinic, Pollnac and Crawford, 2000). The indicator of occupational multiplicity is fundamentally different from our measure of sensitivity since it builds on the households' complete portfolios of occupations, and is therefore able to capture a households general ability to adapt to change. The sensitivity measure, in contrast, only focuses on the extent to which households are engaged in fishery versus non-fishery-related occupations, and how they rank their relative importance. These eight indicators of adaptive capacity were combined into a single metric based on weightings derived from expert opinion from ten regional and international social scientists (McClanahan et al., 2008a).

3. Analysis

We used two techniques to examine vulnerability. First, we developed a quantitative vulnerability score using an equation to combine the three contributing indices (each normalized to 0–1 scale). As a sensitivity analysis we calculated the score based on two previously used formulations, and tested whether they had an impact on the final ranked vulnerability score of the sites. We used the following commonly used equations (Adger and Vincent, 2005; Allison et al., 2009) to create an overall metric of vulnerability to temperature induced changes:

Measure 1: Vulnerability = (exposure + sensitivity) − adaptive capacity
Measure 2: Vulnerability = (exposure × sensitivity)/adaptive capacity

Secondly, to visualize differences in key components of vulnerability, we plotted the three dimensions on a bubble plot, where sensitivity is plotted against adaptive capacity and exposure is indicated as the size of the points (larger point = higher exposure).

4. Results

The two measures of vulnerability were correlated at $R = 0.9$, so we present only the first measure. There was considerable spread of vulnerability both within and among countries (Table 1 and Fig. 1). Mean country levels of exposure varied from a low of 0.26 (SD = 0.01) in Mauritius to highs of 0.58 (SD = 0.04) and 0.57 (SD = 0.3) in Kenya and Seychelles, respectively. Southeast Madagascar had moderate exposure (0.36), but was notable for the considerably higher variation (SD = 0.17) created by differing exposure levels on the different sides of the island. Importantly, at the site level, Madagascar had both the lowest (0.22) in the southwest and highest (0.66) exposure scores in the northwest, encompassing a range of 0.44 (Table 1). Tanzania reefs were moderate to highly exposed to with values ranging from 0.5 to 0.6. The highly exposed reefs in Kenya, Seychelles and north-west Madagascar are exposed to environmental conditions which are conducive to thermal stress induced coral bleaching, i.e. low temperature variability, high ultraviolet and photosynthetic active radiation, high sea water temperature and low wind velocity (Maina et al., 2008). Conversely, Mauritius and southwest Madagascar located in subtropical latitudes (25–28°) experience lower sea water temperature and radiation, and are exposed to high wind velocity and currents, factors which are associated with relatively lower thermal stress to corals. The lowest and highest mean temperature, UV irradiance and PAR were 18–31 °C, 200–313 milliwatts/m^2, and 35–57 Einstein/m^2/day, respectively. Wind speeds ranged from a low of 2.8 m/s to a high of 11.2 m/s.

National-scale averages of sensitivity varied from a low of 0.10 (SD = 0.03) in Seychelles to a high of 0.22 (SD = 0.06) in Tanzania. At the site level, the ten lowest sensitivity scores include all of the Seychelles sites, but also sites from Kenya, Madagascar and Mauritius (Table 1). The lowest sensitivity community (Bamburi, Kenya) had less than 10% of households engaged in fishery-related occupations, whereas in the highest sensitivity community (located near Dar Es Salaam, Tanzania) 73% of households were engaged. The ten sites with highest sensitivity were from Tanzania, Kenya, and Madagascar (Table 1). However, there was potential bias in the Tanzania sensitivity measure because we specifically sampled two sites that were fish landing sites, with extremely high proportions of fishers (Mazizini and Stone Town). However, when these sites were excluded, the national-level sensitivity average for Tanzania was still highest in the region. The range of sensitivity scores in our study spanned 0.25 along our possible 0–1 scale.

Seychelles and Mauritius had the highest overall national-level averages of adaptive capacity, respectively (mean = 0.5, SD = 0.03; mean = 0.45, SD = 0.04) and the five highest adaptive capacity sites were all from these two countries. Madagascar and Kenya, respectively, had the lowest average levels of adaptive capacity (mean = 0.34, SD = 0.06; mean = 0.37, SD = 0.06), with the five lowest adaptive capacity sites hailing from these countries (Table 1). Tanzania had intermediate adaptive capacity relative to other countries in this study (mean = 0.4, SD = 0.04). The range of adaptive capacity scores in our study spanned 0.25 along our possible 0–1 scale. Additional details about the contributions of each indicator to the adaptive capacity score at each site can be found in McClanahan et al. (2008a).

In terms of national-scale averages, Kenya had the highest overall vulnerability (mean = 0.39, SD = 0.08), followed by Tanzania (mean = 0.32, SD = 0.09), Madagascar (0.18, SD = 0.21), Seychelles (0.17, SD = 0.08), and Mauritius (−0.07, SD = 0.05) (Table 1). At the site level, Sahamalaza in Madagascar had the highest vulnerability, but seven of the ten most vulnerable sites were from Kenya.

Table 1
Dimensions of vulnerability in 29 western Indian Ocean coastal communities. Scores for each dimension of vulnerability (exposure, sensitivity, and adaptive capacity) and an overall vulnerability score are presented for each study site.

Country	Site	Exposure	Sensitivity	Adaptive capacity	Cumulative vulnerability
Madagascar	Sahamalaza	0.66	0.17	0.28	0.56
Kenya	Mayungu	0.56	0.29	0.34	0.50
Kenya	Vuma	0.62	0.17	0.32	0.47
Kenya	Takaungu	0.65	0.19	0.37	0.47
Tanzania	Mtangata	0.56	0.22	0.33	0.45
Kenya	Mijikenda	0.56	0.30	0.45	0.41
Tanzania	Dar Es Salaam	0.49	0.32	0.42	0.39
Kenya	Utange	0.56	0.13	0.30	0.39
Kenya	Kuruwitu	0.60	0.09	0.31	0.37
Kenya	Vipingo	0.56	0.16	0.36	0.36
Kenya	Shela	0.56	0.25	0.47	0.33
Tanzania	Stone town[a]	0.49	0.26	0.43	0.31
Tanzania	Buyu	0.49	0.17	0.37	0.29
Tanzania	Mazizini[a]	0.49	0.21	0.43	0.27
Seychelles	Anse Volbert	0.60	0.14	0.48	0.26
Kenya	Bamburi	0.54	0.07	0.37	0.24
Tanzania	Nyamanzi	0.49	0.17	0.44	0.22
Seychelles	Grand Anse	0.60	0.08	0.48	0.20
Seychelles	Roche Caiman	0.55	0.09	0.51	0.13
Madagascar	Tanjona	0.27	0.18	0.33	0.12
Madagascar	Sahasoa	0.39	0.13	0.43	0.09
Seychelles	Belombre	0.54	0.08	0.53	0.09
Madagascar	Ambodilaitry	0.22	0.16	0.31	0.07
Madagascar	Tampolo	0.27	0.15	0.37	0.05
Mauritius	Pointe des Lascars	0.26	0.16	0.41	0.01
Mauritius	St. Martin	0.27	0.10	0.42	−0.06
Mauritius	Pointe aux Piments	0.28	0.12	0.49	−0.08
Mauritius	Le Morne	0.24	0.16	0.49	−0.09
Mauritius	Blue Bay	0.24	0.07	0.45	−0.14

[a] These sites were fishing camps where we primarily targeted resource users.

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5. Discussion

Understanding what makes coastal societies vulnerable to aspects of climate change is a critical task for scientists, governments, donors, and civil society. Using the recognized framework of vulnerability as comprised of exposure, sensitivity, and adaptive capacity, we present the most detailed comparative study to date on the vulnerability of coastal communities to the impact of coral bleaching on the coral reef fisheries that supply livelihoods for millions of people. We plotted the three dimensions of vulnerability to help discern where sources of vulnerability lie at both site and national levels (Fig. 2).

Ranking our national-scale averages of local-scale vulnerability produced results that were broadly consistent with national-scale studies of the vulnerability of national economies to the impacts of climate change on fishing (Allison et al., 2009), but, not surprisingly, these relative rankings were quite different from national-scale studies on social vulnerability to water stress (Adger and Vincent, 2005). Allison et al. (2009) found that some of the countries most vulnerable to the impacts of climate change on fisheries were in east Africa, with Tanzania included in the most vulnerable quartile. Additionally, they found that Madagascar was among the most dependent on fisheries (in terms of the percentage or workforce engaged in fishing) (Allison et al., 2009). Since countries such as Tanzania and Kenya have sizable inland populations, these national-scale statistics may not always reflect socioeconomic realities on the coast. In our sample, our sensitivity metric suggests that, on average, coastal communities in Tanzania and Kenya had the highest level of dependence on fishing, although our purposive sampling strategy prevents us from making inferences about the broader context. In another international comparison, Adger and Vincent (2005) examined national scale vulnerability to water stress across Africa, which encompassed our study countries except Seychelles. Their metric of vulnerability ranked Madagascar, Tanzania, Kenya, and Mauritius as the 4th, 10th, 30th, and 48th most vulnerable of 49 countries included in the study, respectively. Although there may be generic components of vulnerability, these differential relative rankings underscore the importance of clearly defining what people are vulnerable to and the scales at which vulnerability assessments are occurring.

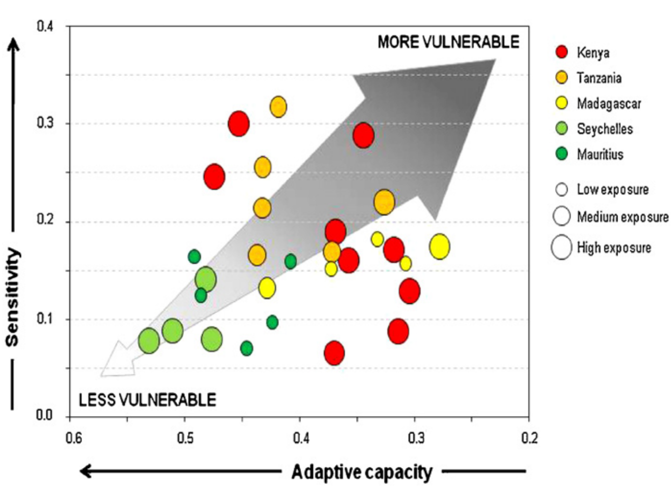

Fig. 2. Plot of the vulnerability of coastal communities to the impacts of coral bleaching on fisheries. Adaptive capacity (*x*-axis; note values reversed so high adaptive capacity is on the left) is plotted against Sensitivity (*y*-axis,) such that more vulnerable communities are in the top right of the graph and less vulnerable communities in the bottom left. These two dimensions of vulnerability can be modified by policy and development. The third dimension of vulnerability, exposure, is represented as the size of the bubble (larger = more exposure). To aid in visualization, exposure values were represented as the lowest, middle, and highest third rather than scaled to actual site values. Colors represent a gradient of vulnerability based on the country's mean vulnerability score from least vulnerable (green) to most vulnerable (red): Dark green = Mauritius, light green = Seychelles, yellow = Madagascar, Orange = Tanzania, Red = Kenya.

These types of overall vulnerability measures provide useful information about the relative state of susceptibility to harm from specific impacts, but the implications of a single quantitative metric can be difficult to interpret and the measure itself is not particularly informative about what policy actions could help to reduce vulnerability at a particular location. However, the approach we utilized allows one to characterize key determinants of vulnerability at a particular location (Fig. 2 and Table 1). For example, even though Madagascar had the lowest levels of adaptive capacity and sites with high sensitivity, exposure was on average low, providing a lower overall vulnerability than the Kenyan sites.

These distinctions in the underlying sources of vulnerability are important because specific policy tools may be required to address different dimensions of vulnerability. For example, specific interventions may be required to reduce sensitivity, whereas others may help build adaptive capacity. Importantly, these actions vary over spatial and temporal scales (Table 2). In the short term, emphasis may be put on reducing the impacts on the most vulnerable, in the medium term on beginning to enhance adaptive capacity and reduce sensitivity at local and national scales, and in the longer term to reducing exposure by mitigating climate change at the international level (Table 2). Here, we describe key policy actions that can help to alter different aspects of vulnerability to the impacts of coral bleaching on fisheries at varying spatial and temporal scales.

5.1. Local actions to reduce vulnerability

Local-scale actions (i.e. steps that can be taken at the community and sub-national scale) in the short-term (i.e. <1 year) can include improved information about weather, evacuations from highly vulnerable areas, and diversification within the fishery. For example, diversification within the fishery to new gears and target species may help to reduce sensitivity to the impacts of bleaching events. Certain artisanal fishing gears (such as handlines) capture a lower proportion of fishes that are most likely to be affected by coral bleaching than other gears (Cinner et al., 2009d). Additionally, fish aggregating devices (which are man-made floating objects used to attract pelagic species) appropriately located could allow artisanal fishers to begin targeting pelagic species close to shore. However, a trade off exists whereby reducing sensitivity to the impacts of coral bleaching on fisheries may increase sensitivity to other possible climate impacts, such as changes to ocean currents or primary productivity that may affect distribution patterns of pelagic fishes (Cheung et al., 2010; Stenseth et al., 2002).

Local-scale actions over medium-term time frames (i.e. <5 years) can include strengthening community groups responsible for managing coastal resources, improvements in coastal infrastructure, and migration to non-coastal areas. In much of the western Indian Ocean, community-based organizations are increasingly empowered with the responsibility of managing coastal resources such as reef-based fisheries (Cinner et al., 2009e). Medium-term investments in institutional capacity building (i.e. financial planning and management, knowledge and information sharing) and cross-scale linkages will likely be critical to facilitating the success of these emerging institutions. Additionally, in medium-term time frames, supplemental livelihood activities could reduce sensitivity by starting to link fishing households with new occupational sectors. This could be a stepping stone for a

Table 2
Examples of key policy actions to reduce aspects of vulnerability at different spatial and temporal scales.

	Short-term	Medium-term	Long-term
International	• Mobilization of relief funds[c]	• Mobilization of funding to invest in infrastructure[a] • Regional conservation planning[a,b,c] • Adaptation investments	• Climate change mitigation[c] • Mobilization of funding to invest in governance[a]
National	• Relief planning & coordination[c] • Social safety nets[a,c] • Flexible regulations that allow for rapid transitions during extreme events[a,b]	• Management measures to make reef ecosystems more resilient[b] • Investment in coastal infrastructure[a] • Investments in information networks and early warning systems[a] • Planned migration[a,c] • Adaptation planning[a,b,c]	• Investment in alternative energy[c] • Carbon trading policies[c] • Developing new industries[b] • Investments in education & literacy[a] • Improving governance[a]
Local	• Evacuations from most vulnerable sites[c] • Diversification within the fishery[b] • Improved information & market terms[a] • Adaptive management approaches (e.g. temporarily imposing or removing fisheries closures)[a,b]	• Supplemental livelihood activities (increase linkages to other economic sectors)[b] • Strengthen community groups, social networks & vertical linkages[a] • Improvements in coastal infrastructure[a] • Migration to non-coastal areas[b,c]	• Alternative livelihoods (transition out of fishing)[b] • Enhance capacities and health status of fishing communities[a] • Poverty reduction[a] • Developing forums to maintain & support ecological knowledge[a] • Investments in strong local governance institutions[a]

[a] Interventions to enhance adaptive capacity.
[b] Interventions to ameliorate sensitivity.
[c] Interventions to lower exposure.

transition out of the fishery for fishermen who are ultimately interested in exiting the sector.

Over longer-time scales, local-scale actions include livelihood diversification out of fishing, investments in health and education, developing forums to maintain and foster ecological knowledge, and broader investments in the local governance institutions highlighted above. Importantly, the main policy action to reduce sensitivity, livelihood diversification, has often failed in developing countries (Sievanen et al., 2005). In places such as Kenya, poverty may be a critical obstacle to livelihood diversification (Cinner et al., 2009b). In this context, diversification may not be an option for all fishers because some are so deeply trapped by poverty that risking something new is unrealistic without some type of social safety net. Additional barriers to livelihood diversification can also include a lack of skills, contacts, and access to capital and other critical resources – areas where the poor are often marginalized (Barrett and Carter, 2001; Boko et al., 2007; Crona and Bodin, 2010; Krishna et al., 2004). Addressing chronic poverty and escaping poverty traps requires policies which focus on social protection, public services and building individual and collective assets before effective diversification can happen (Chronic Poverty Research Centre, 2008).

5.2. National-scale actions to reduce vulnerability

In the short term, national scale efforts to provide social safety nets may help to increase adaptive capacity by preventing the marginally poor from falling into poverty traps (Barrett and Carter, 2001) and reduce exposure to climate change, for example through provision of basic physical infrastructure and planning controls to prevent development and settlement in highly risky situations. Over medium time scales, national-scale actions can include planned migration and investments in information networks and early warning systems, adaptation planning (e.g. national adaptation plans), and coastal infrastructure. For example, information-based tools such as early warning systems can reduce exposure and increase adaptive capacity by helping fishers assess potential risks, reduce lost or unproductive fishing days, and ultimately reduce deaths due to weather-related events (Badjeck et al., 2010).

Over longer time frames, national actions will include investments in alternative energy and new industries to reduce exposure and sensitivity, respectively. Education and literacy are key components in peoples' ability to absorb and process information on the causes and consequences of climate change and will require significant investments in the region. National-level policies that enable a price on carbon (e.g. cap and trade legislation) may be critical longer-term strategies to reduce exposure through mitigating climate change. Lastly, The WIO region is generally characterized by weak national-level governance, which can profoundly influence adaptive capacity at local and national levels (Adger and Vincent, 2005). Addressing issues such as corruption, transparency, and stability of national governments will be key to building effective social organization and adaptive capacity at all scales (Boko et al., 2007).

5.3. International-scale actions to reduce vulnerability

International-scale policy actions are much more general, with little specificity to coral reefs. These policy actions are well covered in depth in numerous reports such as the IPCC Working Group 3 (on climate change mitigation) World Bank's World Development Report in 2010 and the UNDP Human Development Report of 2008 which link development and adaptation to climate change, and are consequently covered in less detail here. At the international scale, short-time frame actions will primarily include mobilization of funding for relief efforts. Over the medium-term, these international efforts will include mobilization of funding to invest in infrastructure, adaptation, and regional conservation planning. Longer-term international efforts will include international negotiations on climate change mitigation and mobilization of funding to invest in environmental governance.

5.4. Making coral reef management reflective of social vulnerability

In addition to climate change, overfishing and pollution are key drivers of change in marine systems (Jackson et al., 2001). Effectively adapting to changes in coral reef fisheries will also require governance of broader marine seascapes. Decades of research on common property institutions have suggested that there is a clear need for governance rules to be congruent with local social and environmental conditions (Agrawal, 2001; Ostrom, 1990; Ostrom et al., 1999, 2002). Aspects of social vulnerability can

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inform the types of strategies managers use to make them more congruent to local conditions.

Some aspects of vulnerability are very specific to the change in question, while others are broadly generic. For example, a certain level of wealth and/or independence may help one adapt to a broad range of changes in a way that the poor are unable to (Barrett et al., 2006; Cinner et al., 2009b; Crona and Bodin, 2010; Enfors and Gordon, 2008). Our metric of adaptive capacity was developed to look at how people are able to adapt to a broad range of changes in the flows of goods and services from coral reef systems, including potential policy actions (McClanahan et al., 2008a). Previous related studies (McClanahan et al., 2008a, 2009), suggested that people with low adaptive capacity may be unwilling or unable to adapt to policy actions that have high adjustment costs, such as protected areas. Areas with low adaptive capacity may be more suited to management actions that require less adaptation, such as shifts in gear-use or fisheries closures that allow for periodic harvests (Cinner, 2007). These actions could be viewed as starting points for management that can help to stabilize or improve resource conditions and fishers incomes (McClanahan et al., 2008b; Worm et al., 2009) while longer-term strategies for building adaptive capacity are enacted (Table 2).

Additionally, different management strategies may be more appropriate for areas with high compared to low exposure. Some sites (such as Seychelles and Mauritius) have similar levels of adaptive capacity and sensitivity (Fig. 1), but levels of exposure are much higher in Seychelles. Importantly, differing levels of exposure may have very different implications for how resources are managed. For example, some reefs in the high exposure areas will be damaged by climate regardless of whether or not management actions to conserve reefs are successful (Graham et al., 2008). Sites with high levels of exposure to climate-induced bleaching would, therefore, be poor targets for protected areas that depend on consistent ecosystem quality to attract tourism for their funding. After a bleaching event severe enough to deter tourists, reduced income from entrance fees could reduce the income required for active enforcement patrols. If people who were dependant on tourism put effort into the fishery as a supplemental livelihood, this could create a situation where funding for enforcement is reduced just as there is increasing effort on the fishery and while ecosystems are recovering and need the most protection. In these areas, supplemental funding sources would be needed to manage protected areas after a bleaching mortality event. Alternatively, areas with low exposure are better targets for protected areas management that relies on user fees for management financing. Critically, though, recent modelling work (Game et al., 2008) has found that payoffs from conserving sites with high or low susceptibility depend on broader ecosystem conditions, which, in the western Indian Ocean, are generally degraded outside protected areas (Cinner et al., 2009c; McClanahan et al., 2008b).

5.5. Critiques, caveats, and challenges to improve indices of vulnerability

This paper concentrated on examining vulnerability to a single stressor at a local scale. There are important trade-offs inherent in evaluating not only local versus larger-scale vulnerability issues, but also specific versus more general climate change impacts. For example, some aspects of social vulnerability can be facilitated or hindered by national-scale conditions (such as governance, gross domestic product, and whether a country is a small island developing state; Allison et al., 2009; Brooks et al., 2005; Yohe and Tol, 2002), which are obviously not represented in our study of local-scale vulnerability.

Likewise, Allison et al. (2009) used a more general exposure indicator of predicted mean surface temperature, while our measure of exposure is specific to the mechanism of coral bleaching. Both approaches have their pros and cons. A generalised indicator of 'climate change' based on mean surface temperature change cannot account for the main pathways of impact by which fisheries are likely to be affected by climate change, both in terms of time-lagged ecological impacts on target species (Pratchett et al., 2008; Wilson et al., 2006) or impacts on the social, economic or cultural context in which coastal communities conduct fishing (Daw et al., 2009). For example extreme events are likely to have the greatest impacts but are not reflected by mean temperature changes.

We have thus focussed on a specific impact pathway (coral bleaching) to study the exposure of fisheries systems to climate change. This allows us to utilize knowledge about the mechanics of the impact and a wider range of available data and projections to accurately predict the distribution of this impact. The disadvantage of a specific vulnerability focus is that it only captures one, of potentially many, impact pathways, and there is no guarantee that this one will be significant compared to other, more complex, unpredictable or poorly understood impacts. For example, time lags between coral mortality from a bleaching event, structural complexity collapse, and demographic changes further up the food web mean that the impacts on fisheries production take over a decade to be realized (Graham et al., 2007). The effects of coral bleaching on fisheries yields and the livelihoods of fisherfolk is difficult to tease out given this time lag and the confounding effects of overfishing and other stressors (Darling et al., 2010; McClanahan et al., 2002). Thus, unlike some other potential climate change impacts, a coral bleaching event is unlikely to be an 'extreme event' from a fisher's perspective. Likewise, given that tropical coastal communities often engage in diverse livelihood portfolios (Allison and Ellis, 2001; Cinner and Bodin, 2010), climate change impacts on agriculture may also have profound impacts on coastal livelihoods (Funk et al., 2008; Funk and Brown, 2009). Thus, what our approach gains in accuracy, it lacks in robustness to multiple poorly understood impact pathways. Single scale and single stressor studies are important to better understand specific aspects of vulnerability, while a multi-scale and multi-stressor approach help to provide a more holistic understanding of vulnerability to climate change (Bunce et al., 2010). Importantly, reducing vulnerability to one set of stressors at one point in time may in fact undermine system resilience in the future and may even constitute 'mal-adaptations' (Barnett and O'Neill, 2010; Cinner et al., 2011; Nelson et al., 2007; Turner et al., 2010).

Our sensitivity index made use of the available data in a novel and comprehensive way, but includes some considerable uncertainties that could be refined in future studies. These uncertainties relate to the mechanisms by which climate change (specifically coral bleaching) will impact on communities. The assumption in our measure of sensitivity is that fisheries are mostly supported by reef-related species that will be negatively affected by coral bleaching. This assumption is strongly supported by empirical data which shows that overall fish catch from artisanal fisheries in Papua New Guinea and Kenya have $<5\%$ of fish landed are dependent on live coral, but $\sim 60\%$ are dependent on the structural habitat that reefs provide, although the proportion varies dependent on specific gear use and local fishing intensity (Cinner et al., 2009d). This makes a strong case for our use of this sensitivity indicator, but this indicates that some key fisheries species are not found exclusively on carbonate reefs. Future studies could potentially improve this sensitivity index by including the degree to which the local fishery targets fishes dependent on live coral and the reef matrix (Cinner et al., 2009d; Pratchett et al., 2008). This would, however, be data intensive and involve information not available for this present study. Additionally, the outcomes of this analysis were, of course, influenced by the indicators that were

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used. These particular indicators were rigorously selected based on both theory and available data (McClanahan et al., 2008b). Future analyses, however, could use other indicators that look at issues such as agency and access to social safety nets.

Lastly, our cumulative metric of vulnerability was most heavily influenced by the exposure metric because it had a larger range within our sample. This larger influence of exposure led to national scale averages in Madagascar and Seychelles being similar, despite Madagascar having considerably higher sensitivity and lower adaptive capacity. Examining relative vulnerability in the region, whereby the metrics were scaled to the range of encountered values, might produce a different picture, but would be less comparable with future studies.

6. Conclusion

Coastal societies are vulnerable to a range of climate-related impacts. By using a detailed empirical study of 29 sites in five countries in east Africa, we provided the most detailed study to date on one key pathway: the impacts temperature-induced coral mortality on coral reef fisheries. Our approach provided a means to understand and visualize how key dimensions of vulnerability vary both within and among countries. For example, sites in Madagascar had an extreme range of exposure, and a moderate range of adaptive capacity. Alternatively, Kenyan sites spanned a large range of both adaptive capacity and sensitivity, but all had high levels of exposure. These different sources of vulnerability require specific types of policy actions to address. We highlight which types of actions could be used to reduce specific aspects of vulnerability at varying spatial and temporal scales.

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Appendix A. Sensitivity score

This sensitivity score builds on a 'livelihood landscape' approach to using network analysis to examine relationships between occupations (see Cinner and Bodin, 2010 for details). The sensitivity score includes three factors. The first one is simply the fraction of households being engaged in fishery related occupations, and the second is the ratio of the total number of households to the total number of occurrences of households being engage in either the fishery or non-fishery sector. The first factor accordingly ranges from 0 to 1.0. Since each household is engaged in at least one sector, and potentially in both, the ratio of the second term ranges from 0.5 to 1.0. If the number of sectors was chosen differently, the range would be different. For example, if we assume that we divide all occupations into three different sectors, the ratio would range from 0.33 to 1.0. The last factor, where ranking of occupational importance is taken into account, is designed to differentiate between cases when fishery is being ranked higher than non-fishery (and vice versa). If the fishery sector is ranked higher, the sensitivity index increases. Furthermore, if there are no linkages whatsoever, the sensitivity score will peak.

We explored two possible approaches in capturing how households ranked fisheries versus non-fisheries occupations for our sensitivity index. The reason for trying out different approaches was that we wanted to account for the effect of households being engaged in varying numbers of occupations within each sector (i.e. fisheries and non-fisheries). The first approach emphasizes the influence of multiple occupations by building on the following assumption: If, for a given household, fishing is ranked higher than, say, three other non-fishery occupations, the strength of the link going from fishery to non-fishery sector at the community scale increases by 3.0. In order to make the link strengths assessments comparable between communities of differing sizes, the values of the link strengths are later divided by the total number of households who are engaged in the sector being ranked higher (e.g. fisheries).

The second approach increases the link strength by 1.0 each time an occupation is ranked higher than the occupation that follows next after on the ranking list (assuming that the other occupation belongs to the other sector). In our previous example, the link going from fishery to non-fishery should therefore only increase by 1.0 and not 3.0. If, however, the occupation number three on the ranking list is the fishery, the link is increased by 2.0. Also, the link going from non-fishery to fishery should in this example be increased by 1.0 since there is one occurrence of a non-fishery related occupation being ranked higher than a fishery related occupation (i.e. position two and three on the ranking list). Irrespectively of the chosen approach, the value of the term will never exceed 1.0. However, the minimum value depends on the number of occupations, and how they are ranked internally, for each household. It will typically be in the range of 0.5–1.0, although it could in theory approach 0 if each household was engage in an infinite number of occupations.

In our dataset, these two approaches were correlated at Pearson's $r = 0.99$, but in other datasets with different numbers of occupations, the distinction between these two measures could be important. Although these approaches are similar, we argue that in our study, the second approach was more desirable because it reduced the effect that engagement in many different occupations would have on the last term of our sensitivity index. The number of occupations is already incorporated in our adaptive capacity metric. By choosing the latter approach in designing the last term of the sensitivity index, we attempted to reduce co-variance between the sensitivity and adaptive.

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