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SOCIAL-ECOLOGICAL VULNERABILITY OF CORAL REEF FISHERIES TO CLIMATIC SHOCKS

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SOCIAL-ECOLOGICAL VULNERABILITY OF CORAL REEF FISHERIES TO CLIMATIC SHOCKS

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PREPARATION OF THIS DOCUMENT

This circular was prepared under the project "Climate Change, Fisheries and Aquaculture: testing a suite of methods for understanding vulnerability, improving adaptability and enabling mitigation (GCP/GLO/322/NOR)". Greenhouse gas accumulation and climate change are forecast to have a wide range of impacts on fisheries and aquaculture resources through, for example, sea-level change and changing precipitation patterns, changes in sea temperature and current patterns and acidification. This analysis will help countries, partner agencies and their staff, researchers and fisheries professionals in understanding how to define and measure vulnerability within complex fisheries systems, using risks of coral reef bleaching in Kenyan reef-dependent fishing communities as an example. Ultimately, the scope of this work is to improve resilience of fisheries systems and dependent communities to multiple drivers of change including climate change and ocean acidification.

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Social-ecological vulnerability of coral reef fisheries to climatic shocks.
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ABSTRACT

This circular examines the vulnerability of coral reef social-ecological communities to one effect of climate change, coral bleaching. The objective was to develop and test in Kenya a community-level vulnerability assessment approach that incorporated both ecological and socio-economic dimensions of vulnerability in order to target and guide interventions to reduce vulnerability. In addition to a range of direct threats such as siltation, overfishing and coral disease, coral reefs are now threatened by climate change. Climate impacts on coral reefs and associated fisheries include: increasing seawater temperatures; changes in water chemistry (acidification); changes in seasonality; and increased severity and frequency of storms, which affect coral reef ecosystems as well as fisheries activities and infrastructure. Coral bleaching and associated coral mortality as a result of high seawater temperatures is one of the most striking impacts of climate change that has been observed to date. As warming trends continue, the frequency and severity of bleaching episodes are predicted to increase with potentially fundamental impacts on the world's coral reefs and on the fisheries and livelihoods that depend on them. The analysis presented in this circular combined ecological vulnerability (social exposure), social sensitivity and social adaptive capacity into an index of social-ecological vulnerability to coral bleaching. All three components of vulnerability varied across the sites and contributed to the variation in social-ecological vulnerability. Comparison over time showed that adaptive capacity and sensitivity indices increased from 2008 until 2012 owing to increases in community infrastructure and availability of credit. Disaggregated analysis of how adaptive capacity and sensitivity varied between different segments of society identified the young, migrants and those who do not participate in decision-making as having both higher sensitivity and lower adaptive capacity and, hence, as being the most vulnerable to changes in the productivity of reef fisheries.

CONTENTS

ACKNOWLEDGEMENTS

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ABBREVIATIONS AND ACRONYMS

ANOVA	analysis of variance
BMU	beach management unit
CV	coefficient of variation
ENSO	El Niño–Southern Oscillation
IPCC	Intergovernmental Panel on Climate Change
MSL	material style of life
PCA	principal component analysis

EXECUTIVE SUMMARY

1. Healthy, functional reefs are important for coastal livelihood sustainability.
Coral reefs and their associated fisheries provide nutrition and livelihoods for millions of people, particularly in developing countries. They also provide cultural and regulating ecosystem services such as coastal protection and support for tourism.

2. Climate change can affect the contributions that reefs make to livelihoods.
In addition to a range of direct threats such as siltation, overfishing and coral disease, coral reefs are now threatened by climate change. Climate impacts on coral reefs and associated fisheries include: increasing air and seawater temperatures; changes in water chemistry (acidification); changes in seasonality; and increased severity and frequency of storms, which affect coral reef ecosystems as well as fisheries activities and infrastructure. Coral bleaching and associated coral mortality as a result of high seawater temperatures is one of the most striking impacts of climate change that has been observed to date. Periods of high water temperatures at sites across the Indian Ocean in the last 15 years have caused corals to "bleach" (lose their symbiotic algae) and die en masse, radically altering habitat structure and fish communities. As warming trends continue, the frequency and severity of bleaching episodes are predicted to increase with potentially fundamental impacts on the world's coral reefs and on the fisheries and livelihoods that depend on them.

3. Understanding climate impacts and identifying vulnerable places, people and ecosystems helps to guide investments in adaptation.
Climate change impacts on reefs and their fisheries may be inevitable if current trends in global emissions continue. The key scientific challenge is to understand how these impacts will be distributed, and the ways in which reef-dependent people will be affected and can withstand impacts. This "vulnerability" is a combination of the degree of exposure to an impact, the sensitivity of ecosystems or communities to that impact, and the capacity of people to adapt by perceiving, mitigating and recovering from impacts, and taking advantage of new opportunities created by change. As resources become available for developing countries to adapt to climate impacts, there is a need for tools to guide the where and how funds should be spent to mitigate most efficiently the most negative impacts of climate change.

4. Aims and objectives: Developing and testing (in Kenya) a community-level vulnerability assessment approach that incorporates both ecological and socio-economic dimensions of vulnerability, and can be used to target and guide interventions to reduce vulnerability.
This study aims to develop and test community-level indicators of vulnerability that incorporate detailed information on both ecological and social characteristics of different locations. By comparing the vulnerability of reef fisheries to coral bleaching at different locations along the Kenyan coast, the study s how different components of vulnerability are spatially distributed and how a linked social-ecological concept of vulnerability can be practically applied using empirical data.

5. Methodology development: vulnerability analysis framework.
Following previous climate impact research, vulnerability is conceptualized as a function of the exposure of a system to a given impact, the sensitivity of the system to that impact, and the adaptive capacity of that system to recover from impacts and evolve to mitigate future impacts and take advantage of new opportunities. This study advances the dominant model by considering how ecological and social elements of exposure, sensitivity, recovery potential and adaptive capacity are linked. In essence, the combination of ecological exposure (e.g. predicted levels of bleaching), ecological sensitivity (e.g. the degree to which coral species present are susceptible to bleaching) and recovery potential (e.g. factors affecting recruitment of new young corals) determines the ecological vulnerability of a site. This ecological vulnerability can be considered the exposure experienced by the social system. Social

vulnerability is then understood as a combination of this exposure plus social susceptibility (e.g. how reliant a community is on coral reef resources) and social adaptive capacity (e.g. resources and conditions that facilitate development of alternative livelihoods).

6. Testing the methodology: identifying indicators and designing a survey to measure them.
The study built on previous research in the region to develop indicators for the different components of social-ecological vulnerability. New empirical data on these indicators were then collected at 12 sites along the Kenyan coast by: (i) applying multivariate models of coral bleaching impact to global oceanographic data to determine exposure; (ii) conducting underwater ecological surveys of coral, fish, habitat and algal production and grazing as indicators of ecological sensitivity to, and recovery potential from, bleaching in both fished and protected areas; and (iii) carrying out household and community-level surveys of adjacent communities, interviewing key informants and obtaining detailed fisheries data on gear types and catch composition to derive indicators of social sensitivity to fisheries impacts and adaptive capacity.

The collection and analysis of these data under the social-ecological vulnerability framework allowed an examination to be made of how components of vulnerability varied between different locations, as well as between different types of fishing stakeholders. The collected data were compatible with previous research, so allowing spatial and temporal comparisons with previous surveys to indicate how sensitivity and adaptive capacity can evolve over time.

7. Key findings of the ecological vulnerability analysis.
The ecological sites covered a range of conditions in terms of coral abundance, fish biomass and herbivore grazing diversity, and rates of algal production and grazing in fished sites, marine reserves and small community-based closures (called tengefus). The three components of ecological vulnerability did not seem to be related, suggesting that they are independent aspects of ecological vulnerability. Tengefus and no-take reserves were associated with lower ecological vulnerability owing to low sensitivity and high recovery potential, despite medium to high exposure. Overall, marine parks had lower vulnerabilities than did the small community-based closures and open fished areas.

8. Key findings of the socio-economic analysis.
Sensitivity was indicated by the occupational composition of each community, including the importance of fishing relative to other occupations, as well as the susceptibility of different types of fishing gear to the effects of coral bleaching on the fish species targeted by each. Lines, nets and spearguns targeted species that show a positive response to coral bleaching (according to a database of observed impacts of bleaching on fish abundance), while beach seines and traps targeted more species negatively affected by bleaching. These gear sensitivities should be considered preliminary as there are limited data on the response of some key species to coral bleaching, responses to climate impacts on seagrasses are not accounted for, and the analysis is based on a static picture of catch composition that may be affected by the heavily exploited status of the fishery and thus should not be expected to apply in other reef fisheries.

Social adaptive capacity as indicated by, in particular, access to credit, debt, human agency, capacity to change, social capital, community infrastructure, and material style of life varied considerably among the communities, suggesting relative strengths and weaknesses in terms of adaptive capacity. The different components of adaptive capacity were not correlated; for example, sites with better infrastructure and a higher material style of life had lower occupational multiplicity.

9. Key findings of the integrated analysis.
Ecological vulnerability (social exposure), social sensitivity and social adaptive capacity were compared across the study sites and combined into an index of social-ecological vulnerability. All three components of vulnerability varied across the sites and contributed to the variation in social ecological vulnerability. Comparison over time showed that adaptive capacity and sensitivity indices increased from 2008 until

2012 owing to increases in community infrastructure and availability of credit. Disaggregated analysis of how adaptive capacity and sensitivity varied between different segments of society identified the young, migrants and those who do not participate in decision-making as having both higher sensitivity and lower adaptive capacity and, hence, as being the most vulnerable to changes in reef fisheries productivity.

10. Identification of limitations and gaps, and recommendations for future work.
This study has advanced the application of climate-change impact and adaptation theory to empirical data and demonstrated a method to derive a quantitative social-ecological vulnerability index. While adaptive capacity indicators are thought to be relatively generic to a range of impacts, indicators of exposure and sensitivity are limited in scope to bleaching impacts on fish production. Other key caveats around the vulnerability index values include the use of current conditions to predict future sensitivity and adaptive capacity, lack of consideration of positive impacts such as novel possibilities for exploitation, and uncertainties as to whether all relevant components of adaptive capacity have been captured, are well represented and are appropriately weighted. These omissions and shortcomings can be overcome by further research.

11. Key recommendations on wider application of vulnerability analysis methodology.
The approach outlined here could be adapted and expanded to other areas and to conduct vulnerability analysis for other climate change impacts to guide adaptation policy. These would require development of new indicators for ecological exposure, sensitivity and recovery potential and for social sensitivity. Given the uncertainties around adaptation processes, any vulnerability analysis such as this should be accompanied by caveats and sources of uncertainty, which should be carefully considered when they are used to guide adaptation policy.

1. INTRODUCTION

Millions of people depend on the ecosystem goods and services provided by coral reefs. Coral reefs are particularly important for fishing and tourism, but they also contribute to coastal protection and are associated with high aesthetic values and, in places, high cultural values. Although coral reefs are one of the most productive and biologically diverse aquatic environments on Earth, they are also one of the most ecologically sensitive (Paulay, 1997; Reaka-Kudla, 1997) and the people who depend on them for food and income are among the world's poorest (Donner and Potere, 2007). The current era of rapid anthropogenic-driven climate change has the potential to undermine coral-reef-associated livelihoods. The extent to which people's livelihoods are vulnerable to the impacts of climate change is dependent on: their exposure to climate impacts (i.e. if impacts are felt in their location); their sensitivity (i.e. the extent to which their livelihood is affected by an impact); and their capacity to adapt to the likely impacts (Adger, 2006).

Climate change is emerging as a key threat to coral reefs (Hughes *et al.*, 2003) and marine fisheries more broadly (Allison *et al.*, 2009; Cheung *et al.*, 2010). Climate change is altering long-term mean environmental conditions (air and sea-surface temperatures, annual rainfall, and sea level), multiannual cycles and seasonality (e.g. El Niño–Southern Oscillation [ENSO] events, and monsoon weather) and short-term variability, including the frequency and severity of extreme climate events (typhoons, cyclones, hurricanes, floods and droughts). The increasing frequency and/or intensity of extreme climatic events can affect fish habitat, productivity or distribution, as well as have direct impacts on fishing operations and the physical infrastructure of coastal communities. Extreme events such as high-intensity cyclones and increased sea surface temperatures can have profound impacts on coral reef ecosystems and the communities that depend on them. For example, coral bleaching and mortality resulting from elevated sea temperature events may alter the goods and services that coral reefs provide by reducing reef fisheries productivity or changing the species compositions of fish that people harvest from reefs (Graham *et al.*, 2007; Hoegh-Guldberg, 1999; Hughes *et al.*, 2003; MacNeil and Graham, 2010; Westmacott *et al.*, 2000). In turn, people dependent on reef goods and services may need to adapt their resource-use patterns to maintain the flow of goods and services.

A question of critical importance to resource users and policy-makers is how reef-dependent societies are likely to be affected by climate variability and change and whether they have the capacity to adapt to these impacts. The answer is complicated because the impacts of climate change are not evenly spread. There is considerable heterogeneity in: (i) places that experience climate-change-related events such as bleaching; (ii) the ways that coral reef ecosystems are affected by, and can recover from, these impacts; (iii) the ways that societies and individuals are affected by these changes; and (iv) the capacity of people to cope with and adapt to these changes.

An increasingly critical aspect of sustaining coral reefs and the livelihoods of dependent people is understanding the vulnerability of particular reefs and their associated human communities to climate change (Folke, 2006; McClanahan *et al.*, 2009). Vulnerability, in the context of social and environmental change, is defined as the state of susceptibility to harm from perturbations (Adger, 2006). Vulnerability to environmental change varies spatially and temporally, and even varies among different people within a society (for example, the poor or migrants are often considered more vulnerable [Bene, 2009]). Knowledge about how vulnerable a system is, and about the specific conditions that make it vulnerable, can help to provide a foundation for developing actions that minimize the impacts of environmental change on people.

The conceptual model of vulnerability to climate change promoted by the Intergovernmental Panel on Climate Change (IPCC) (2007) and widely adopted for ecological vulnerability assessments (Bell, Johnson and Hobday, 2011) provides a basis for operationalizing and assessing the vulnerability of linked social and ecological systems. Assessments of vulnerability to environmental change typically examine three inter-related concepts: (i) exposure; (ii) sensitivity; and (iii) adaptive capacity (Box 1; Adger, 2006; Adger, 2000; Adger and Vincent, 2005; Folke, 2006; Gallopín, 2006; Kelly and Adger, 2000; Smit and Wandel, 2006).

Exposure is the degree to which a system is stressed by climate, such as the magnitude, frequency and duration of a climatic event such as temperature anomalies or extreme weather events (Adger, 2006; Cutter, 1996). In a practical sense, exposure is the extent to which a region, resource or community experiences change (IPCC, 2007). For fishing communities, exposure would capture how much the resource they depend on will be affected by environmental change. In tropical reef fisheries, exposure can vary depending on factors such as oceanographic conditions, prevailing winds, and latitude, which increase the likelihood of being affected by events such as cyclones or coral bleaching (Maina, McClanahan and Venus, 2008). For a coral reef ecosystem, exposure to higher-than-normal sea surface temperatures, for example, can be a major driver of mass coral bleaching and high coral mortality. Although, for climate change, exposure is often ecological and environmental, exposure could also be the extent to which a region, resource or community experiences climate-related policies. For example, some places are attempting to build ecological resilience in coral reefs by implementing large, no-take marine protected areas. These may reduce the amount of fishing grounds available to fishers, thus creating exposure in the social system.

Sensitivity, in the context of environmental change, is the susceptibility to harm of a defined component of the system resulting from exposure to stresses (Adger, 2006). The sensitivity of social systems depends on economic, political, cultural and institutional factors that allow for buffering of change. For example, social systems are more likely to be sensitive to climate change if they are highly dependent on a climate-vulnerable natural resource. These factors can confound (or ameliorate) the social and economic effects of climate exposure.

Adaptive capacity is a latent characteristic that reflects people’s ability to anticipate and respond to changes, and to minimize, cope with and recover from the consequences of change (Adger and Vincent, 2005). Adaptive capacity refers specifically to the preconditions that enable adaptation to change (Nelson, Adger and Brown, 2007). For example, people with low adaptive capacity may have difficulty adapting to change or taking advantage of the opportunities created by changes in the availability of ecosystem goods and services stimulated by climate change or changes in management.

BOX 1

What are the components of vulnerability?

Vulnerability generally comprises three components:

- **Exposure** (E) of the system to changes. For example, this could be the magnitude, duration, or likelihood of an extreme event affecting a particular location.
- **Sensitivity** (S) of the system to these changes.
- **Adaptive capacity** (AC) of the system, which captures the ability of the system to deal with change or tak**e advantage** of the opportunities arising from change.

The above examples illustrate the three dimensions of social vulnerability, but they also have ecological components. For example, the sensitivity of ecological systems to climate change can include physiological tolerances to change and/or variability in physical and chemical conditions (i.e. temperature, pH, etc.). Examples include certain corals that are highly sensitive to increases in sea temperatures, or harvested crab species that are sensitive to drought periods. A trend is emerging of integrating studies on social vulnerability to environmental change with a new multidisciplinary literature on linked social-ecological systems (Adger *et al.*, 2005; Folke, 2006; Gallopín, 2006; Nelson, Adger and Brown, 2007). The central idea behind linked or coupled social-ecological systems is that human actions and social structures profoundly influence ecological dynamics, and vice versa, to such a degree that distinctions between the two are artificial (Adger, 2006; Hughes *et al.*, 2005). Previously published applications of the "IPCC model" have implicitly integrated ecological and social vulnerability by using the sensitivity term to represent the response of the ecological components of the system to changes in climate, and the adaptive capacity term to represent the response of the social system to changes in the biophysical system (Allison *et al.*, 2009).

This study presents an application of the commonly used IPCC conceptual framework of vulnerability that explicitly links social-ecological systems. The application allows assessments of sensitivity and adaptive capacity to be undertaken for both social and ecological subsystems. The modification entails linking two vulnerability models: one represents the components of ecological vulnerability to exposure to climate change, while the other represents social vulnerability to changes in the ecological system (Figure 1). The potential impact of climate change on ecological systems results from the physical exposure to climatic stressors combined with the sensitivity of those ecosystems, due for example to the species inhabiting that ecosystem, to those stressors. Whether these potential impacts are fully experienced in the long term depends on the potential of the ecosystem to recover its basic structure and function in response to impacts. Thus, the combination of exposure, sensitivity and recovery potential result in the degree to which climate change will affect the continued supply of ecosystem goods and services. In turn, this ecological vulnerability represents the exposure of the socio-economic subsystem to climate threats. The overall social-ecological vulnerability is then a result of the sensitivity of socio-economic systems to ecological impacts, and the adaptive capacity of the society to adapt to such impacts. This can be explained in the following equation:

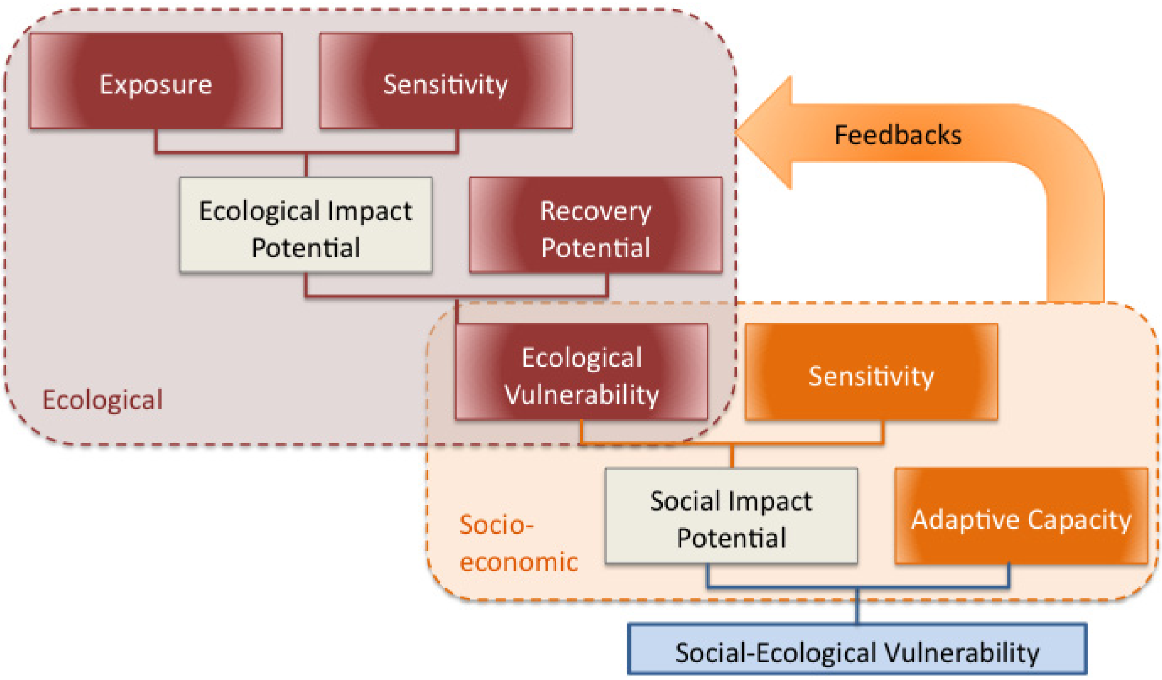
$V_{S.E} = E_s + S_S - AC_S$

where $E_S = V_E = E_E + S_E - AC_E$

and $_S$ = social, $_E$ = ecological

Given the profound impacts that climate change may have on coral reef ecosystems and the importance of these ecosystems to food and livelihoods, understanding how communities may be affected and whether they are likely to adapt to these changes are issues of critical importance. To date, few studies have specifically examined how vulnerable coastal communities are to climate-related changes in coral reef ecosystems (Marshall and Marshall, 2007; McClanahan *et al.*, 2008) and few studies have attempted to integrate both social and ecological dimensions of vulnerability (Cinner *et al.*, 2012a; McClanahan *et al.*, 2009).

FIGURE 1
Heuristic framework for linked social-ecological vulnerability



Notes: In the ecological domain, exposure and sensitivity create impact potential. The impact potential and the recovery potential together form the ecological vulnerability, or exposure, in the social domain. This ecological vulnerability combined with the sensitivity of people forms the impact potential for society. The social adaptive capacity and the impact potential together create social-ecological vulnerability.
Source: Adapted from Marshall *et al.* (2010).

The aim of this project is to develop and test a methodology to assess the social-ecological vulnerability of coral-reef-fishing-based communities. The project is focused on assessing vulnerability to climate change of small-scale fisheries that operate in coral reef systems and provide information for the development of strategies that might minimize vulnerability. However, the vulnerability assessment, framework and survey that are developed in this project are adaptable to other kinds of fishery or natural-resource-dependent systems. Similarly, they could be adapted to explore vulnerability to other kinds of environmental, economic or social stresses.

Specifically, the objectives of the project are:

1) DEVELOP METRICS FOR SOCIAL-ECOLOGICAL VULNERABILITY
In meeting the first objective, this study show how vulnerability can be assessed across ecological and social systems using the nested vulnerability framework (Figure 1). It improves upon previously developed metrics of vulnerability by referring to a specific case study in the Kenyan region that integrates information about the differential sensitivity of specific fishing gears and ecological conditions. Coral reef fishers can often use a range of fishing gear types, each of which targets specific sizes and species of fish. These differences in selectivity can be used to examine how sensitive certain gear types are to changes in coral reef ecosystems (Cinner *et al.*, 2009a). This study shows how a sensitivity index for each gear type can be created using existing species-level data on catch composition. In addition, it expands the ecological dimensions of vulnerability by developing several novel indicators of sensitivity and recovery potential to climate disturbances.

2) EXAMINE HOW SENSITIVITY AND ADAPTIVE CAPACITY VARY OVER TIME AND AMONG ACTORS

It is often important to understand the temporal aspects of vulnerability in order to appreciate the broader nature of vulnerability. In addressing the second objective, data from objective 1 are combined with an identical survey of the same sites conducted in Kenya in 2008, which allows the dynamics and stability of each dimension of social vulnerability to be examined. The study compares key components of social vulnerability over time and among different user groups and highlights key aspects that reef managers should be aware of.

The wider purpose of the research is to use the insights gained from applying this framework and the lessons learned from piloting the methodology to inform the development of tools for future local-level vulnerability analyses in small-scale fisheries systems.

SECTION SUMMARY

Understanding the ways in which people and communities are vulnerable can help to provide policy-makers, practitioners and stakeholders with the information necessary to facilitate adaptation planning. However, there have been few vulnerability studies specific to communities that are dependent on coral reef resources, and even fewer that integrate social and ecological data. This section has shown how it is possible to adopt the widely used IPCC vulnerability framework to incorporate both social and ecological aspects of vulnerability.

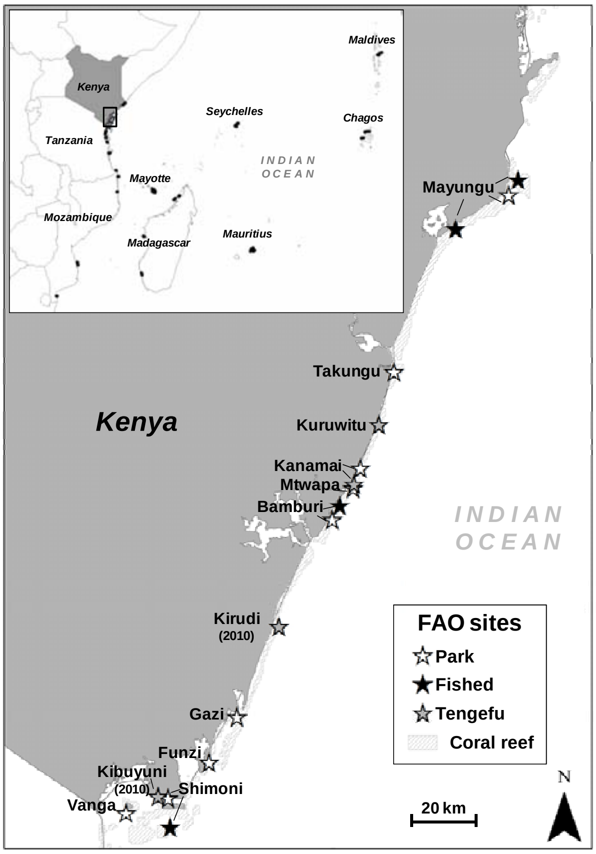
2. METHODS

Vulnerability assessments provide information about the nature and magnitudes of impacts expected from climate change, and inform decisions about the form and urgency of adaptation activities and strategies. This chapter presents an approach for assessing social-ecological vulnerability based on the linked exposure–sensitivity–adaptive capacity framework introduced in Figure 1. This approach provides the foundations for developing novel metrics of vulnerability and helps to identify the sources of variability within vulnerability metrics.

The linked social-ecological vulnerability assessment framework used was developed as an outcome of a previous project, and is here extended, modified and tested for the first time by applying it to a comparative study based on a total of 12 coastal communities and their associated fishing grounds along the coast of Kenya (Figure 2). As part of this project, social and ecological vulnerability assessments of ten communities along the Kenyan coast were conducted in 2012. Eight of these areas had previously been studied in 2008 as part of a larger project exploring fisheries comanagement institutions. The 2008 study surveyed ten sites that had been randomly sampled from a list of pilot comanagement sites (Cinner *et al.*, 2012b). However, pirate activity near Somalia prevented the 2012 project from re-visiting all ten sites surveyed in 2008. In addition, two coastal communities were also studied in 2010 as part of a separate project. Together, these data form the basis for this report.

STUDY SITES

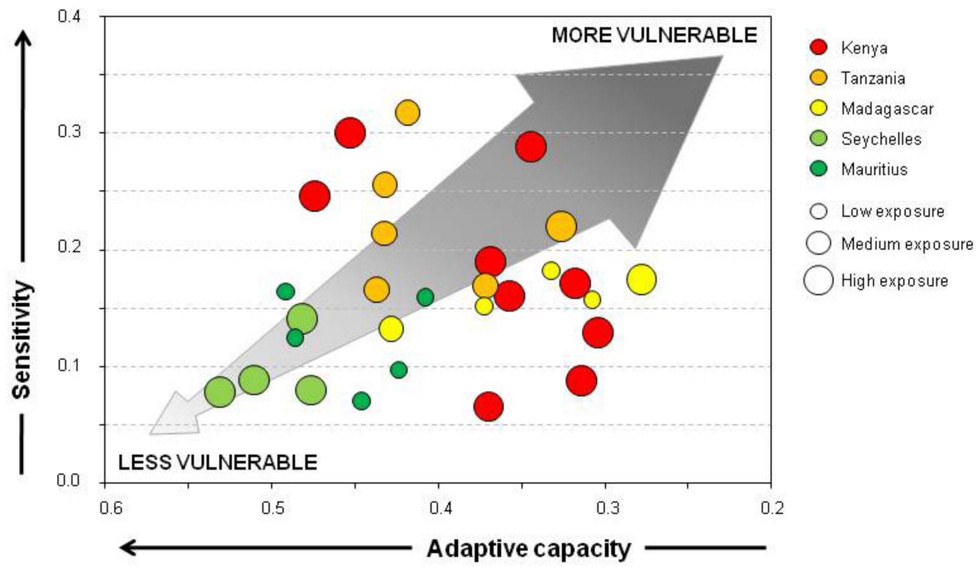
FIGURE 2
Map of study sites



Kenya presents an interesting case study to evaluate social-ecological vulnerability for four key reasons. First, in a previous comparison of vulnerability across five Western Indian Ocean countries, Kenyan sites were the most vulnerable overall (Cinner *et al.*, 2012a), but there was considerable spread in both sensitivity and adaptive capacity (Figure 3). Indeed, some Kenyan sites had adaptive capacity scores greater than or equal to some sites in the more affluent nations of Mauritius and Seychelles, but other sites had adaptive capacity scores lower than most sites in the poorer nation of Madagascar. Similarly, Kenyan sites spanned the range of sensitivity values in the region. Thus, much of the variability encountered in the region is contained within Kenya.

Second, Kenya is at the frontline of climate change – its reefs have been severely affected by the 1998 El Niño-related coral-bleaching event. Temperature records suggest that the scale of this temperature anomaly was unprecedented (Nakamura *et al.*, 2011; Saji *et al.*, 1999) and resulted in high levels of coral mortality in the northern Indian Ocean, similar to the wealthier countries of Seychelles and Maldives (Ateweberhan *et al.*, 2011). Consequently, extreme climate events are a current reality rather than a distant possibility. Coral mortality from temperature-induced coral bleaching is used here as an indicator of climate threat and this study develops the vulnerability indicators specific to this.

FIGURE 3
Plot of the vulnerability of coastal communities to the impacts of coral bleaching on fisheries

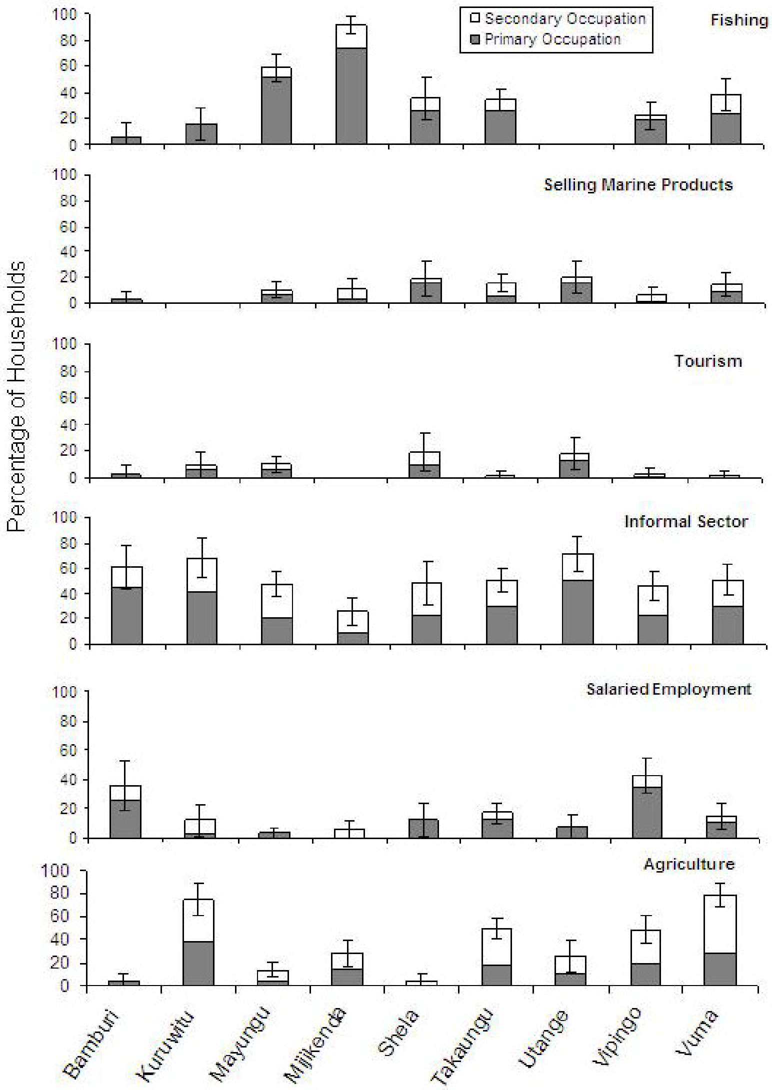


Notes: Adaptive capacity (x-axis; note values reversed so high adaptive capacity is on the left) is plotted against Sensitivity (y-axis,) such that more vulnerable communities are in the top right of the graph and less vulnerable communities in the bottom left. These two dimensions of vulnerability can 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 are represented as the lowest, middle and highest third rather than scaled to actual site values. Colours 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 = United Republic of Tanzania, red = Kenya.
Source: From Cinner *et al.* (2012a).

Third, people in coastal Kenya are heavily dependent on natural resources for their livelihoods (Figure 4). As in many coastal communities around the world, the livelihoods of coastal peoples are diverse and integrate a range of livelihood activities. However, fishing, selling marine products, tourism and agriculture form a significant proportion of the local coastal economy (Cinner and Bodin, 2010), and are all very likely to be affected by climate change.

Last, Kenya has a range of marine resource governance regimes, ranging from large national marine parks enforced by paramilitary organizations to largely open-access areas where regular use of destructive beach seine nets damages marine habitats. In between are community controlled comanaged areas called beach management units (BMUs) (Cinner *et al.*, 2012c; Cinner *et al.*, 2012b). In recent years, BMUs have started developing community-based fishery closures. Together, this governance spectrum presents an opportunity to examine whether and how different governance regimes have the potential to influence vulnerability.

FIGURE 4
Percentage of households participating in select occupational sectors, highlighting the percentage of households that rank them as the primary occupation



Source: Adapted from Cinner and Bodin (2010).

KENYA'S BIOPHYSICAL ENVIRONMENT

The shoreline of most of southern Kenya is fronted by a fringing reef that lies between a few hundred metres to a few kilometres off shore. The reef lagoon can contain coral reefs, seagrass, and mangrove habitats. The physical environment is highly seasonal, with a strong southeast monsoon from May to

September (McClanahan, 1988), creating conditions that promote heavy use of the near-shore environment (McClanahan, Hicks and Darling, 2008). Consequently, most fishing is focused on the near-shore habitats of creeks, reef lagoons, and shallow reef and seagrass environments. The calmer northeast monsoon allows easier access to areas farther offshore. Kenya also has a high tidal range of 4 m and many fishers follow the tidal cycle and use this tidal power to transport their small boats. A combination of the rough conditions beyond the reef and lower ecological productivity results in fishing effort that is focused close to shore.

The biophysical environment of the Kenyan coast has been undergoing changes over the past 100 years that are best explained by climate change or global warming (McClanahan and Cinner, 2012). Specifically, these are a rise in seawater temperatures (Cole *et al.*, 2000), greater intensity of the oceanographic oscillation, and changes in seasonality (Nakamura *et al.*, 2011). In the past 50 years, seawater temperatures have risen by 0.5 °C and, while this rise may have social-ecological consequences, the most noticeable impacts are the oceanographic oscillations of the El Niño and Indian Ocean Dipoles that oscillate on a 2–8-year cycle and can cause rapid rises in seawater temperatures over short periods. These two oscillations interact and, when the two warm phases coincide, the seawater can rise far above mean temperatures and kill corals and other temperature-sensitive organisms. This synchronicity occurred in 1998 and killed more than half of the coral in the Western Indian Ocean (Ateweberhan *et al.*, 2011). The intensity and frequency of the Indian Ocean Dipole has been increasing since the 1920s and this is changing seasonality, such that the short rains are becoming stronger than the long rains, and the short-rain weather is becoming more variable over time. The highest fish catches are associated with cold-water conditions (Jury, McClanahan and Maina, 2010), and global models suggest that warm water is expected to reduce tropical fish catches in many areas, including Kenya (Cheung *et al.*, 2010).

ECOLOGICAL SAMPLING

While the biophysical environment of Kenya is not necessarily representative of other coral reef systems around the world, this study describes how exposure, sensitivity, potential impacts and recovery potential were sampled so others can follow the same techniques to assess vulnerability of the ecological components of the reef system. The methods are technical and it is probable that a high level of expertise (postgraduate at least) will be required to lead and conduct scientific ecological surveys of this type. Therefore, the method is suitable for use by national university or research organizational personnel but is not intended as a tool to be used independently by local communities or local planning authorities.

The project surveyed 17 ecological sites associated with the 10 coastal communities, including heavily fished reefs; reefs within small, recently established community comanaged fisheries closures (“tengefus” in Swahili); and larger, well-established no-take national marine parks managed by the Kenya Wildlife Service. All reef surveys were conducted in shallow back-reef flat habitat or shallow reef slope (< 4 m). Surveys were conducted in 2011 and 2012, with the exception of the Kisite Marine National Park, which was surveyed in 2009 (marked as Shimoni Park in Figure 2).

At each site, standard underwater survey methods were used to evaluate coral reef benthic habitat and associated reef fish communities. Coral reef habitat was quantified using 10-m line intercept transects (n = 4–9 transects per site). The lengths of major benthic components (hard coral, soft coral, turf algae, macroalgae, and crustose coralline algae) underlying each transect line were measured to the nearest centimetre. Percentage cover was calculated as the sum of the lengths of each benthic group divided by the total transect length. Hard corals were identified to genus, and the genus *Porites* was subdivided into three distinct morphological groups: massive *Porites*, branching *Porites* and a subgenus *Synaraea* (*Porites rus*).

Hard coral communities were also evaluated using roving observer surveys to quantify coral genera richness and community structure over a larger reef area. On each survey, an observer haphazardly delineated about twenty quadrats of 2 m^2 and within each quadrat identified coral colonies to genus and scored each colony for observed bleaching intensity and mortality on a six-point scale (c_0 = normal, c_1 = pale live coral, c_2 = 0–20 percent, c_3 = 20–50 percent, c_4 = 50–80 percent, c_5 = 80–100 percent of the live coral surface area fully bleached, and c_6 = recently dead). Estimates of bleaching occurrence and the relative abundance of hard coral genera were used to estimate the bleaching susceptibility of the coral community (see section Ecological Indicators below).

Reef fish communities were surveyed using 2–4 replicate 5 × 100 m belt transects at each site. Individuals were identified to family and estimated into 10-cm size class bins. Wet weight biomass per family was estimated from length–weight correlations established from measurements of the common species in each family taken at local fish landing sites in Kenya (McClanahan and Kaunda-Arara, 1996). Total reef fish biomass was calculated as the sum of family wet weights on each transect. species richness and abundances of the fish community were also estimated from the number of observed species in four species families (Acanthuridae, Chaetodontidae, Labridae and Scaridae). Species richness estimates were then standardized and expressed as the number of species per 500 m^2. This method to survey reef fish species richness has been used in other studies and it is expected to be a useful proxy for the total number of reef fish species present (Allen and Werner, 2002).

ECOLOGICAL INDICATORS OF VULNERABILITY

A set of indicators for ecological vulnerability were developed to explain key aspects of the exposure, sensitivity and recovery potential of coral reef ecosystems to the impacts of climate-change-associated coral bleaching (Table 1 and Box 2).

TABLE 1
Ecological indicators of sensitivity and recovery potential

Ecological sensitivity indicators	**Statement of evidence**	**Weight of scientific evidence (–5 to 5)**
Coral		
Coral bleaching susceptibility	Some species (e.g. branching or plating corals) are often severely affected by disturbance, and a high abundance of these species confers higher sensitivity.	4.07
Fish		
Fish bleaching susceptibility	Certain fish species are more heavily affected by disturbance, and a high abundance of these species confers higher sensitivity.	3.2
Recovery potential indicators		
Autotrophs/Corals		
Coral cover	Coral cover is linked to increased resilience and recovery but most field studies showing no correlation between coral cover pre- or post-disturbance with recovery rates.	2.27
Coral to macroalgae cover	Macroalgae is a significant factor limiting the recovery of corals following disturbance by increasing competition for benthic substrate, allelopathy and by trapping sediment that smothers coral recruits.	3.37
Calcifying to non-calcifying cover	Calcifying organisms are important for reef framework (e.g. processes of settlement, recruitment and cementation of reef structure), and more calcifying organisms relative to non-calcifying organisms are expected to increase or accelerate recovery following disturbances. However, the interactive effects of settlement induction, competition and increased predation make the influence unclear.	1
Coral size distribution	There is scientific evidence that evenness across size classes increases recovery. An even distribution across size classes indicates a recovering community of coral recruits, juveniles and adult colonies, whereas the under-representation of juvenile colonies suggests recruitment failure and a suppressed recovery rate. Moreover, the lack of large adult coral colonies may limit spawning stock and indicate environmental stress that has caused partial colony mortality and fragmentation.	2.5
Coral richness	Coral richness is expected to promote recovery; however; there is limited evidence that coral diversity promotes recovery following disturbance.	2.5
Heterotroph/Fish		
Fish biomass	Stock, potential growth, ecological metabolism.	4.5

Ecological sensitivity indicators	Statement of evidence	Weight of scientific evidence (–5 to 5)
Herbivore grazing rate relative to algal production	Most studies have linked increased herbivory to reduced macroalgal cover and an increase in coral recruitment despite higher corallivory. One study has gone further and shown that increased herbivore biomass led to a reversal in the reef trajectory from one of coral decline to coral recovery. Relative importance of fish and urchins varies geographically and with fishing intensity.	3.32
Fish species richness	Species richness is often used as a proxy for functional redundancy and is expected to promote ecological recovery by avoiding undesired ecological states.	3.5
Substrate complexity (rugosity)	Evidence that habitat complexity promotes recovery for corals occurs at small-scale sediment tiles but has not been scaled up. There is good evidence that habitat complexity promotes refuge and recovery for fish	1.52
Fish size distribution	Large individuals in an assemblage indicate more even size-spectra and can increase fecundity to promote recovery of fish communities.	4
Herbivore functional diversity	Experimental evidence indicates that the presence of a diverse guild and functional groups of herbivores (reef fishes, sea urchins) can enhance coral recovery.	2.46

Note: Weight of scientific evidence examines the consistency and type of evidence for each component, following the method of McClanahan *et al.* (2012).

Ecological exposure

Ecological exposure to coral bleaching was described by a multivariate global model of temperature, light, currents, tidal variation, chlorophyll and water quality to quantify important oceanographic conditions used to predict climate change and coral bleaching impacts (Maina *et al.*, 2011; Maina *et al.*, 2008). The model evaluated the relationships between the above oceanographic factors and relationships to coral bleaching based on reported intensity of bleaching from observations available in ReefBase (2008). Each variable was weighted by the strength of the oceanographic-factor-bleaching relationships, and all factors summed and normalized in order to obtain a site-specific exposure or index of bleaching stress. Higher exposure values indicate environmental conditions that are more likely to result in thermal stress and subsequent coral bleaching, while lower values indicate sites that are less likely to experience thermal stress and coral bleaching.

Ecological sensitivity

The sensitivity of a site to coral bleaching was estimated using two indicators: the susceptibility of the coral community to bleaching; and susceptibility of the fish community to population declines associated with coral habitat loss from bleaching (Table 1). Coral bleaching susceptibility was estimated from the coral community structure estimated on roving observer surveys, weighted by the regional taxa-specific bleaching sensitivity of each genus (McClanahan *et al.*, 2007; McClanahan *et al.*, 2005). The bleaching response of each genus in the Western Indian Ocean was calculated from 141 surveys (n = 48 798 coral colonies) that occurred during bleaching events (i.e. where > 10 percent of the coral colonies at a site displayed bleaching) at 125 sites in 10 countries (the Comoros, Kenya, Madagascar, Maldives, Mauritius, Mayotte, Mozambique, Réunion, Seychelles, South Africa and the United Republic of Tanzania) over seven years (1998, 2004, 2005, 2007–2010). Bleaching susceptibility of coral communities was estimated at each site based on the relative abundance of coral taxa and their observed bleaching response:

$$\text{Coral bleaching susceptibility} = \sum_{i}^{n}(RA_i \times BR_i)$$

Where *RA* is the relative abundance of each coral taxon, *i*, multiplied by its taxon-specific bleaching response, BR_i, and then summed across all observed taxa at a site. Reef fish susceptibility at each site was similar to the coral susceptibility index, in that the relative abundance of each species, *j*, was multiplied by a taxon-specific climate vulnerability index (V_{climate}) and then summed across all species observed at a site to provide a site-level estimate of the vulnerability of the reef fish assemblage to habitat loss associated with coral bleaching.

$$\text{Fish susceptibility to bleaching} = \sum_{j}^{n} (RA_j \times V_{\text{climate}, j})$$

Climate vulnerability for reef fishes was assessed by Graham *et al.* (2011) from four variables that are known to relate to fish population declines following coral bleaching and mortality: diet specialization, habitat specialization, recruitment specialization to live coral, and body size.

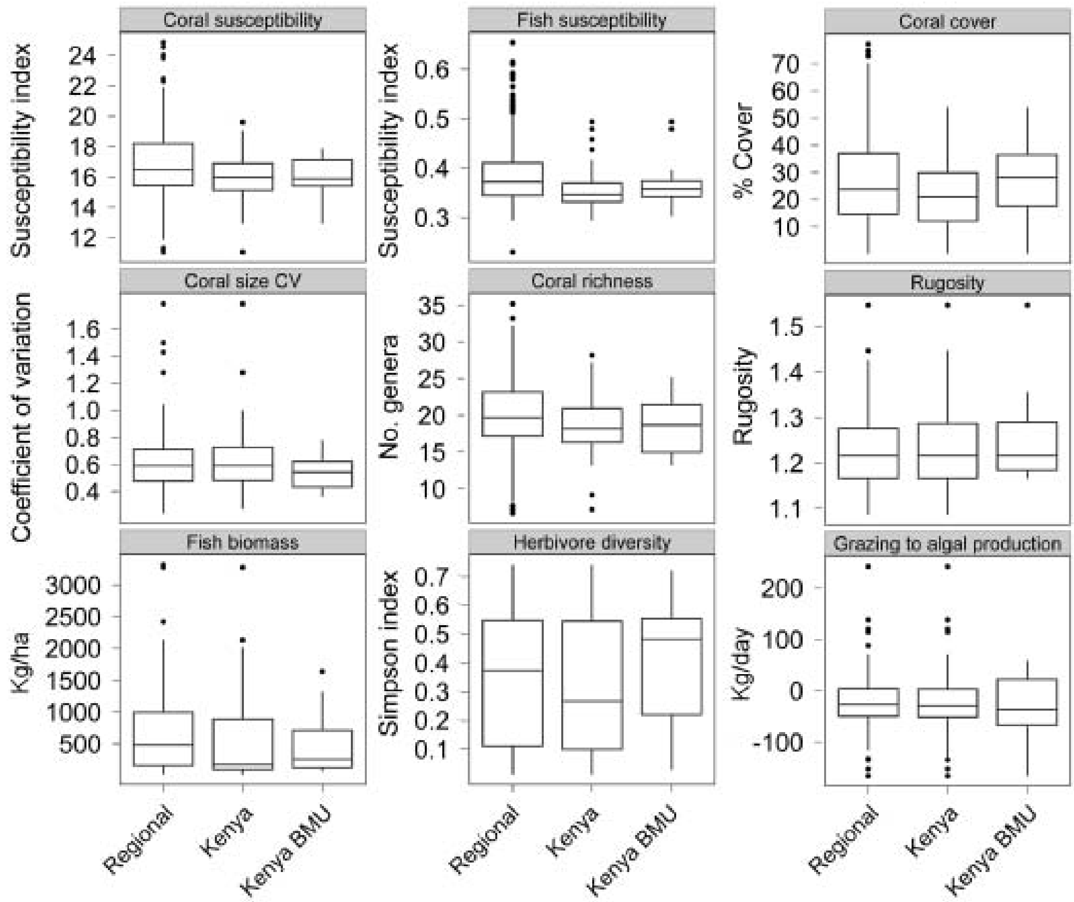
Ecological recovery potential

Seven ecological indicators were identified to estimate the potential for recovery at each site (Table 1). Hard coral cover was estimated as the average percentage cover of live coral from replicate transects at each site. Coral to macroalgae cover was calculated as the ratio of hard coral cover to the combined cover of fleshy macroalgae and turf algae. Calcifying to non-calcifying cover was calculated as the ratio of the combined cover of hard corals, crustose coralline algae and calcareous algae (e.g. *Halimeda* spp.) to the combined cover of fleshy macroalgae and turf algae. Coral size distribution was estimated as the coefficient of variation (CV, mean size / standard deviation of size) of the average size of each coral genus at a site. Higher coral size CV values indicate more evenly sized coral assemblages with smaller recruits, juvenile corals and larger colonies of more mature adults. Lower values of coral size CV indicate assemblages that do not have an even distribution across size classes, which may indicate either recruitment limitation (i.e. few recruits and juvenile corals) or limited adult reproductive stock (i.e. few large reproducing adult colonies). Coral richness was calculated as the number of genera observed in the community from roving observer surveys, a method that surveys more reef area and can provide a more accurate estimate of coral diversity than line intercept transects (T. McClanahan and E. Darling, unpublished data).

Fish biomass (in terms of kilograms per hectare) was calculated as total wet weight of all surveyed reef fishes from replicate 5 × 100 m belt transects at each site (see ecological sampling methods). Species richness of fishes was also calculated from replicate belt transects as the total number of species per 500 m^2 in four surveyed families (Acanthuridae, Chaetodontidae, Labridae and Scaridae). Substrate complexity (or rugosity) was calculated on each transect using the standard measure of the contour of the habitat over 10 m divided by the straight-line distance under the contour; replicate transect rugosity values were then averaged to estimate site-level rugosity. Fish size distribution was estimated as the CV of family-level fish abundances measured to 10 cm bins. Herbivore diversity was estimated from energetic-based grazing rate of three herbivorous fish families (Acanthuridae – surgeonfishes; Scaridae – parrotfishes; and Siganidae – rabbitfishes) and sea urchins. Herbivorous fishes and sea urchins have been reported to consume 22 percent and 2 percent of their body mass per day, respectively (McClanahan, 1995; McClanahan, 1992). The average algal consumption (in kilograms per day) was calculated for each of the four major herbivore groups (acanthurids, scarids, siganids and sea urchins) and the Simpson diversity index was calculated as a functional estimate of herbivore grazing diversity. Finally, the amount of herbivore grazing relative to algal production was quantified as the difference between the total herbivore grazing rates on algae (fishes and sea urchins; kilograms per hectare per day) and the rate of algal production (kilograms per hectare per day) at each site. To estimate algal production, an estimate of daily gross algal production of 196 kg/ha at 100 percent algal cover was used (McClanahan, 1995; McClanahan, 1992) multiplied by the observed average percentage cover of algae (turf, macroalgae, calcareous and coralline algae) estimated at each site from coral habitat transects.

For each indicator of exposure, sensitivity and recovery potential, values were calculated for the 17 ecological study sites and box plots were used to compare how these values were distributed among sites studied along the entire Kenyan coastline (n = 214), as well as sites from regional surveys throughout the Western Indian Ocean (n = 482) (Figure 5). This enabled the range of values from the current Kenya study to be put in a broader Kenyan and regional context to assess how representative of extreme values the data are (Figure 2 and Figure 5).

FIGURE 5
Ecological indicators compared across sites in the Western Indian Ocean, Kenya and the 17 Kenyan sites included in this study

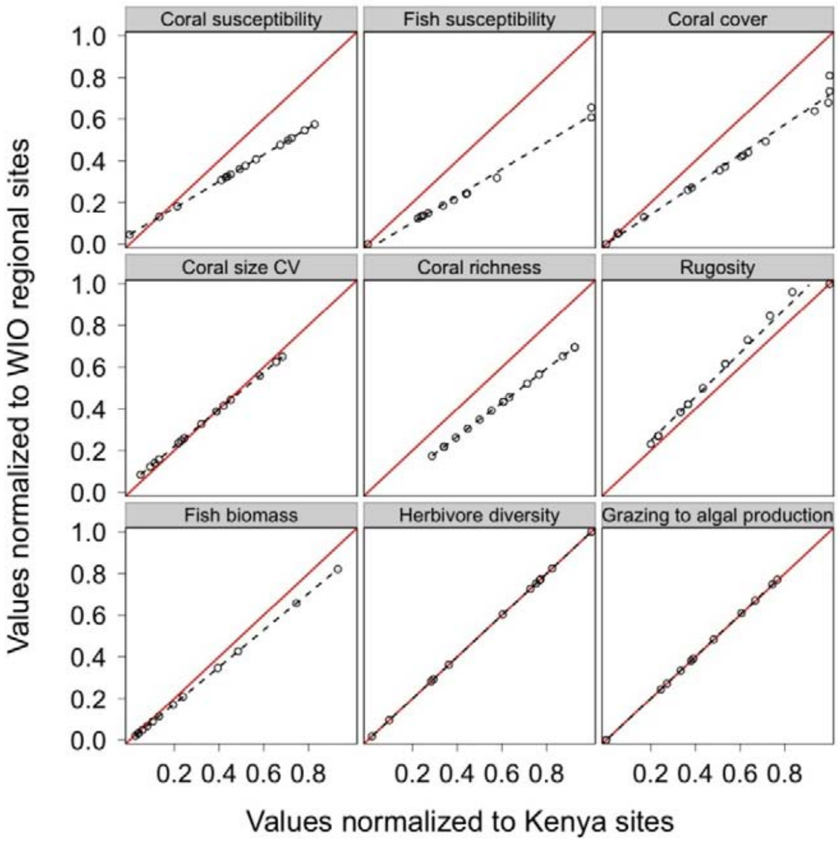


Notes: Western Indian Ocean sites (n = 482), Kenya (n = 214), and the 17 Kenyan sites included in this study (labelled Kenya BMU). Box plots show 25 percent and 75 percent quartiles (box) with median (line) and outliers.

Variable normalization and composite indices

Each indicator was normalized between 0 and 1 in order to calculate composite variables of ecological exposure, sensitivity and recovery potential and ecological vulnerability. For each indicator, values were normalized in two ways, both of which aimed at bounding the ecological variables within a broader geographic variation; first, to 2 percent and 98 percent percentiles from 214 Kenyan sites, and second, to 2 percent and 98 percent percentiles from 482 Western Indian Ocean sites. Percentiles were used as "minimum" and "maximum" estimates to "bound" the site-level variables between 0 and 1 and are a better estimate of "true" ecological minimum and maximum values and not potentially biased by influential outliers. Across all indicators, the normalized values using the Kenyan bounds were positively correlated to the indicator values normalized to the Western Indian Ocean regional bounds (linear regression, $R^2 = 0.85$, $P < 0.0001$). In general, the regional Western Indian Ocean range of values was greater than the Kenyan range of values, although generally these two bounding estimates are fairly similar (Figures 5 and 6). The regional bounds for normalizing the indicators were used for further analyses to ensure the current study is framed in a larger geographical context.

FIGURE 6
Comparison between normalized indicator values



Notes: Comparison between indicator values normalized to Kenya 2 percent and 98 percent percentiles, vs Western Indian Ocean regional site 2 percent and 98 percent percentiles. The red line indicates the 1:1 line.

Ecological data analysis

Ecological vulnerability was calculated from composite metrics of ecological exposure, sensitivity, and recovery potential indicators (Table 1). Normalized indicators were averaged into composite metrics of sensitivity and recovery using an evidence-weighted framework based on expert opinion that evaluated the strength of evidence in support of each indicator (McClanahan *et al.*, 2012) (Table 1). Ecological vulnerability was then estimated as: (Exposure + Sensitivity) – Recovery Potential.

Within the Kenyan study sites, four indicators of recovery potential (coral:macroalgae cover, calcareous:non-calcareous cover, fish size CV and fish species richness) were highly collinear as identified from Pearson correlation coefficients with the other recovery indicators and variance inflation factors. These variables were removed from further analysis to prevent bias within the composite recovery potential metric. Importantly, the ecological processes represented by the four excluded indicators were represented by other variables that remained in the analysis.

Ecological variability was evaluated across the three management groups (fished reefs, tengefus, and no-take marine reserves) using a one-way analysis of variance (Figure 7). The multivariate relationships among the exposure, sensitivity and recovery potential indicators of ecological vulnerability were described using a correlation-based principal components analysis on Euclidean distances among indicators (Figure 8). The differences among the three components of ecological vulnerability were visualized using a bubble plot, where sensitivity is plotted against recovery potential and exposure is indicated by the size of the points (Figure 9) (see Cinner *et al.*, 2012a).

BOX 2

How can ecological vulnerability to climate change be assessed?

Ecological vulnerability includes the potential impact on the ecosystem (i.e. exposure plus sensitivity) minus the recovery potential. For the exposure metric, this study used an existing spatial model that examines the environmental conditions (tides, temperature variability, etc.) that predispose a particular location to mortality from coral bleaching. The literature was then reviewed to find the scientific evidence behind 13 potential indicators of sensitivity and recovery potential for corals and fish assemblages. Each of these indicators was normalized (i.e. put on a scale of 0–1) and then weighted based on the scientific evidence supporting its importance. To ensure that the normalization used appropriate bounding (i.e. high and low values), national and regional variation in the indicators was examined. These indicators were then combined to create metrics for ecological sensitivity and recovery potential.

KENYA'S SOCIO-ECONOMIC ENVIRONMENT

In terms of material well-being and infrastructure, Kenyan coastal communities are intermediate for the region (i.e. generally poorer than places such as Mauritius and Seychelles, but better off than Madagascar and parts of the United Republic of Tanzania) (Cinner *et al.*, 2009b). However, there is considerable variability within the country (Cinner, McClanahan and Wamukota, 2010). Livelihoods in Kenyan coastal communities often include a mix of fishing, agriculture and the informal economy, although the proportion of the community dependent on any one sector varies considerably between rural and peri-urban locations (Cinner and Bodin, 2010).

Fishing in Kenya is typically conducted from the beach to the fringing reef within the sand, coral and seagrass habitats of the fringing reef lagoon. Fishing pressure is high and, from 1997 to 2007, remained relatively stable, although spatial differences exist (McClanahan, Hicks and Darling, 2008a). Five main gear types are in operation: beach seine, speargun, trap, net and hand line. Current fisheries laws prohibit the use of beach seine, speargun and any gear with a mesh smaller than 6.35 cm (Kenya gazette Notice 7565). However, beach seine and spearguns are both in use along the majority of the coastline (McClanahan, Hicks and Darlin, 2008a). There is heavy use of ecosystems close to shore with annual production exceeding 5 tonnes/km^2 and composed of small-bodied and low-trophic fish and octopus (McClanahan and Mangi, 2000). Offshore areas have lower sustainable potential yields and many do not currently have a net economic return even in the short term at current prices (Kamukuru, 2002).

SOCIO-ECONOMIC DATA COLLECTION

The vulnerability to climate change of socio-economic components of coral reef systems is also assessed using knowledge of the three components – exposure, sensitivity and adaptive capacity (Box 3). Data that provide reef managers with information about the vulnerability of the human dimension of coral reefs can be gathered in various ways. They can be as simple as a brief summary of expert opinion or as complex as an integrated, multidisciplinary research programme. This Kenyan case study employed a combination of surveys targeted at resource users' (fishers, fish sellers, etc.) households and semi-structured interviews with key informants (community leaders, resource users, and other stakeholders) to gather information and triangulate results in each study site. In total, 310 household surveys, 9 key informant interviews, 10 community leader interviews, and 10 organizational leader interviews were conducted. All interviews were conducted in Swahili by trained interviewers. Respondents for the household surveys were randomly selected from lists of resource users provided by local leaders. Lists were cross-referenced with other fishers for accuracy. Key informant interviews were conducted using three semi-structured interview forms to target specifically: (i) knowledgeable fishers; (ii) community leaders; and (iii) fishery landing site leaders. Key informants were selected using non-probability sampling techniques. One key informant was interviewed per site.

SOCIAL INDICATORS OF VULNERABILITY

Based on all of these survey types, 13 socio-economic indicators were generated, which were separated into sensitivity and adaptive capacity measures.

Social exposure

Social exposure of coastal communities to climatic shocks was described by the ecological vulnerability of a community's fishing grounds to coral bleaching (see section on Ecological Methods).

> BOX 3
>
> **How can the exposure of social systems to climate change be assessed?**
>
> Social systems dependent on coral reefs are vulnerable to climate changes (such as increases in temperature and extreme events) through the extent to which ecological components are vulnerable (V_e).
>
> Hence, assessing the extent to which ecological components are vulnerable is a matter of understanding how coral reefs are sensitive to climate changes (S) and knowing their capacity to recover from potential impacts (AC).
>
> Exposure of social systems can also be described as the vulnerability of ecological components of the system: $V_e = E + S - AC$

Social sensitivity

Sensitivity is the susceptibility to harm resulting from exposure to stresses (Box 1). This study is interested in how sensitive Kenyan resource users are to climate-related coral bleaching events. A metric of sensitivity was developed based on two key aspects: (i) the level of dependence on marine resources (Allison *et al.*, 2009; Marshall *et al.*, 2010); and (ii) data on how susceptible the catch composition of different gear types is to climate change impacts (Box 4; Cinner *et al.*, 2009a; Pratchett *et al.*, 2011).

First, to develop the dependence component of the sensitivity metric, respondents were asked 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, gleaning, mariculture, tourism, farming, cash crops, salaried employment, the informal sector, other, and "none" (for details, see Cinner and Bodin, 2010). To better understand sensitivity to the impacts of temperature events on fisheries, a decision was taken to consider fishing, fish trading, gleaning, and mariculture together as the "fisheries" sector and all other categories as the "non-fisheries" sector. The metric of sensitivity incorporates the proportion of households engaged in fisheries, whether these households also engage in non-fisheries occupations (what are called "linkages" between sectors), and the directionality of these linkages (i.e. whether respondents ranked fisheries as more important than, say, agriculture).

Second, the study used data on species composition of fisheries catches from small-scale artisanal fishers in ten sites in Kenya (McClanahan and Hicks, 2011). Catch abundance data were collected at landing sites between October 2004 and May 2008, with a lesser amount collected in 1998. Where possible, the entire catch was sampled, but where this was not possible a subsample was taken, ensuring that each gear used at each site was sampled and that each species landed was recorded. Each of the 4 205 fishes was identified to species level (Randall, Allen and Steane, 1997). For each catch, the gear used by the fisher was recorded. This allowed the species selectivity for each gear type to be ascertained. These gear selectivity data from Kenya were then integrated with a global database on species-specific responses of fishes to coral bleaching, which provides a rate of decline per standardized percentage loss of coral cover (Pratchett *et al.*, 2011). This resulted in data on species-specific responses to bleaching for 90 of the 265 species in the catch records. The standardized response for each species was then entered into the catch records and pooled by gear type in order to determine how gear types selectively target species that have been shown to decline from coral bleaching, and to provide a single value of mean expected decline for each gear:

$$S = \frac{\left(\frac{F}{(F+NF)} \times \frac{N}{(F+NF)} \times \frac{(\frac{r_{fn}}{2}+1)}{(r_{fn}+r_{nf}+1)} \right) + \sum_{i=1}^{n} G_i}{2}$$

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} = number of times fisheries-related occupations were ranked higher than non-fishing occupations (normalized by the number of households), r_{nf} = number of times non-fisheries related occupations were ranked higher than fishery occupations (normalized by the number of households), G = the susceptibility of each specific gear type used (described above), and n = is the number of gear. In the first bracket of the equation, the first term 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 where many households are engaged in both occupational categories. The third term captures the directionality 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. The fourth term captures the selectivity of fishing gear and the differential impacts this may have on sensitivity to climate change.

BOX 4

How can the sensitivity of marine dependent communities be assessed?

Coastal communities that are dependent on coral reefs will be sensitive to changes in the coral reef. People can be dependent on coral reefs if their livelihoods are reliant on fishing and depending on what fish they target. This study shows how to develop an occupational sensitivity score based on two measures:

1. Livelihood sensitivity: Dependence can be assessed through identifying livelihoods within a household or community, and the importance of each livelihood in the household or community
2. Gear sensitivity: Target species and catch composition can be assessed through observing the specificity of gear used. Different gear will target different species, and some species are more susceptible to climate changes. This study shows how to develop a single value of mean expected decline for each gear.

By providing knowledge of the factors that contribute to sensitivity, decision-makers can prioritize their efforts and provide a basis for early engagement with reef users.

Social adaptive capacity

Adaptive capacity reflects people’s ability to anticipate, respond to, and take advantage of change (Box 5). This study modified the social adaptive capacity index developed in McClanahan *et al*. (2008) and Cinner *et al*. (2012a). Based on both the household surveys and key informant interviews described above, 11 indicators of local-scale adaptive capacity were examined (Table 2).

TABLE 2
Indicators of social adaptive capacity

Indicator	Description	Bounding
Human agency *"HumanAgency"*	Recognition of causal agents affecting marine resources (measured by content organizing responses to open-ended questions about what could affect the number of fish in the sea)	Binomial 0; 1
Access to credit[*] *"AccessCredit"*	Measured as whether the respondent felt he or she could access credit through formal institutions or informal means (e.g. family, friends, intermediaries/dealers)	Binomial 0; 1
Occupational mobility *"OccupMob"*	Indicated as whether the respondent changed jobs in the past five years and preferred their current occupation	Binomial 0; 1
Occupational multiplicity *"OccupMult"*	The total number of person-jobs in the household	Continuous 1st quartile = 1; 3rd quartile = 3
Social capital *"SocialCapital"*	Measured as the total number of community groups the respondent belonged to	Continuous min. = 0; max. = 3
Material style of life *"MSL"*	A material style of life indicator measured by factor analysing whether respondents had 15 material possessions such as vehicle, electricity and the type of walls, roof, and floor	Continuous 1st quartile; 3rd quartile
Gear diversity *"GearDiv"*	Technology (measured as the diversity of fishing gear used)	Binomial 0 = 1 gear; 1 = more than 1 gear
Community infrastructure *"CommInfrastr"*	Infrastructure (measured by factor analysing 20 infrastructure items such as hard-top road, medical clinic [Pollnac and Crawford, 2000])	Continuous min. = 0; max. = 26
Trust[*] *"Trust"*	Measured as an average of Likert-scale responses to questions about how much respondents trusted community members, local leaders, police and local government	Continuous min. = 0.8; max. = 5
Capacity to change[2012] *"CapacityChange"*	Capacity to anticipate change and to develop strategies to respond (measured by content organizing responses to open-ended questions relating to a hypothetical 50 percent decline in fish catch)	Binomial 0; 1
Debt[*2012] *"NoDebt"*	Measured as whether or not the respondent was currently in debt of more than one week's pay (this indicator negatively contributed to adaptive capacity, so the inverse was taken).	Binomial 0 = in debt; 1 = not in debt

[*] New indicators added to the adaptive capacity compared with previous.
[2012] Only used for 2012 analysis.

The next critical step was to normalize (or bound) each indicator, so that it ranged from 0 to 1. This is important because each raw indicator is on a different scale, and is comprised of different units. By bounding the data between 0 and 1, all indicators are on a common scale, which can then be combined to develop a metric of adaptive capacity. Unlike in a previous study that developed weightings derived from expert opinion from ten regional and international social scientists (McClanahan *et al.*, 2008), this study used principal component analysis (PCA) to weight the indicators. Future users of these data may wish to conduct an expert workshop to develop weightings, but that was beyond the scope of this present study.

BOX 5

How can the adaptive capacity of social systems be assessed?

By providing knowledge of the factors that contribute to adaptive capacity, decision-makers can prioritize their efforts and provide a basis for early engagement with reef users. This study shows how to develop a single metric to assess adaptive capacity based on 11 important indicators. Data for each indicator can be collected through household surveys and/or key informant interviews. The indicators are:

1. recognition of causal agents affecting marine resources
2. access to credit
3. occupational mobility
4. occupational multiplicity
5. social capital
6. material assets
7. technology
8. infrastructure
9. trust of community members, local leaders, police, etc.
10. capacity to anticipate change and to develop strategies to respond
11. debt levels

To create a metric of adaptive capacity, these indicators then need to be bounded (i.e. placed on a scale of from 0 to 1), weighted (to reflect that some indicators may contribute more to adaptive capacity than others), and combined. It is absolutely critical to examine the data after they are bounded to ensure that there is enough variation (i.e. that some values are at or close to 0 and other values are at or close to 1). If the choice of how to bound the indicators does not allow for sufficient variation, then the indicator will simply not contribute much to the overall adaptive capacity score. There is no hard-and-fast rule about exactly how much variation is enough, so it is advisable to try a couple of different bounding options to see how they influence the adaptive capacity score.

ANALYSIS

Objective 1 - Develop metrics for social-ecological vulnerability

Integrating the socio-economic and ecological dimensions into an integrated assessment enables the intrinsic link between system components to be considered. Specifically, integration between socio-economic and ecological systems allows the codependence between the systems components to be appreciated; where vulnerability of one system depends on the other. A review of the literature found few examples depicting how this relationship can be described. Yet, under the growing threat of climate change, and because of the interdependences between people and ecosystems, understanding the linkages is likely to be as important for effective reef management as are efforts to understand vulnerability of any one system component. Following Cinner *et al.* (2012a), this study used two techniques to examine social-ecological vulnerability. First, a quantitative vulnerability score was developed using an equation to combine the three contributing indices (each normalized to 0–1 scale) (vulnerability = [exposure + sensitivity] – adaptive capacity). Second, to visualize differences in key components of vulnerability, the three dimensions were plotted 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).

Objective 2 - Examine how sensitivity and adaptive capacity vary over time and among actors

For objective 2, two types of analyses were conducted. First, the indicators of the adaptive capacity scores described above were compared over two points in time (2008 and 2012). This step used a limited number of sites (eight) for which there were adaptive capacity data from both 2008 and 2012. However, a methodological problem in 2008 meant that the indicator on response to decline could not be compared. In addition, the indicator on debt was only developed for the 2012 study, and consequently could not be compared. To analyse whether there were consistent differences over time in the interval scale adaptive capacity indicators, a nested analysis of variance (ANOVA) was conducted, with “community” as a random factor, year as the independent variable, and indicator as the dependent variable. In this way, it was possible to examine whether the mean of each adaptive capacity indicator varied significantly over time, while explicitly accounting for the differences between communities. For the binary data, a chi-squared test was used.

Second, the study examined whether vulnerability varied between different segments of society, including: (i) migrants/non-migrants; (ii) those who felt that comanagement was a) beneficial, b) neutral, or c) detrimental to their livelihoods; (iii) those who were a) actively, b) passively, or c) not involved in local decision-making processes; (iv) age; and (v) fortnightly expenditure. As above, nested ANOVAs and chi-squared tests were used to look for statistical differences in adaptive capacity indicators between these groups, and spider plots were used to visualize these relationships.

As several different types of analyses are conducted in this report, the number of study sites varies from section to section. For ecological analyses, and for social-ecological analyses where both social and ecological data are used, all ten 2012 sites plus two sites from 2010 are used. For the comparison of data over time, eight sites common to the 2008 and 2012 studies are used.

SECTION SUMMARY

This section has outlined the specific steps necessary to conduct an integrated social-ecological vulnerability analysis. It has explained, step by step, how to create indicators of vulnerability for both the social and the ecological systems, and described how to combine them. It has also described how differences in vulnerability could be compared over time and between different segments of society.

3. RESULTS

OBJECTIVE 1: DEVELOP METRICS FOR SOCIAL-ECOLOGICAL VULNERABILITY

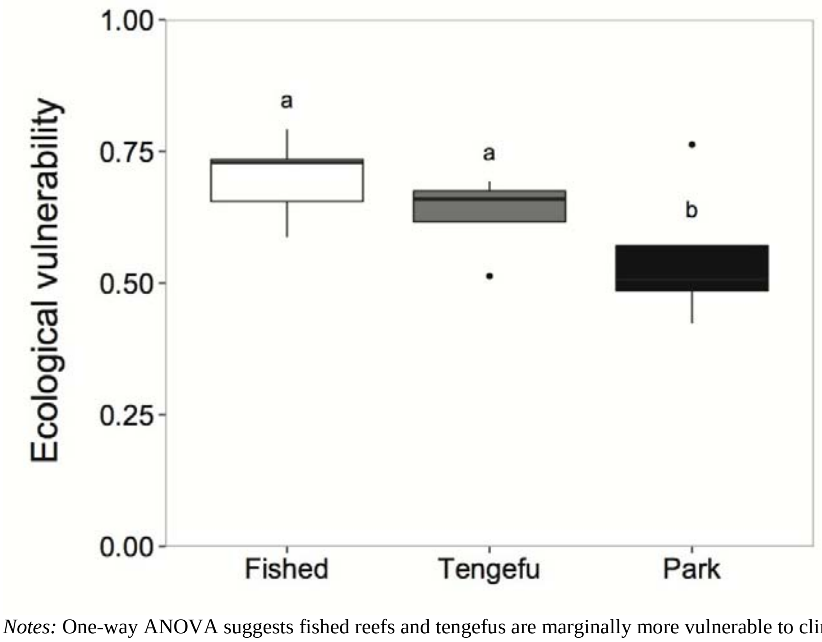
Ecological aspects of vulnerability

The ecological indicators were highly variable across the 17 study sites (Table A1.1; Box 6). Sites included degraded reefs with low coral abundance (< 1 percent absolute live coral cover, Takaungu), limited coral diversity (13 genera, Kuruwitu), low reef fish biomass (< 100 kg/ha, Kanamai, Takaungu, RasIwatine), limited herbivore grazing diversity (< 0.01, Kanamai, RasIwatine) and herbivore grazing rates that were substantially less than estimated rates of algal production (> 100 kg/day deficit, Mayungu, Takaungu). More-intact reefs had higher coral cover (> 50 percent, Mradi), diverse coral assemblages (25 genera, Changai, Kisite) and more productive fish communities (about 1 600 kg/ha reef fish biomass, Kisite) with greater herbivore diversity (about 0.7, Mombasa) and higher herbivore grazing relative to algal production (> 50 kg/day surplus, Changai, Kisite).

The wide range of ecological condition across the 17 coral reef sites in Kenya led to considerable spread in the composite ecological vulnerability index (Table A1.1). Ecological vulnerability ranged from 0.42 to 0.79 (mean 0.64 ± 0.11 SD, vulnerability index scaled between 0 and 1). The three facets of ecological vulnerability (exposure, sensitivity and recovery potential; Table A1.2) were not strongly correlated, suggesting these different components of ecological resilience are not related (Pearson correlation coefficients: exposure to sensitivity, $r = -0.46$, exposure to recovery potential, $r = -0.15$, sensitivity to recovery potential, $r = 0.11$). Overall, fished sites and tengefus were marginally more vulnerable than sites within no-take marine reserves (one-way ANOVA, $F = 3.2$, $df = 2{,}14$, $P = 0.07$; Table A1.2; Figure 7).

FIGURE 7

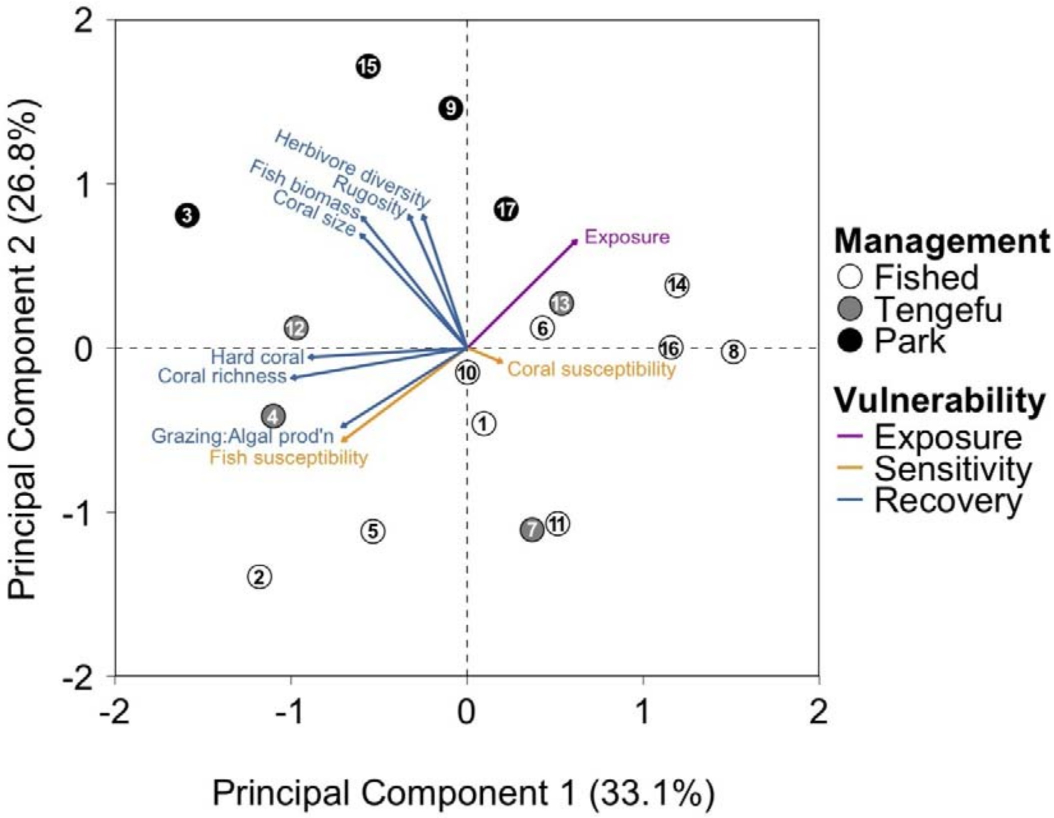
Ecological vulnerability on 17 Kenyan reefs across three types of fisheries management: open-access fished reefs, community-managed "tengefus", and national marine parks



Notes: One-way ANOVA suggests fished reefs and tengefus are marginally more vulnerable to climate change than are no-take parks (one-way ANOVA, P = 0.07). Letters indicate where significant differences exist across management groups).

The two principal-component axes explained 59.9 percent of the variation among indicators across the sites (Figure 8). Exposure was not distinguished by management as some fished reefs, community-managed tengefus, and government no-take marine reserves were associated with high levels of exposure (upper-right quadrant of Figure 8). Fished reefs and one tengefu (Tiwi) were associated with higher climate sensitivities of coral and fish assemblages. Recovery potential indicators separated into two groups. Herbivore diversity, rugosity, fish biomass and coral size were associated with the no-take marine reserves (upper-left quadrant of Figure 8), while coral richness, hard coral cover and higher rates of fish grazing:algal production were associated with some tengefus and to fished reefs (lower-left quadrant of Figure 8). Overall, indicators of exposure, sensitivity and recovery potential described different facets of ecological vulnerability, which provides justification to the effort in this study to identify indicators that could describe different aspects of the vulnerability of a coral reef fishery to climatic shocks.

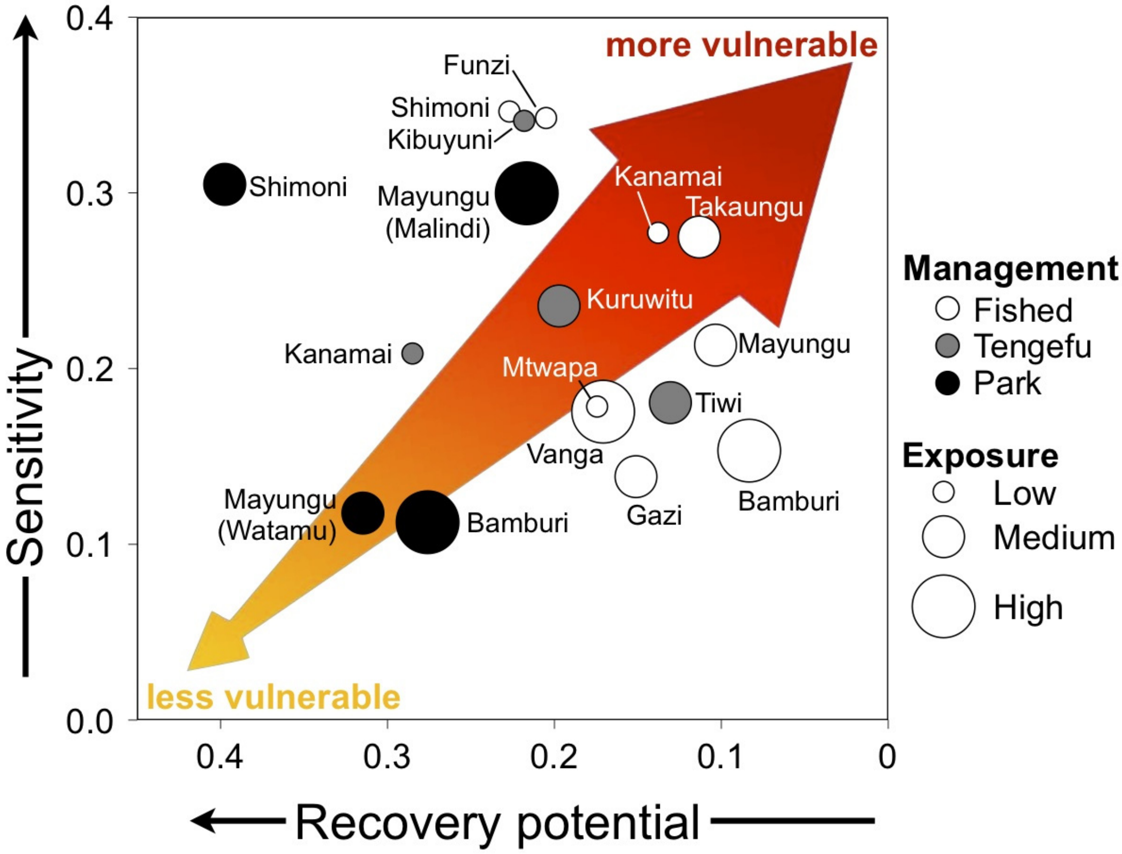
FIGURE 8
Principal components analysis of ecological vulnerability



Notes: Eigenvectors describe normalized indicators of exposure, sensitivity and recovery potential. Points indicate reefs within different management groups (white – fished; grey – community comanaged areas; black – no-take marine reserves). Numbers indicate study sites (see Table A1.1).

There was a wide spread of ecological vulnerability across different types of fisheries management. High ecological vulnerability was identified for fished sites, tengefus and no-take marine reserves with variable exposure, high sensitivity and low recovery potential to coral bleaching events. Tengefus and no-take reserves were associated with lower ecological vulnerability owing to low sensitivity and high recovery potential, despite medium to high exposure (Table A1.1; Figure 9).

FIGURE 9
Ecological vulnerability of Kenyan coastal communities to the impacts of coral bleaching on reef fisheries



Notes: Ecological sensitivity is plotted against recovery potential (note: axis is reversed) and exposure is indicated by bubble size. The arrow highlights less-vulnerable to more-vulnerable communities.

BOX 6
Key messages from ecological vulnerability analysis

1. The analysis revealed that the indicators used for exposure, sensitivity and recovery potential were describing unique aspects of ecological vulnerability of a coral reef fishery to climate shocks (Figure 8).
2. There was a wide spread of ecological vulnerability across the study sites (Figure 9). Importantly, the ways in which the sites were vulnerable varied considerably. Sites in the lower right (i.e. below the arrow in Figure 9) are most lacking in recovery potential, and efforts are needed to ensure that recovery potential can be maximized. Similarly, sites above the arrow in Figure 9 have relatively high sensitivity.
3. Importantly, ecological vulnerability varied between different types of fisheries management. Fished sites had the highest ecological vulnerability. No-take reserves were associated with lower ecological vulnerability owing to lower sensitivity and higher recovery potential. Small community-based closures (called tengefus) had slightly lower vulnerability than fished reefs, although differences were not statistically significant.

Social aspects of vulnerability

Sensitivity

The sensitivity index comprised two components: (i) occupational sensitivity, and (ii) gear sensitivity. The first part of the sensitivity metric used data on how much people depend on marine resources, on how many linkages households have to other economic sectors (i.e. do people also engage in, say, farming?), and on the directionality of those linkages (i.e. is fishing consistently ranked as more important than, say farming?). Using the bracketed part of the sensitivity equation described in the methods section (above), an occupational sensitivity score was developed for each community (Table 3).

TABLE 3
Occupational sensitivity scores by community

Community	Occupational sensitivity
Bamburi	0.32
Funzi	0.28
Gazi	0.27
Kanamai	0.34
Kuruwitu	0.23
Mayungu	0.30
Mtwapa	0.34
Shimoni	0.26
Takaungu	0.27
Vanga	0.35

Note: A score of 1 would mean all respondents depended on marine resources and had no livelihood alternatives, while a score of 0 would mean that none of the respondents had marine-resource-based livelihoods.

The second part of the sensitivity index used data from a global database on species-specific responses of fishes to coral decline (Pratchett *et al.*, 2011) and catch records from Kenya (Cinner *et al.*, 2009a) to determine the use of which specific fishing gear types might make people more or less sensitive to coral bleaching. The species-specific response to decline data reviewed the scientific literature on how abundances of a number of species changed before and after a bleaching event, and standardized the response per 1 percent loss in coral cover. Species-specific responses were obtained for about 50 percent of the landings data (Figures 10 and 11).

FIGURE 10
Relative contribution in fish abundance from catch data of species, genus, family-level data and species with no data

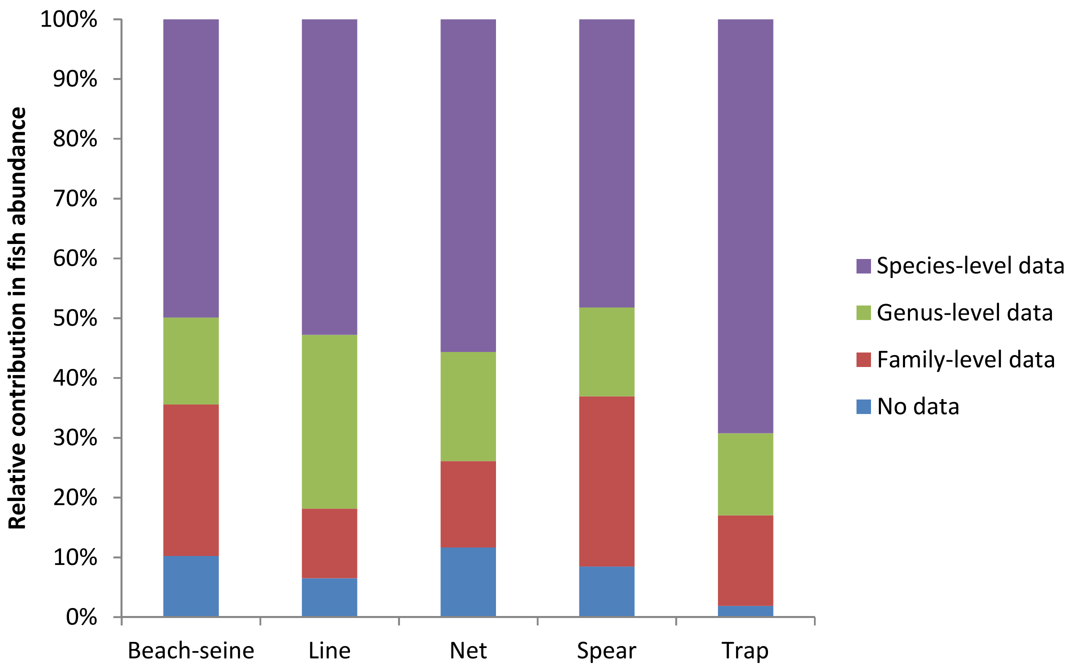
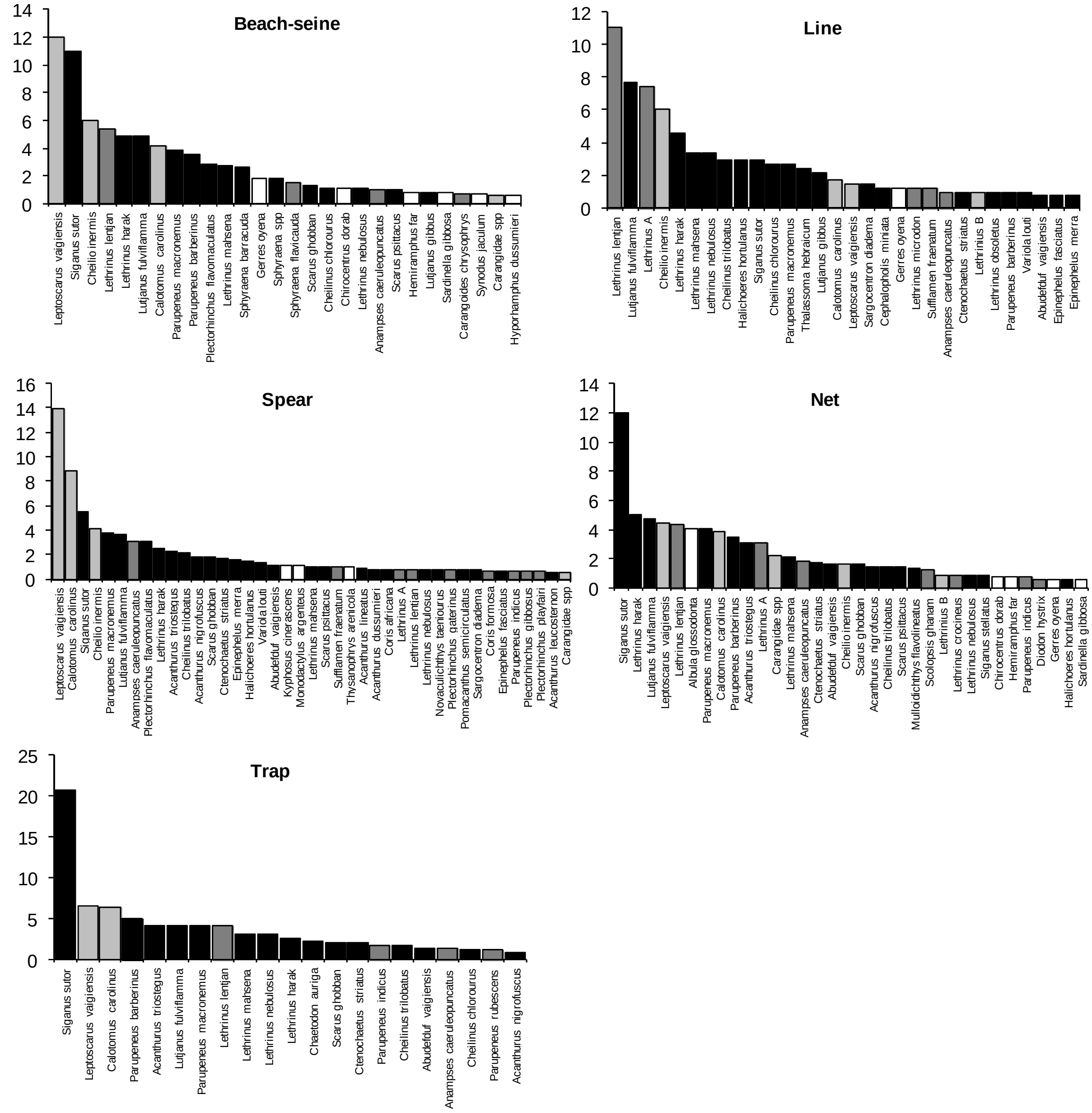


FIGURE 11
Relative abundance of species targeted by gear type

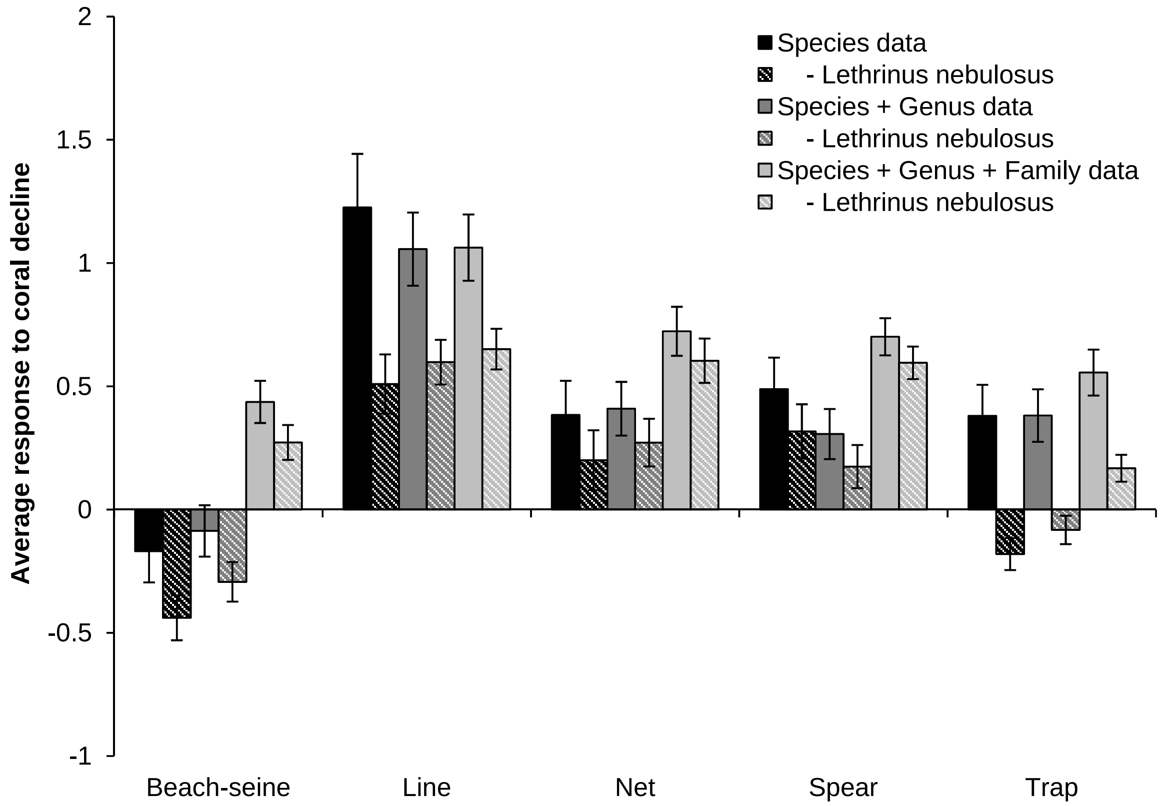


Note: Species are coloured as to whether they indicate species-level data (black), genus-level averages (dark grey), family-level averages (light grey) or no data (white) on their response to coral mortality.

The aim was to see whether genus or family level averages of these species-specific responses could be used as a surrogate, to fill in the missing data. Genus-level averages added another 15–20 percent to the catch records, and family-level information on vulnerability was available for about 90 percent of the catch records. The analysis explored how using genus or family averages might change the responses, and also whether the data were heavily influenced by one particular species (Figure 11). The estimates did not change significantly when genus-level averages were used to fill in missing data; however, family-level averages did change the results considerably (Figure 12). Consequently, genus-level surrogates were used where data were available. In addition, one species in particular stood out as having a very strong influence on the data and was consequently removed from subsequent analyses. *Lethrinus nebulosus* was heavily caught by many of the gear types (Figure 11), but the changes in abundance relative to coral loss were extremely high (a 12 percent increase per percentage of coral loss, Figure 13), which came from only one study in the global database of species response to coral loss (Pratchett *et al.*, 2011). Because the abundance changes were so high and this result was from only one study in Seychelles, this species was dropped from further analyses (Figure 12).

FIGURE 12

Average fish response to coral decline of each gear using only species data, or species and genus data, or species, genus and family data, ±SE



The initial investigation indicated how different types of fishers might be affected by, or benefit from, expected changes to coral reefs. Based on species-specific plus genus-level average responses to declining coral cover (and not including *Lethrinus nebulosus*), it was found that the only gear types that showed a probable decrease in catch were traps and beach seines (0.08 and 0.29 percent, respectively; Figure 12, Table 4). The other three gear types showed a potential for a small increase in catch with coral mortality. This is largely because, in Kenya, fishers use a mosaic of habitats and many of the most commonly caught species are associated with seagrass and algae; habitats that would be unaffected by, or possibly benefit from, coral mortality. Line fishing showed a potential for a substantial (0.6 percent) increase in abundance of target species per percentage loss in coral cover. One caveat to the analysis is that the Kenyan reefs are highly degraded and the lagoon fishery is heavily overfished. Consequently, the catch consists of many short-lived species that depend on seagrass and algae. Critically, the results here should not be generalized to how other reef fisheries may respond to further bleaching events. The analysis could produce extremely different results in places such as Papua New Guinea, where many of the species captured by artisanal fishers are more reef associated and the starting condition of the fisheries are often much better.

A limitation of this approach is that it did not examine changes in catch sensitivity over time. A key concept in fisheries is that catches change over time. Often, the species most vulnerable to overfishing are caught first, and as a system becomes more overfished, less-vulnerable species are targeted (because the more-vulnerable ones have been removed). This study used a static estimate for species composition targeted by different gear types. One research area, which was beyond the scope of this project, would be to examine how gear sensitivity has changed over time.

TABLE 4

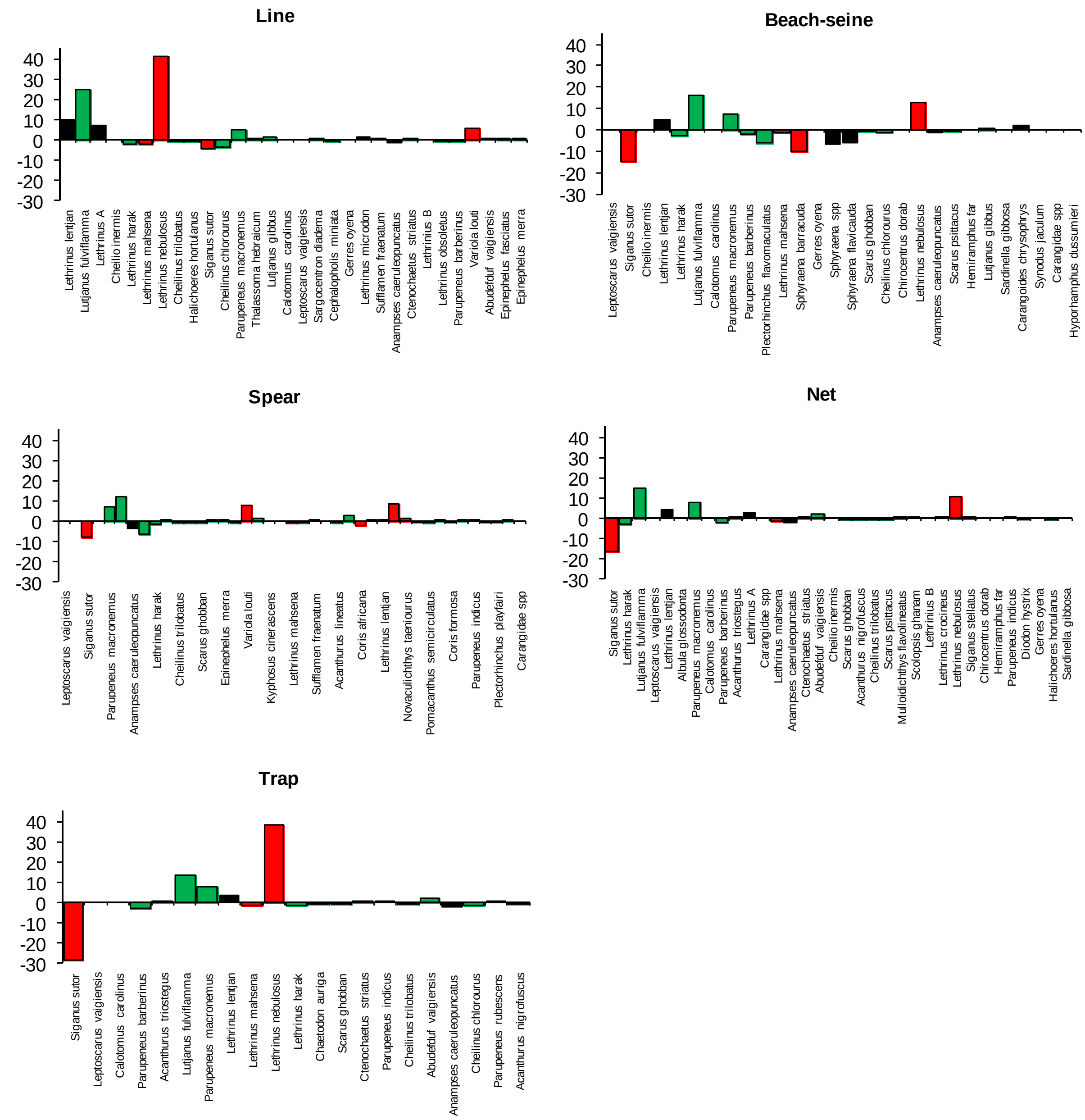
Average percentage change in abundance of fish per percentage decline in coral cover to decline by gear type, using species-specific and genus average responses to decline (and also without *Lethrinus nebulosus*)

Gear	Average response to coral decline (%)
Beach seine	-0.29 (±0.08)
Line	0.60 (±0.09)
Net	0.27 (±0.10)
Spear	0.17 (±0.09)
Trap	-0.08 (±0.06)

Species-specific data for many of the most commonly captured species were still missing, so these figures might be expected to change when critical data gaps are filled. The analysis helped to highlight critical research priorities for how species important to the fishery respond to coral loss. In particular, there were five species (*Leptoscarus vaigiensis*, marbled or green parrotfish; *Lethrinus lentjan*, pink ear emperor [genus-level average exists]; *Calotomus carolinus*, Carolines parrotfish; *Cheilio inermis*, cigar wrasse; and *Anampses caeruleopunctatus*, bluespotted wrasse [genus-level average exists]) that accounted for ~15–30 percent of the catch per gear (Table 5). By collecting data on these five species, there would be species-specific responses for > 72–88 percent of the catch abundance for each gear (Table 5; Box 7). Critically, several of these species are not coral associated, such as *Leptoscarus vaigiensis,* which is predominantly found in seagrass habitat. Seagrass habitats can be severely affected by temperature anomalies, sea-level rise, and changes in rainfall patterns (e.g. Rasheed and Unsworth, 2011), all of which are expected to change under a climate change scenario. However, this study did not have data on species-specific responses to changes in seagrass ecosystems, but the hope is that this framework and the data gaps will enable this type of research data to be collected and compiled, as has been done with coral reefs.

FIGURE 13

Relative abundance * response to decline of fish species targeted by gear type



Notes: This figure illustrates the influence of each species on the results and helps to identify critical research directions. The colour indicates the number of studies in the global database of species response to coral loss that were used for each species: green for more than 1 study, red for only 1 study, and black where genus data were used.

TABLE 5

Missing information on five species creates a significant gap in understanding on how species respond to coral mortality

	1. Relative abundance of 5 species	2. Species-specific data relative abundance	3. Column 1 + column 2
Beach seine	28.5	49.9	78.4
Line	21.2	52.8	73.9
Net	16.1	55.6	71.7
Spear	30.0	48.2	78.2
Trap	19.2	69.2	88.5

Notes: Column 1 shows the relative abundance of the five critical species without species-specific data on responses to coral mortality by gear type. Column 2 shows existing species-level data by gear type. Column 3 shows the proportion of catch data for which there would be species-specific understanding of if just five species were studied.

BOX 7

Key messages from sensitivity analysis

1. The occupational component of sensitivity had relatively little variation when compared with another study that included non-fishing households and encompassed the broader region (Cinner *et al*., 2012a). However, the most-sensitive communities still had half again the sensitivity score as the least-sensitive communities.
2. The gear sensitivity analysis found that certain gear types are more likely to target species that are more likely to be negatively affected by coral bleaching. In particular, beach seine nets and traps are more likely to experience negative impacts.
3. Information about how specific fisheries species respond to change is incomplete. The metric in the present study uses the best available information to date, but it still has major data gaps. Thus, the metric should be viewed as a methodological contribution that will become more reliable as better information becomes available. As a key research priority, species-specific information on five particular heavily targeted species would substantially increase knowledge.

To develop a community-level score of gear vulnerability to decline, the survey data were used to determine the proportion of gear use in each community. An inverse of the response to coral decline by gear type (Table 4) was then used to create a sensitivity measure for each gear (Box 8). This resulted in negative sensitivity scores if the assemblage of gear used was likely to have positive effects on catch and positive scores if the yields were likely to be negatively affected. To create a gear vulnerability score for each community, the gear usage was multiplied by the gear vulnerability (Table A1.3).

BOX 8

Policy implications: how can sensitivity to change be reduced?

Sensitivity could be reduced in two key ways:

1. Communities that are highly sensitive to climate changes because of a high reliance on fisheries-based livelihoods could be assisted through a livelihood diversification programme where alternative livelihoods are identified and "matched" to fishers.
2. Fishers using gear that are highly selective for species sensitive to climate changes could be encouraged to diversify their techniques and approaches, particularly toward gear types that target fishes less likely to be affected by coral mortality.

Both of these approaches would have the added benefit of also resulting in higher adaptive capacity. By providing knowledge of the relative sensitivity of coastal communities, decision-makers can prioritize their efforts and provide a basis for early engagement with reef users.

SECTION SUMMARY

The study found that the sensitivity of certain gear types varied considerably. The species captured by traps and beach seine nets in the Kenyan fishery are expected to decline as a result of bleaching-induced mortality. However, available information to date suggests that the species currently targeted by other gear types may actually demonstrate short-term increases in abundance as a result of bleaching mortality.

For example, the algae that often grow over dead corals could promote the abundance of certain types of herbivorous fishes. Sensitivity is not always negative; climate change could affect some fish species, some gear and some people positively. Using fish catch data and fish response to coral decline to construct a gear sensitivity indicator has many limitations here, owing to the lack species-specific data, to the fact that it only considers fish species response to coral decline, that no other habitat declines are considered and that it only looks at direct impacts. However, this is a first step and it highlights the importance of maximizing the use of all available data when assessing the vulnerability of a place.

ADAPTIVE CAPACITY

The ten communities displayed considerable variation in many of the indicators of adaptive capacity that were measured (Table A1.4; Box 9), particularly access to credit, debt, human agency, capacity to change, social capital, community infrastructure, and material style of life. For example, the proportion of respondents in debt (recorded as more than one week's typical earnings) ranged from 10 to 45 percent. Alternatively, several of the indicators displayed little variation between the highest and lowest values, particularly, occupational mobility, gear diversity, and trust. The occupational mobility measure (recorded as whether the respondent had changed jobs in the last 5 years and preferred the current occupation) was extremely low (the highest was < 8 percent of respondents [in Gazi]). However, an earlier study (McClanahan *et al.*, 2008) found that in the broader community (i.e. not only surveying fishers and resource users) 16–34 percent of respondents had changed to a preferred occupation. In Mayungu, the 2012 survey of resource users found 0 percent of respondents had occupational mobility according to this indicator, whereas 34 percent of broader community members did in a 2005 survey (McClanahan *et al.*, 2008). The findings for the present study suggest that few people had recently (in the past five years) transitioned into fisheries and preferred it to their previous occupation. Because of the low variability in this particular variable, and the high proportion of communities with values of 0, it was dropped from the index.

Because this study seeks to investigate methods for assessing vulnerability, a comparison was made of adaptive capacity metrics that were both weighted (i.e. where each indicator will contribute differently to the overall score) and unweighted (where each indicator will contribute evenly). The indicators were weighted using a PCA, which is an ordination technique often used by social scientists to construct indices (e.g. Pollnac and Crawford, 2000). The first analytical steps were to examine whether there were high levels of correlations among the adaptive capacity measures, and several of the variables were found to be significantly correlated (Table A1.5). Absence of debt was significantly negatively correlated with access to credit (rho = –0.976, $p < 0.01$), meaning that those who were in debt also reported that they had access to credit. Given the correlation and that they reflect the same process, debt (rather than credit) was removed from the analysis because information on credit had been collected in 2008, so this indicator could be used in the time analyses (Chapter 4).

A PCA was run based on the co-variance matrix (because the units were all on the same scale) (Figure 14). Visual inspection of screen plots revealed that the first three principal components, which explained 83 percent of the variance (Table A1.6), could be used. Social capital, capacity to change, access to credit, community infrastructure, gear diversity, and material style of life (MSL) all had substantial factor loadings on PC1 (Table A1.7); while MSL, occupational multiplicity, and community infrastructure dominated PC2, but gear diversity and access to credit also had substantial loadings on that principal component. While MSL and community infrastructure loaded negatively on PC2, gear diversity and occupational multiplicity loaded positively. This suggests that there may be trade-offs inherent in flexibility versus assets aspects of adaptive capacity. This finding is supported by studies of livelihood diversification, which have found occupational specialization with increasing socio-economic development (Cinner and Bodin, 2010; Daw *et al.*, 2012). Human agency loaded highly on the third principal component (Table A1.7). Trust did not load highly on any of the components, primarily because there was little variation in trust between communities. Although there was substantial variation in trust at the individual level, community-level means and standard errors were relatively similar (Table A1.4).

BOX 9

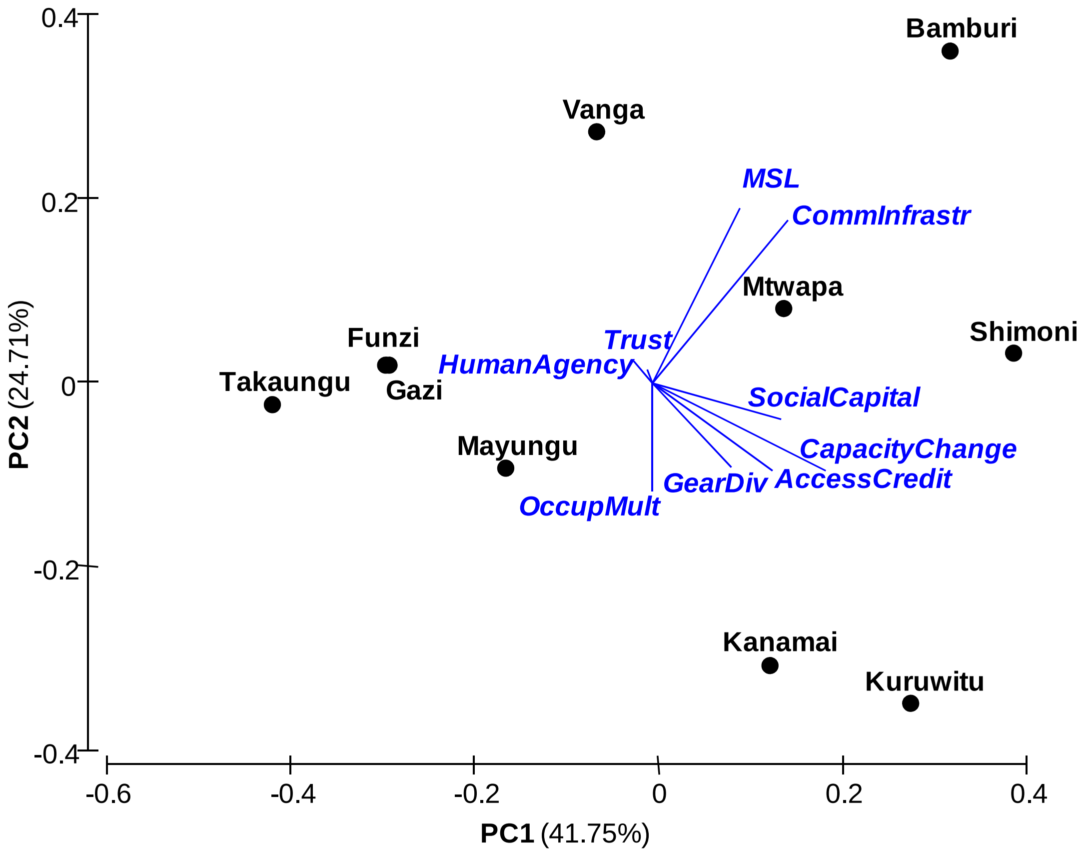
Key messages: measuring adaptive capacity

There is considerable variation in many adaptive capacity indicators across communities. This means that it is possible to identify a community's strengths and weaknesses compared with other communities. Strategies could be developed that either play to a community's strengths (e.g. Gazi has high occupational mobility and could therefore be the recipient of strategies that encourage fishers to enter into another livelihood) or focus on mitigating a weakness (e.g. Gazi has the lowest gear diversity, so new gear types could potentially be introduced to Gazi).

To calculate weights for the indicators based on the PCA, the absolute (i.e. positive) values of the factors loadings on PC1, PC2 and PC3 were used (Table A1.8). Those absolute factor loadings are considered as representing capacity of each indicator to explain different dimensions (whether positive or negative). Then, the average of each normalized indicator per community was calculated, and these were used to calculate the unweighted average and weighted average of those indicators, which is the adaptive capacity.

FIGURE 14

Principal component analysis of the nine adaptive capacity indicators analysed at an aggregate community level



Notes: The nine adaptive capacity indicators analysed: material style of life (MSL), community infrastructure (CommInfrastr), trust, social capital, human agency, capacity to change (CapacityChange), gear diversity (GearDiv), access to credit (AccessCredit) and occupational multiplicity (OccupMult) (except no debt and occupational mobility).

The weights of each indicator were calculated as follows:

$$\mathbf{W_i} = \sum_{k=1}^{3} \mathbf{E_j F_{ij}}$$

where: i = indicator, k = principal component, W_i, = weight of indicator I, E_j = eigenvalue of principal component k, and F_{ij} = factor loading of indicator i on principal component k. The weights of all indicators were then normalized, so that the sum of all weights (nine indicators) is equal to 1.

Those weights were then used to calculate the weighted adaptive capacity index for each community as follows:

$$\mathbf{AC} = \sum_{i=1}^{9} \mathbf{nW_i V_i}$$

where: i = indicator, nW_i = normalized weight of indicator I, and V_i = normalized value of indicator i.

Figure 14 and Table A1.5 show that some adaptive capacity indicators were positively correlated, such as those related to wealth and development, but that these were negatively correlated with occupational multiplicity and relatively unrelated to indicators of social capital, access to credit and human agency. Using weighted averages aims to reflect the relative importance of different adaptive capacity indicators but has little influence on the final adaptive capacity scores if all indicators are positively correlated. However, weightings become more crucial for adaptive capacity weights if indicators are uncorrelated, or negatively correlated, as for example between wealth and flexibility. Given the current emerging theory on adaptive capacity, there did not appear to be a well-justified rationale for weighting indicators, so a straightforward average of normalized values was used. However, final adaptive capacity scores may be sensitive to weightings, particularly, for example, the weight placed on occupational multiplicity. If this indicator was heavily weighted as important for adaptive capacity, then poorer, less-developed communities with high occupational multiplicity would be assessed as having higher adaptive capacity (Box 10). Conversely, adaptive capacity indicator weightings that prioritized the importance of wealth and infrastructure would penalize the adaptive capacity score of these communities.

This exercise of constructing each component of social vulnerability by combining indicators highlighted the importance of the normalization procedure. Careful thinking is needed to choose appropriate and meaningful bounding for each indicator, because each indicator has to capture the largest possible variation in the original variable. The minimum and maximum values of the original variables cannot always be considered as the 0 and 1 of the normalized indicator. For example, if a variable does not have much variation with the communities considered (but it is known that it can have more variation), or if a variable has outliers, then the minimum and maximum will not be meaningful as bounding and using them would reduce or amplify the variation in the normalized indicator and hence its relative importance to other indicators when combining them. Therefore, it is important to go through each indicator and think carefully about its bounding for normalization and what it means in order to have appropriate indicators.

SECTION SUMMARY

This study integrated 11 different socio-economic indicators into a single metric of adaptive capacity. This technique allows one to gather information about how specific aspects of adaptive capacity differed between communities (e.g. Table A1.4). This study also looked at how these indicators fit together by conducting a PCA (Figure 14), which helped to show some trade-offs in adaptive capacity. For example, on factor 2, occupational multiplicity loads in an opposite direction to material style of life and community infrastructure. Thus, communities tend to have adaptive capacity by either having high occupational multiplicity or assets, but not both.

BOX 10

Policy implications: how can adaptive capacity be enhanced?

Communities that rate poorly in their adaptive capacity could be assisted through policy investments and other investments targeted towards improving: social capital, community infrastructure, human agency (based on environmental education), technology, trust, and the capacity to anticipate and respond to change among others that are perhaps less feasible to manage (debt levels, mobility and multiplicity, material assets).

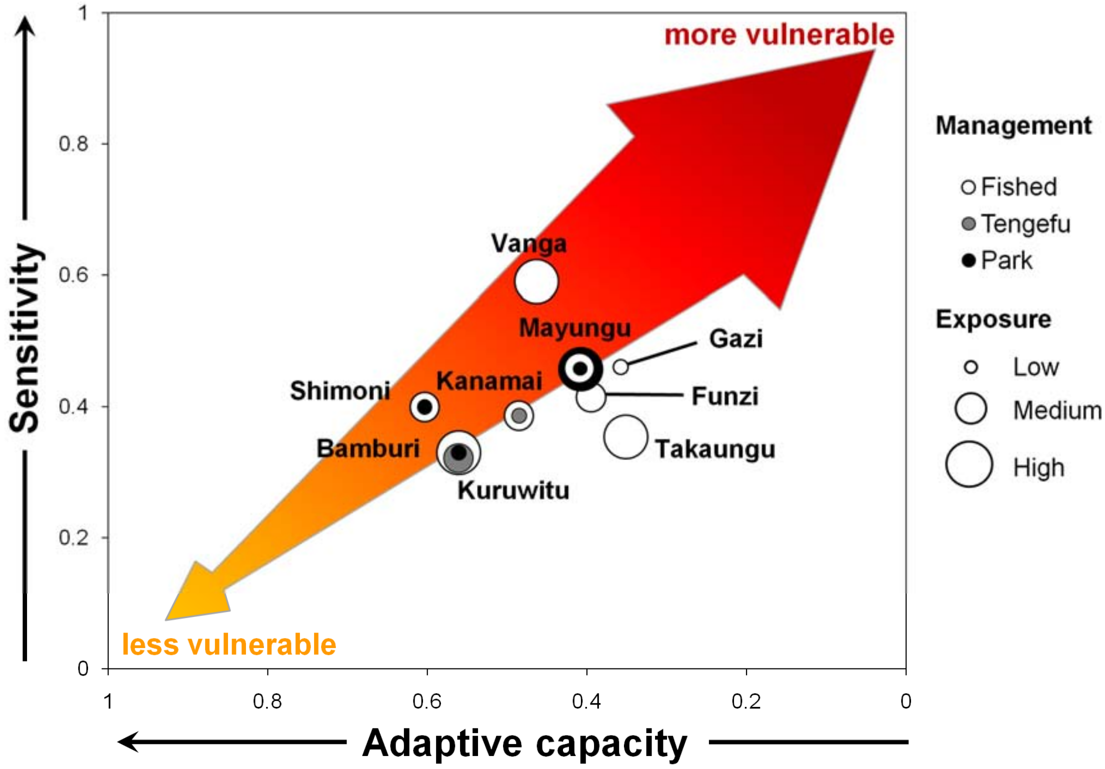
However, as some dimensions can be significantly correlated with others, investing in certain dimensions may assist to enhance capacity concurrently along other dimensions. For example, in Kenya, higher access to finance is correlated with higher levels of social capital and higher debt levels. Investments in developing social capital within a community may thus have benefits by enabling higher access to finance and encouraging investments in asset development within an industry (debt levels).

By providing knowledge of the factors that contribute to adaptive capacity, decision-makers can prioritize their efforts and provide a basis for early engagement with reef users.

Social-ecological vulnerability

The measure of social-ecological vulnerability used in this study comprised three components: ecological vulnerability (= social exposure), sensitivity, and adaptive capacity. Figure 15 presents a bubble plot to visualize social-ecological vulnerability at the study sites. This visualization helps to show how the communities compares with one another in terms of vulnerability and helps demonstrate which component (or components) contributes most to their vulnerability, so that specific actions can be taken for each of them. For example, Takaungu has a high vulnerability mainly because of its high exposure and low adaptive capacity, but its sensitivity is low. Therefore, actions to reduce the vulnerability of this community should focus on increasing the adaptive capacity (it is more difficult to have actions that can reduce exposure). Vanga has a high vulnerability also because of its high exposure, but on the contrary it has a high sensitivity and a high adaptive capacity. Therefore, actions to reduce the vulnerability of this community should focus on decreasing sensitivity.

FIGURE 15
Social vulnerability of Kenyan coastal communities to the impacts of coral bleaching on reef fisheries

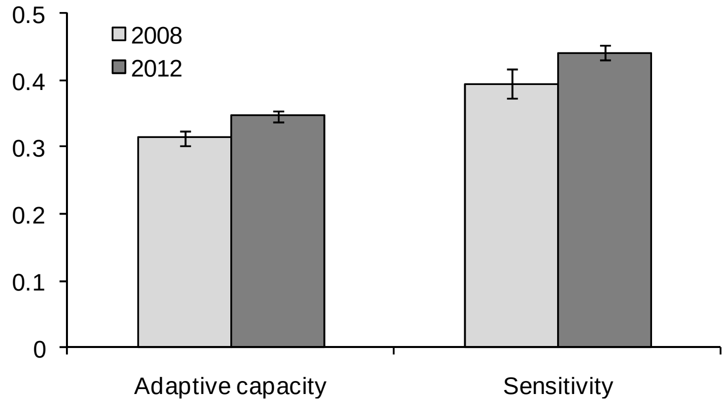


Notes: Social sensitivity is plotted against social adaptive capacity (note: axis is reversed) and exposure (= ecological vulnerability) is indicated by bubble size. The arrow highlights less-vulnerable to more-vulnerable communities.

OBJECTIVE 2: EXAMINING HOW ADAPTIVE CAPACITY AND SENSITIVITY VARY OVER TIME AND AMONG ACTORS

A critical issue in developing vulnerability metrics is ensuring that the indicators chosen are relatively stable over time. If one chooses indicators that fluctuate wildly over time, the metrics could be highly subject to bias regarding the timing of the vulnerability assessment. To assess the temporal robustness of the indicators in this study, the results of surveys conducted in 2008 were compared with those conducted in 2012. Overall, it was found that both sensitivity and adaptive capacity rose slightly but significantly over the four-year period (Figure 16). Figure 17a contrasts the magnitude of adaptive capacity components in 2008 and 2012 and shows that adaptive capacity in generally seems to be higher in 2012 owing to greater availability of credit and improved community infrastructure. Increases in community infrastructure were evident in six of the eight communities where comparable data were available (with one other remaining constant and another decreasing slightly) (Table A1.10). Similarly, access to credit increased in every community. No other significant differences were apparent when considering all sites (Figure 17a, Table A1.10).

FIGURE 16
Variation over time of social adaptive capacity and social sensitivity



Note: There are significant differences in adaptive capacity ($F_{1,291} = 5.698$, $p = 0.018$) and sensitivity ($F_{1,291} = 4.504$, $p = 0.035$) between both years.

In the previous section, aggregate vulnerability indices were calculated for communities. However, vulnerability is also socially differentiated within locations (Box 11). Thus, the study also examined whether and how vulnerability varied with five socio-economic characteristics: age, type of marine resource dependence (i.e. fisher or fish trader), fortnightly expenditures (USD purchasing power parity), migration status, and whether the respondent felt that comanagement was beneficial or detrimental to his or her livelihood. This last indicator aims to differentiate between winners and losers from resource comanagement, one of the key governance responses for coastal resources in Kenya. Previous research has found that the poor may benefit less from comanagement, so this study aimed to identify whether comanagement could benefit those most vulnerable to the impacts of coral bleaching. Table A1.9 shows the distribution of responses in the ten communities surveyed in 2012, while Tables A1.10 and A1.11, respectively, show the mean adaptive capacity indicators and sensitivity indicators for 2008 and 2012 for the eight communities for which comparable data were available. These results for the adaptive capacity indicators are summarized in Figure 17.

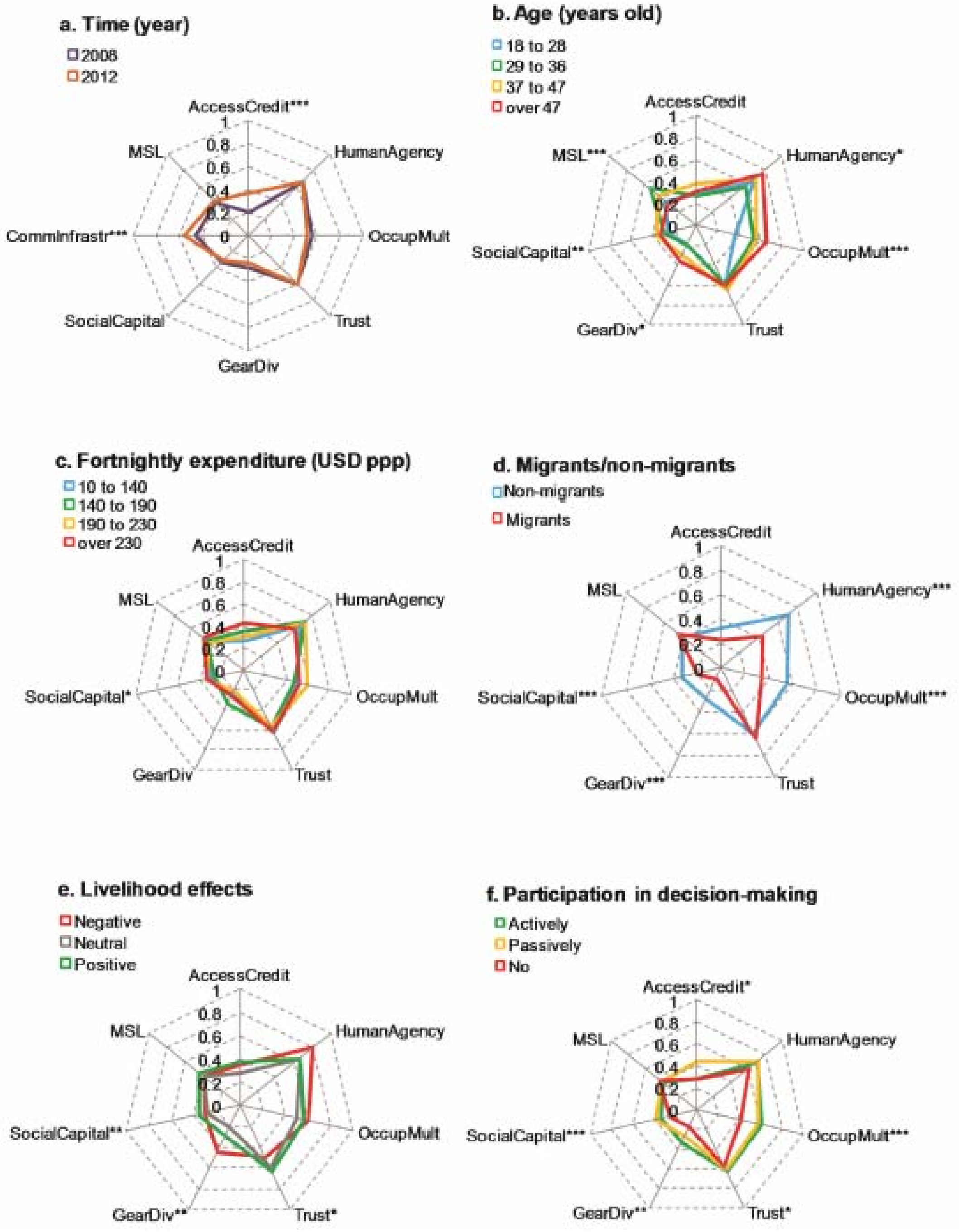
BOX 11
Who lacks adaptive capacity?
Key aspects of adaptive capacity were lacking among:

- the youth;
- migrants;
- those who do not participate in decision-making.

It will be particularly important to target adaptive capacity building measures at these subgroups.

Figure 17b–f illustrates how adaptive capacity components are socially differentiated (Box 12) by a number of different characteristics. Adaptive capacity is differentiated by age. Older individuals tended to have greater occupational multiplicity, understanding of human agency, gear diversity and social capital than do those in the youngest quartile. Community infrastructure was higher for the 29–36 year bracket, but as this indicator is determined at the site level, this is an artefact of the demographic distribution of the samples (hence, the non-significant result). Wealth (as indicated by expenditure) was not a statistically significant predictor of any of the adaptive capacity variables, but it was positively related to MSL.

FIGURE 17
Variation in adaptive capacity indicators among factors aggregated across all sites



*** = significant at p = 0.01, ** = significant at p = 0.05, * = significant at p = 0.1.
Notes: The spider plots show the variation in adaptive capacity indicators among factors aggregated across all sites: a) over time; b) by age; c) by household expenditure; d) between migrants and non-migrants; e) among those who perceive beneficial, neutral, or positive livelihood effects from comanagement; and f) among those with different levels of participation in community decision-making. Indicators bounded from 0 to 1 based on Table 2.

Figure 17d shows that these adaptive capacity indicators predict that migrants have lower adaptive capacity than non-migrants. This echoes studies of fishers in West Africa in which migrants, while not poorer in an economic sense (see MSL in Figure 17d), were found to have higher vulnerability (Bene, 2009). In this study, higher vulnerability was as a result of lower social capital, gear and occupational diversity and understanding of human agency. A caveat to this finding is that migrants may have greater willingness for geographical mobility, which may contribute to their adaptive capacity in a way that is not captured in this analysis.

People who reported that their livelihoods were enhanced by comanagement felt greater levels of trust with their community and had more membership of community groups (Figure 17e). People with least participation in local decision-making had the lowest adaptive capacity as a result of lower occupational and gear multiplicity, trust, social capital and access to credit. This result identifies political marginalization of a section of society that also has the lowest adaptive capacity. These people do not participate in decision-making and have limited agency to influence resource governance and how it affects them, and they are also least able to respond to negative effects. Therefore, they are doubly vulnerable as decisions are not likely to consider their interests or protect their livelihoods (so exposure may be high) while their adaptive capacity is low. This group is not distinguishable by MSL (Figure 17e), which suggests that such political and social marginalization would go undetected by simple uni-dimensional monetary analysis of poverty.

BOX 12

Key message: investing in adaptive capacity

The example in Kenya shows that while adaptive capacity components are relatively stable over time, they can be socially differentiated. Policies aimed at enhancing adaptive capacity in a region may need to consider that there may be different needs between, for example, younger and older people, migrants and non-migrants, and those already involved in comanagement, and those that are not and that those components can also vary over time. Aiming adaptation funding at those with lower adaptive capacity may have a larger payoff.

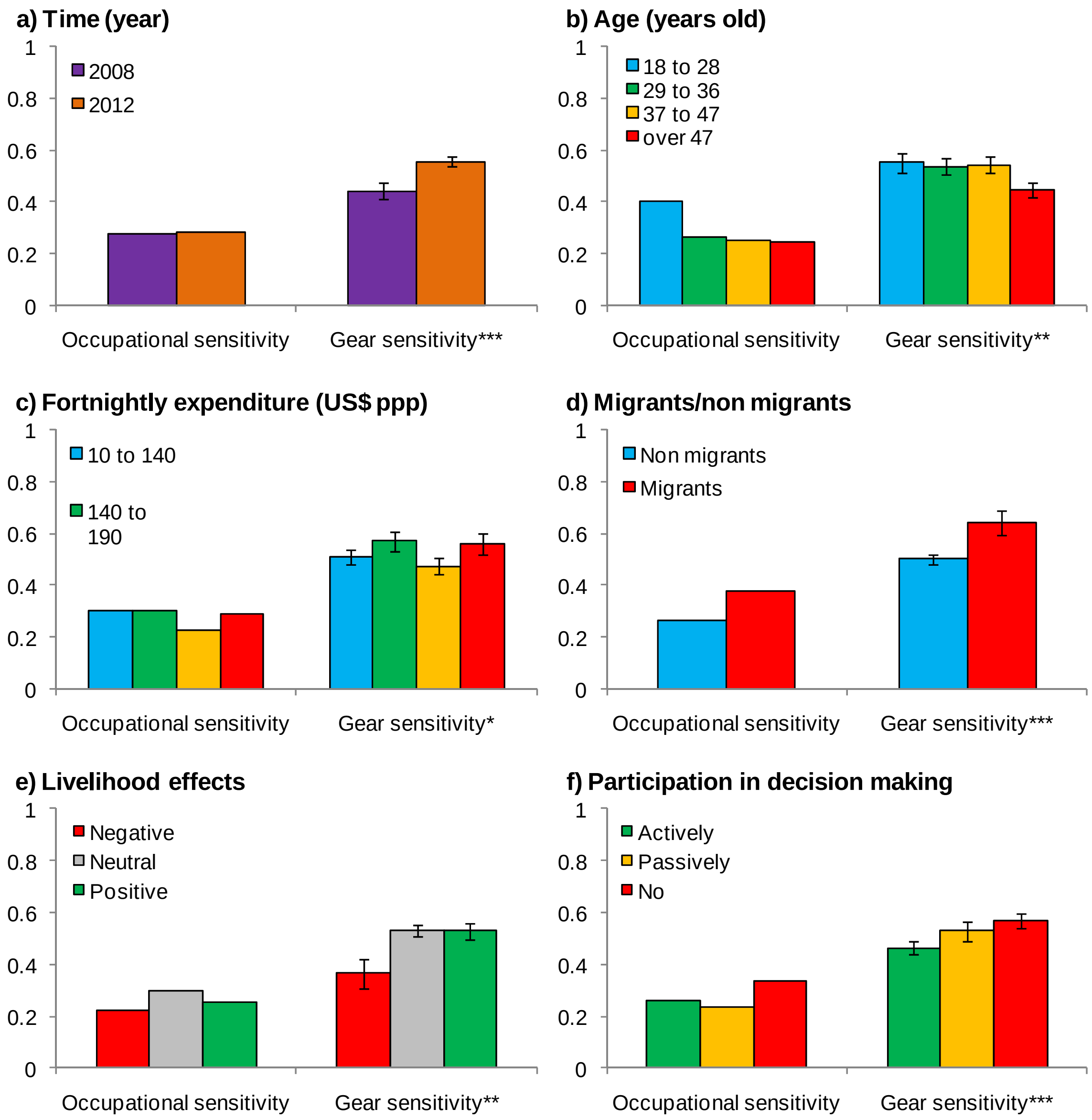
Sensitivity increased slightly, but significantly, between 2008 and 2012 (Box 13). The sensitivity metric included two components: occupational and gear sensitivity. The occupational sensitivity metric was calculated at an aggregate level (i.e. for a community, or for migrants). Thus, there is no variation in the estimates, which means statistics cannot be used to discern differences. However, some trends in Figure 18 are clear. For example, occupational sensitivity does not change over time, but the youth, migrants, and those that are not involved in decision-making have higher levels of occupational sensitivity. Alternatively, the gear aspect of sensitivity varied at the individual level and consequently, it was possible to use statistics to evaluate where differences were significant (Figure 18). It was found that gear sensitivity increased from 2008 to 2012. Migrants and those not involved in decision-making had significantly higher gear sensitivity. The elderly fishers (> 47 years old) had lower gear sensitivity, probably because of the prevalence of line fishing in this group. Those who perceived detrimental livelihood impacts from comanagement had lower gear sensitivity than those who perceived that comanagement provided neutral or beneficial livelihood outcomes.

BOX 13
Who is most sensitive to the impacts of coral bleaching?
Sensitivity was higher among:

- the youth;
- migrants;
- those who do not participate in decision-making.

Critically, these are the same groups that displayed lower adaptive capacity.

FIGURE 18
Variation in sensitivity indicators among factors aggregated across all sites



*** = significant at p = 0.01, ** = significant at p = 0.05, * = significant at p = 0.1.

SECTION SUMMARY

This section explored whether the social dimensions of vulnerability varied over time and between different subgroups in the community. It found that certain aspects of sensitivity and adaptive capacity increased between 2008 and 2012 – in particular, gear sensitivity, access to credit, and community infrastructure. In addition, certain subgroups were found to have higher levels of vulnerability.

Specifically, the youth, migrants, and those who did not participate in decision-making had lower adaptive capacity and also higher sensitivity. These subgroups should be considered key targets for adaptation planning. Critically, each of these subgroups has specific aspects of adaptive capacity that are lacking (Figure 17). These should be considered priority areas for reducing vulnerability.

4. DISCUSSION

This study has demonstrated how integrated vulnerability analyses that incorporate social and ecological processes could be calculated at the community and household scales. Such analyses can be used to identify trends and possible opportunities for adaptation in the face of climate change. In particular, this study has shown that local-level management can influence the sensitivity and recovery potential of corals and associated fish assemblages, ultimately reducing exposure in the social domain (in contrast to ecological exposure, which can only be reduced by international action to reduce carbon emissions). Similarly, social adaptive capacity and sensitivity are also amenable to policy actions at local and national scales. In simple terms, local-level actions can help to reduce the vulnerability of coastal communities to the impacts of bleaching-induced coral mortality.

However, the results of this study highlight the fact that one-size-fits-all adaptation planning is unlikely to be helpful. The study has highlighted where specific aspects of adaptive capacity were relatively low and where different types of sensitivity were relatively high – both geographically (i.e. for different communities) and also for different segments of society (i.e. migrants vs non-migrants). Adaptation planning is likely to be more effective if it can reflect of existing capacities. Again, in simple terms, people have different types of vulnerabilities and different strengths that require consideration.

By examining the types of vulnerability that different communities and segments of the population have (e.g. Figure 17 and Figure 18), different policy priorities become apparent (Table 6). Policy responses to reduce exposure or sensitivities may be impact-specific and thus relevant where the key impacts are known. Where the relative importance of different global change impacts are unknown, the most appropriate policy impact from this analysis may be to identify how generic adaptive capacity of communities can be enhanced, as it should help people to adapt to a range of (even unforeseen) climate impacts and opportunities. Some aspects of the vulnerability metric, such as infrastructure, can be directly and predictably enhanced by physical development projects, while other livelihood or cognitive dimensions are not so amenable to enhancement by central government (Table 6). Non-governmental organizations and development organizations may be better placed to build these aspects of adaptive capacity.

TABLE 6
Possible policy responses to influence different types of social-ecological vulnerability

Vulnerability component	Potential to influence	Possible policy actions for enhancement
Social exposure (i.e. ecological vulnerability)	Medium	Develop local-level management to increase ecological recovery potential and ecological sensitivity (e.g. marine protected areas, gear-based management).
Social sensitivity		
Gear sensitivity	High	Promote the use of gear types less likely to be negatively affected by coral bleaching (e.g. hand lines)
Occupational sensitivity	Medium	Develop supplemental livelihood activities
Social adaptive capacity		
Capacity to change livelihood	Low	Skills and capacity building
Access to credit	High	Microcredit schemes, support for community savings
Community infrastructure	High	Infrastructure development projects in rural areas
Gear diversity	Low	Training, gear provision
Trust	Low	Eradication of corruption
Occupational multiplicity	Low	Support for economic growth
Wealth (MSL)	Low	Poverty alleviation plans and pro-poor growth policies
Recognition of human agency	Medium	Education and participation in research
Social capital	Medium	Support for community initiatives/organizations

FURTHER RESEARCH PRIORITIES

This study has advanced the application of climate change impact and adaptation theory to empirical data, and identified several key gaps in understanding that require further research. These include:

1. The relative importance of different components of adaptive capacity for adapting to different types and magnitudes of impacts over time. For example, how is it possible to understand the trade-off between infrastructure and wealth resources with development and the loss of occupational flexibility?
2. The susceptibility of fish (particularly non-reef-associated species) to climate impacts other than coral bleaching.
3. Species-specific responses to bleaching of five key fishes that make up a large proportion of the catch. These are: *Leptoscarus vaigiensis*, marbled or green parrotfish; *Lethrinus lentjan*, pink ear emperor; *Calotomus carolinus*, Carolines parrotfish; *Cheilio inermis*, cigar wrasse; and *Anampses caeruleopunctatus*, bluespotted wrasse.

APPLICATION OF THIS METHODOLOGY TO OTHER VULNERABILITY MAPPING EXERCISES

This study used the example of coral bleaching impacts on fisheries as a proxy for climate change impacts on reefs. Thus, the results regarding exposure and sensitivity are specific to this particular climate change impact and impact pathway. Climate change is a multifaceted threat that comprises multiple interacting impacts on fisheries (Daw *et al.*, 2009). The approach outlined here could be adapted and expanded to conduct vulnerability analysis for other climate change impacts, such as impacts of bleaching on other ecosystem services (e.g. tourism), which would require different social sensitivity indicators, and climate impacts on seagrass ecosystems, which would require new indicators of ecological exposure, sensitivity and recovery potential. Given the uncertainties around the processes driving vulnerability, any vulnerability analysis such as this should be accompanied by caveats and sources of uncertainty, which should be considered when they are used to guide adaptation policy. The key caveats associated with this study are listed below.

SPECIFIC CAVEATS FOR THE RESULTS OF THIS VULNERABILITY ANALYSIS

The present study is the most comprehensive of its kind, particularly for reef fisheries. However, there are a number of caveats that must accompany the results of this vulnerability analysis. These include:

1. The adaptive capacity index is relatively generic to a wide range of impacts. However, the indices of exposure and sensitivity are specific to the impacts of coral bleaching on fisheries production. Direct impacts of climate change on fisheries through coral bleaching may, in the short term, be overwhelmed by existing trends such as overexploitation (e.g. Grandcourt and Cesar, 2003), or the knock-on effects of climate impacts on other related systems, such as such as demographics, migration and the provision of food and employment from agriculture. The relative values of this community vulnerability index may not hold for other global change impacts.
2. The method predicts future sensitivity and adaptive capacity based on a snapshot of current conditions. Thus, the indices are subject to considerable uncertainty over the ability of people to adapt, for example, for gear types to target non-affected species or for fishers to change gear. It is also limited to predict vulnerability in the face of large-scale systematic change or reorganization that may result from climate impacts or other external forces such as development projects (e.g. port development and complete economic and social restructuring of communities around Lamu).
3. While this study focuses on impacts on currently targeted species and current modes of livelihood occupation, climate change may also generate novel possibilities for exploitation. For example, climate anomalies in Peru that severely affected the dominant anchovy fishery also created opportunities for exploitation of different species in different areas, which were taken up fishers who had the spatial and technological flexibility to exploit them (Badjeck *et al.*, 2010).

4. Ecological indicators and available data are focused on coral-reef fish species, while non-coral associated species (e.g. *Leptoscarus* and *Siganus sutor*) make up a significant proportion of catches for the gear types studied. In addition, pelagic or semi-pelagic fish (e.g. barracuda) and non-fish resources (e.g. lobsters, octopus) are also significant fishery resources supporting livelihoods and food security.
5. The adaptive capacity indicator is applied with the assumptions that: (i) all relevant components of adaptive capacity are captured (necessarily the components recorded are based on pragmatic considerations of measurability or availability of data); (ii) each component of adaptive capacity is well represented by the indicators used (for example, the use of membership of organizations as an indicator of social capital has been questioned [Krishna, 2002]); and (iii) a non-weighted average of adaptive capacity indicators properly reflects the importance of different dimensions of adaptive capacity (for example, it is currently unknown how the trade-off between occupational multiplicity and wealth should be represented within an adaptive capacity index).

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APPENDIX TABLES

TABLE A1.1

Ecological vulnerability indicators of exposure, sensitivity and recovery potential for 17 ecological sites in Kenya

				Exposure	Sensitivity		Recovery potential						
Site no.	**Community**	**Management**	**Ecological site**	**Exposure, stress model**	**Coral susceptibility index**	**Fish susceptibility index**	**Coral cover, %**	**Coral size, CV**	**Coral richness, no. genera**	**Rugosity**	**Fish biomass, kg/ha**	**Herbivore diversity, Simpson index**	**Grazing to algal production, kg/day**
1	Vanga	Fished	Vanga	0.65	13.34	0.43	20.96	0.47	19	1.22	229.72	0.14	27.82
2	Shimoni	Fished	Changai	0.55	15.65	0.49	43.94	0.49	25	1.18	254.83	0.21	53.21
3	Shimoni	Park	Kisite	0.60	17.19	0.39	49.91	0.63	25	1.30	1 643.39	0.59	58.84
4	Kibuyuni	Tengefu	Kibuyuni	0.57	15.89	0.48	46.50	0.76	24	1.24	161.97	0.22	–49.64
5	Funzi	Fished	Funzi	0.59	15.56	NA	30.63	NA	20	NA	NA	NA	NA
6	Gazi	Fished	Gazi	0.60	15.40	0.31	12.02	0.59	18	1.33	107.76	0.04	–21.70
7	Tiwi	Tengefu	Tiwi	0.60	14.47	0.39	30.20	0.40	14	1.18	69.07	0.02	31.17
8	Bamburi	Fished	RasIwatine	0.67	16.04	0.30	7.10	0.39	15	1.22	96.46	0.08	–71.96
9	Bamburi	Park	Mombasa	0.67	13.74	0.35	20.23	0.71	19	1.27	867.97	0.72	–37.95
10	Mtwapa	Fished	Mtwapa	0.59	15.82	0.33	26.36	0.61	22	1.23	153.25	0.20	–43.42
11	Kanamai	Fished	Kanamai	0.59	17.90	0.34	34.77	0.36	14	1.21	70.60	0.02	34.01
12	Kanamai	Tengefu	Mradi	0.59	15.51	0.37	54.58	0.61	22	1.27	440.43	0.52	18.56
13	Takaungu	Fished	Takaungu	0.63	16.98	0.34	26.16	0.54	13	1.21	364.08	0.55	–12.66
14	Kuruwitu	Tengefu	Kuruwitu	0.63	17.28	0.36	0.76	0.59	14	1.18	91.10	0.55	–165.38
15	Mayungu	Fished	Mayungu	0.62	14.22	0.34	31.51	0.78	16	1.55	1 320.94	0.54	–35.42
16	Mayungu	Park	Malindi	0.62	16.33	0.34	7.28	0.42	17	1.17	204.99	0.43	–151.95
17	Mayungu	Park	Watamu	0.68	17.63	0.37	27.18	0.48	21	1.36	711.05	0.26	–65.08

Note: Detailed description of the rational for indicators and how indicators were calculated can be found in Table 1 and the Methods.

TABLE A1.2

Dimensions of ecological vulnerability for 17 coral reef sites in Kenya

Site no.	Community	Management	Ecological vulnerability	Exposure	Sensitivity	Recovery potential
14	Takaungu	Fished	0.79	0.63	0.27	0.11
17	Mayungu	Park	0.76	0.68	0.30	0.22
5	Funzi	Fished	0.74	0.59	0.34	0.20
8	Bamburi	Fished	0.74	0.67	0.15	0.08
16	Mayungu	Fished	0.73	0.62	0.21	0.10
11	Kanamai	Fished	0.73	0.59	0.28	0.14
4	Kibuyuni	Tengefu	0.69	0.57	0.34	0.22
13	Kuruwitu	Tengefu	0.67	0.63	0.24	0.20
2	Shimoni	Fished	0.67	0.55	0.35	0.23
7	Tiwi	Tengefu	0.65	0.60	0.18	0.13
1	Vanga	Fished	0.65	0.65	0.18	0.17
10	Mtwapa	Fished	0.59	0.59	0.18	0.17
6	Gazi	Fished	0.59	0.60	0.14	0.15
12	Kanamai	Tengefu	0.51	0.59	0.21	0.29
3	Shimoni	Park	0.51	0.60	0.30	0.40
9	Bamburi	Park	0.51	0.67	0.11	0.28
15	Mayungu	Park	0.42	0.62	0.12	0.31

Notes: Ecological vulnerability was calculated from normalized and weighted indicators as (Exposure + Sensitivity) – Recovery Potential. Sites are ranked from most vulnerable to least vulnerable.

TABLE A1.3

Gear sensitivity scores by community

Community	Beach seine (%)	Line (%)	Net (%)	Spear (%)	Trap (%)	Other (%)	Community aggregate of gear sensitivity to coral decline (inverse of response to decline)
Bamburi	0.0	36.4	54.5	0.0	13.6	18.2	–0.30 (±0.18)
Funzi	11.1	27.8	11.1	0.0	11.1	72.2	–0.11 (±0.24)
Gazi	35.5	0.0	45.2	3.2	6.4	16.1	–0.02 (±0.23)
Kanamai	0.0	5.9	47.1	58.8	5.9	5.9	–0.22 (±0.08)
Kuruwitu	0.0	7.4	66.7	40.7	0.0	33.3	–0.23 (±0.06)
Mayungu	33.3	20.8	20.8	0.0	12.5	25.0	–0.05 (±0.26)
Mtwapa	14.8	11.1	63.0	25.9	3.7	14.8	–0.19 (±0.18)
Shimoni	0.0	20.8	20.8	8.3	50.0	54.2	–0.12 (±0.10)
Takaungu	8.3	8.3	62.5	25.0	0.0	16.7	–0.20 (±0.16)
Vanga	66.7	3.7	11.1	0.0	11.1	22.2	0.14 (±0.24)

TABLE A1.4

The 11 adaptive capacity indicators aggregate values at community level shown as a percentage or mean ± standard deviations

Community	Access Credit	No Debt	Human Agency	Occupational Multiplicity	Capacity to Change	Trust	Gear Diversity	Social Capital	Occupation al Mobility	Community Infrastructure	MSL
Bamburi	43.3	80.0	63.3	1.90 (±1.32)	73.3	3.07 (±1.05)	1.23 (±0.53)	1.30 (±0.75)	3.3	24	0.7 (±1.23)
Funzi	15.0	90.0	90.0	2.30 (±1.49)	60.0	3.26 (±0.9)	1.33 (±0.49)	0.30 (±0.66)	0.0	09	–0.25 (±0.32)
Gazi	26.3	89.5	47.4	1.95 (±0.9)	57.9	3.54 (±0.81)	1.06 (±0.25)	0.53 (±0.6)	7.9	13	–0.24 (±0.88)
Kanamai	60.7	64.3	53.6	2.25 (±1.53)	89.3	3.04 (±0.87)	1.35 (±0.49)	0.89 (±0.5)	3.6	10	–0.32 (±0.61)
Kuruwitu	58.8	70.6	70.6	2.41 (±0.78)	82.4	3.06 (±0.99)	1.48 (±0.58)	1.76 (±0.74)	0.0	14	–0.34 (±0.63)
Mayungu	53.3	73.3	46.7	2.83 (±3.34)	53.3	3.48 (±0.71)	1.13 (±0.34)	0.80 (±0.89)	0.0	12	–0.2 (±0.97)
Mtwapa	43.8	75.0	46.9	1.97 (±1.75)	65.6	3.27 (±0.85)	1.48 (±0.58)	0.97 (±0.47)	0.0	19	0.08 (±1.12)
Shimoni	60.0	55.0	70.0	2.53 (±2.39)	82.5	3.28 (±0.65)	1.58 (±0.78)	1.38 (±0.81)	0.0	18	0.35 (±1.18)
Takaungu	33.3	81.5	66.7	3.00 (±2.39)	22.2	3.04 (±0.85)	1.25 (±0.44)	0.74 (±0.53)	0.0	10	–0.28 (±0.74)
Vanga	40.7	77.8	66.7	1.81 (±0.92)	48.1	3.54 (±0.83)	1.15 (±0.36)	0.85 (±0.53)	50.0	16	0.39 (±1.17)

TABLE A1.5

Spearman correlations between the 11 adaptive capacity indicators (correlations conducted at the community scale)

	Access to Credit	**No Debt**	**Human Agency**	**Occupational Multiplicity**	**Capacity to Change**	**Trust**	**Gear Diversity**	**Social Capital**	**Occupational Mobility**	**Community Infrastructure**	**MSL**
Access to Credit	1.000										
No Debt	**–.976****	1.000									
Human Agency	–.158	.091	1.000								
Occupational Multiplicity	.321	–.358	.419	1.000							
Capacity to Change	**.709***	**–.636***	.158	.079	1.000						
Trust	–.297	.152	–.249	–.382	–.418	1.000					
Gear Diversity	.505	–.505	.378	.219	.626	–.523	1.000				
Social Capital	**.758***	**–.758***	.116	.139	**.661***	–.224	.620	1.000			
Occupational Mobility	–.143	.164	–.216	–.471	–.075	.314	–.541	–.157	1.000		
Community Infrastructure	.297	–.321	–.207	–.479	.297	.297	.182	**.709***	.157	1.000	
MSL	.055	–.079	.286	–.418	.224	.042	.164	.285	.068	.467	1.000

** Significant at 0.01.

* Significant at 0.05.

TABLE A1.6

Eigenvalues and percentage of variation explained by the different principal components (PCs)

	Eigenvalues	% of variance	Cumulative %
PC1	0.082	41.75	41.75
PC2	0.049	24.71	66.47
PC3	0.031	15.79	82.26

TABLE A1.7

Factor loadings of adaptive capacity indicators

	PC1	PC2	PC3
Social Capital	**0.842**	0.182	–0.045
Capacity to Change	**0.813**	0.319	0.059
Access Credit	**0.731**	**0.410**	–0.331
Community Infrastructure	**0.697**	**–0.641**	–0.209
Gear Diversity	**0.529**	**0.435**	**0.473**
Trust	–0.346	–0.336	–0.335
Occupational Multiplicity	0.004	**0.767**	0.292
MSL	**0.491**	**–0.757**	0.342
Human Agency	–0.027	–0.072	**0.971**

Note: Factor loadings greater than 0.4 (in bold) on any given principal component are generally considered to contribute substantially to that component.

TABLE A1.8

Absolute factor loadings, weights and normalized weights of each adaptive capacity indicator

	PC1	PC2	PC3	Weight	Normalized weight
Eigenvalues	**0.082**	**0.049**	**0.031**		
Social Capital	0.842	0.182	0.045	0.079	0.122
Capacity to Change	0.813	0.319	0.059	0.084	0.129
Access Credit	0.731	0.410	0.331	0.090	0.138
Community Infrastructure	0.697	0.641	0.209	0.095	0.145
Gear Diversity	0.529	0.435	0.473	0.079	0.121
Trust	0.346	0.336	0.335	0.055	0.084
Occupational Multiplicity	0.004	0.767	0.292	0.047	0.071
MSL	0.491	0.757	0.342	0.088	0.134
Human Agency	0.027	0.072	0.971	0.036	0.055

TABLE A1.9

Raw data of community descriptors (+/– SE, where applicable)

Community	Year	Number of households	Age (years)	% Fishers*	% Gleaners*	% Mariculture*	Fortnightly expenditure	Livelihood effect **	% Migrant
Bamburi	2008	9	47 (±12)	100	0	0	174 (±44)	0 (±0.5)	0
	2012	22	35 (±11)	100	0	0	172 (±65)	0.14 (±0.47)	27.3
Funzi	2008	17	45 (±19)	100	0	0	136 (±68)	0.12 (±0.33)	11.8
	2012	18	41 (±11)	100	0	5.6	197 (±86)	0.5 (±0.51)	16.7
Gazi	2008	8	35 (±15)	100	0	0	149 (±39)	0.13 (±0.35)	25
	2012	31	34 (±10)	100	0	0	226 (±89)	0.29 (±0.46)	32.3
Kuruwitu	2008	10	41 (±12)	100	0	0	145 (±61)	0.4 (±0.84)	0
	2012	28	37 (±12)	100	0	0	207 (±115)	0.25 (±0.44)	0
Mayungu	2008	11	35 (±10)	100	0	0	178 (±45)	–0.55 (±0.52)	0
	2012	25	33 (±10)	100	0	0	206 (±82)	0.2 (±0.41)	16
Shimoni	2008	9	34 (±10)	88.9	11.1	0	121 (±51)	0.67 (±0.5)	0
	2012	25	43 (±15)	100	0	4	338 (±301)	0.48 (±0.51)	24
Takaungu	2008	13	46 (±14)	100	7.7	0	126 (±43)	0.15 (±0.8)	7.7
	2012	24	40 (±14)	100	0	0	217 (±91)	0.04 (±0.69)	0
Vanga	2008	16	33 (±11)	100	0	0	157 (±59)	0.13 (±0.5)	12.5
	2012	27	40 (±13)	100	0	0	184 (±95)	0.26 (±0.53)	22.2

* Respondents could be engaged in multiple occupational categories. Consequently, the sum of these four columns could be > 100%.

** Recorded as the mean of a three-point Likert scale about the resource-users' perceptions of the impacts of comanagement on their livelihood, with –1 = comanagement had a detrimental effect on the respondent's livelihood, 0 = comanagement had a neutral effect on the respondent's livelihood, and +1 = comanagement had a beneficial effect on the respondent's livelihood.

Note: Fortnightly expenditures does not account for inflation between 2008 and 2012.

TABLE A1.10

Adaptive capacity indicators from 2008 and 2012 studies

Community	Year	% Access Credit	% Human Agency	Occupational Multiplicity	Trust	Gear Diversity	Social Capital	% Occupational Mobility	Community Infrastructure	MSL
Bamburi	2008	22.2	66.7	2.56 (±1.24)	3.21 (±0.81)	1.56 (±0.73)	1.44 (±0.73)	11.1	22	0.33 (±1.07)
	2012	36.4	72.7	2.09 (±1.44)	3.06 (±1.13)	1.23 (±0.53)	1.32 (±0.78)	4.5	24	0.57 (±1.41)
Funzi	2008	5.9	70.6	3.12 (±2.91)	3.52 (±1.17)	1.12 (±0.33)	0.24 (±0.44)	29.4	7	–0.51 (±0.22)
	2012	11.1	88.9	2.33 (±1.57)	3.32 (±0.93)	1.33 (±0.49)	0.22 (±0.55)	0.0	9	–0.27 (±0.34)
Gazi	2008	0.0	37.5	1.50 (±0.76)	3.45 (±0.91)	1.13 (±0.35)	1.00 (±0.76)	12.5	9	–0.45 (±0.50)
	2012	22.6	45.2	1.94 (±0.96)	3.55 (±0.83)	1.06 (±0.25)	0.45 (±0.57)	9.7	13	–0.45 (±0.60)
Kuruwitu	2008	30.0	90.0	4.00 (±3.02)	3.14 (±0.71)	1.30 (±0.48)	1.40 (±0.52)	0.0	10	–0.58 (±0.17)
	2012	53.6	75.0	2.46 (±0.74)	3.02 (±0.98)	1.48 (±0.58)	1.75 (±0.80)	0.0	14	–0.33 (±0.61)
Mayungu	2008	27.3	81.8	2.45 (±1.29)	2.91 (±0.69)	1.27 (±0.47)	1.20 (±0.42)	0.0	10	–0.44 (±0.41)
	2012	52.0	48.0	3.12 (±3.60)	3.55 (±0.72)	1.13 (±0.34)	0.68 (±0.80)	0.0	12	–0.31 (±0.80)
Shimoni	2008	22.2	44.4	1.78 (±0.97)	3.82 (±0.70)	1.22 (±0.44)	1.11 (±0.33)	0.0	14	–0.46 (±0.29)
	2012	44.0	72.0	2.84 (±2.95)	3.14 (±0.58)	1.58 (±0.78)	1.24 (±0.78)	0.0	18	0.29 (±1.21)
Takaungu	2008	23.1	76.9	5.00 (±3.70)	2.78 (±1.13)	1.62 (±0.77)	1.38 (±0.51)	0.0	10	–0.24 (±0.61)
	2012	29.2	70.8	3.17 (±2.46)	3.16 (±0.80)	1.25 (±0.44)	0.71 (±0.46)	0.0	10	–0.27 (±0.81)
Vanga	2008	31.3	56.3	2.94 (±2.43)	3.65 (±1.05)	1.19 (±0.40)	0.81 (±0.83)	0.0	17	0.53 (±0.74)
	2012	40.7	66.7	1.81 (±0.92)	3.54 (±0.83)	1.15 (±0.36)	0.85 (±0.53)	3.7	16	0.48 (±1.29)

TABLE A1.11
Sensitivity indicators from 2008 and 2012 studies

Community	Year	Gear sensitivity	Occupational sensitivity
Bamburi	2008	–0.28 (±0.18)	0.21
	2012	–0.30 (±0.21)	0.32
Funzi	2008	–0.43 (±0.19)	0.36
	2012	–0.11 (±0.26)	0.28
Gazi	2008	–0.19 (±0.13)	0.38
	2012	–0.02 (±0.25)	0.27
Kuruwitu	2008	–0.13 (±0.19)	0.23
	2012	–0.23 (±0.07)	0.23
Mayungu	2008	–0.31 (±0.24)	0.28
	2012	–0.05 (±0.28)	0.30
Shimoni	2008	–0.35 (±0.15)	0.25
	2012	–0.12 (±0.13)	0.26
Takaungu	2008	–0.24 (±0.21)	0.16
	2012	–0.20 (±0.17)	0.27
Vanga	2008	0.20 (±0.18)	0.40
	2012	0.14 (±0.24)	0.35

TABLE A1.12

Nested ANOVA results of variation of continuous adaptive capacity and sensitivity indicators among factors: Year, Age, Fortnightly expenditure, Livelihood Effect, Migrant, and Expenditure

Factor	Indicator	Df1	Df2	F value	p value
Year	OccupMult	1	277	1.01	0.32
(nested by community)	SocialCapital	1	276	0.95	0.33
	Trust	1	276	0.03	0.87
	MSL	1	277	0.08	0.78
	CommInfrastr	1	277	113099.90	0.00***
	GearSensi	1	277	15.40	0.00***
Age	OccupMult	3	231	7.06	0.00***
(nested by year & community)	SocialCapital	3	230	3.21	0.02**
	Trust	3	231	1.40	0.24
	MSL	3	231	5.11	0.00***
	GearSensi	3	231	3.34	0.02**
Fort expend	OccupMult	3	238	1.00	0.39
(nested by year & community)	SocialCapital	3	237	2.18	0.09*
	Trust	3	237	1.90	0.13
	MSL	3	238	0.40	0.75
	GearSensi	3	238	2.33	0.07*
Livelihood Effect	OccupMult	2	254	1.20	0.30
(nested by year & community)	SocialCapital	2	253	3.24	0.04**
	Trust	2	253	2.83	0.06*
	MSL	2	254	0.58	0.56
	GearSensi	2	254	5.11	0.01**
Migrant	OccupMult	1	267	10.57	0.00***
(nested by year & community)	SocialCapital	1	266	12.59	0.00***
	Trust	1	266	2.03	0.15
	MSL	1	267	0.43	0.51
	GearSensi	1	267	14.02	0.00***
Decision	OccupMult	3	245	5.52	0.00***
(nested by year & community)	SocialCapital	3	244	6.41	0.00***
	Trust	2	245	2.67	0.07*
	MSL	3	245	0.62	0.60
	GearSensi	3	245	5.72	0.00***
Community	OccupMult	7	277	3.41	0.00***
(nested by year)	SocialCapital	7	276	17.35	0.00***
	Trust	7	276	2.20	0.03**
	MSL	7	277	9.92	0.00***
	GearSensi	7	277	20.27	0.00***

*** Significant at p = 0.01.
** Significant at p = 0.05.
* Significant at p = 0.1.
Note: ANOVAs were nested by Year and Community.

TABLE A1.13

Chi-square results of binomial adaptive capacity indicators among factors: Year, Age, Fortnightly expenditure, Livelihood Effect, Migrant, and Expenditure

Factor	Indicator	Df	Chi-square	p value
Year	AccessCredit	1	7.30	0.01***
	HumanAgency	1	0.00	0.98
	GearDiv	1	0.43	0.51
Age	AccessCredit	3	2.58	0.46
	HumanAgency	3	6.90	0.08*
	GearDiv	3	7.08	0.07*
Fort expend	AccessCredit	3	4.61	0.20
	HumanAgency	3	1.90	0.59
	GearDiv	3	2.95	0.40
Livelihood Effect	AccessCredit	2	2.54	0.28
	HumanAgency	2	1.83	0.40
	GearDiv	2	6.31	0.04**
Migrant	AccessCredit	1	1.03	0.31
	HumanAgency	1	10.77	0.00***
	GearDiv	1	5.51	0.02***
Decision	AccessCredit	3	7.03	0.07*
	HumanAgency	3	4.59	0.20
	GearDiv	3	9.03	0.03**
Community	AccessCredit	7	20.70	0.00***
	HumanAgency	7	16.98	0.02**
	GearDiv	7	19.82	0.01**

*** Significant at p = 0.01.
** Significant at p = 0.05.
* Significant at p = 0.1.