Identifying Reefs of Hope and Hopeful Actions: Contextualizing Environmental, Ecological, and Social Parameters to Respond Effectively to Climate Change

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Abstract: Priorities for conservation, management and associated activities will differ based on the interplay between nearness of ecosystems to full recovery from a disturbance (‘pristineness’), susceptibility to climate change (‘environmental susceptibility’) and capacity of human communities to cope with and adapt to change (social ‘adaptive capacity’). We studied 24 human communities and adjacent coral reef ecosystems in 5 countries of the southwestern Indian Ocean. Ecological measures of abundance and diversity of fish and corals along with estimated reef pristineness and socioeconomic household surveys were used to determine the adaptive capacity of communities adjacent to selected coral reefs. We also used Web-based oceanographic and coral mortality data to predict each site’s environmental susceptibility to climate warming. Coral reefs of Mauritius and eastern Madagascar had low environmental susceptibility and consequently were not predicted be affected strongly by warm water , although these sites were differentiated by the adaptive capacity of the human community. The higher adaptive capacity in Mauritius may increase the chances for successful self-initiated recovery and protective management of their reefs. In contrast, Madagascar may require donor support to build adaptive capacity as a prerequisite to preservation efforts. The Seychelles and Kenya had high environmental susceptibility, but their levels of adaptive capacity and disturbance differed. High adaptive capacity in the Seychelles could be used to develop alternatives to dependence on coral reef resources and to reduce the effects of climate change. Pristineness weighted toward measures of fish recovery was greatest for Kenya’s marine protected areas; however, most protected areas in the region reflect ecosystems that are far from pristine. Conservation priorities and actions with realistic chances for success require knowledge

of where socioecological systems lie among the 3 axes of environment, ecology, and society.

Introduction

A contemporary challenge for management of biodiversity is characterizing sustainable socioecological systems by coupling attributes of the environment, biological diversity, ecology, and social organization (Berkes & Folke 1998; Adger 2000). This perennial challenge is further heightened by environmental susceptibility to climate change, where the effects of local-scale resource extraction often interact with larger-scale disturbances caused by global climate change (Clark et al. 2001; McClanahan et al. 2006a, 2008). Integrating these factors is becoming increasingly urgent for conservation of coral reefs, where large-scale and acute warm-water events have caused widespread environmental stress, bleaching, and mortality of corals (Wilkinson 2004), particularly in the Indian Ocean (McClanahan et al. 2007a).

Environmental factors create conditions for coral bleaching and mortality (Coles & Brown 2003), and these have been modeled, tested with field observations, and used to predict the susceptibility of sites in the western Indian Ocean (Maina et al. 2008). This is leading to a better understanding of management needs and activities based on susceptibility to climate change (West & Salm 2003; Wooldridge & Done 2004; McClanahan et al. 2008). These efforts are necessary and laudable, but they are based largely on environmental and biological attributes without adequate consideration of the socioeconomic context (Chapin 2004). This may leave little scope for management actions in areas that are considered a low priority based on climate-change predictions (McClanahan et al. 2008a). Such a limited focus can undermine proposed biodiversity conservation actions that depend on the capacity of social and governance systems to adapt to change (Folke 2006).

An increasingly critical aspect of conservation planning and action is understanding and incorporating the heterogeneity in peoples' ability to cope with or adapt to changes in coral reefs and fishery resources resulting from environmental change or management interventions (Christie et al. 2005; Folke 2006; Adger 2006). The common assumption among conservation biologists is that fisheries closures benefit people by improving or maintaining fish catch. However, these net benefits may not be realized unless resource extraction is already beyond some maximum sustained yield (Sladek-Nowlis & Roberts 1999), may not be equitably distributed among people, and may not be perceived by potential beneficiaries (Berkes 2004; McClanahan et al. 2005). Additionally, people with low adaptive capacity may not be able to tolerate the hiatus in resources during recovery times, adapt to changes in regulations, or take advantage of opportunities created by conservation. Here we define *social adaptive capacity* (AC), as a latent characteristic of people that reflects their ability to anticipate and respond to changes in coral reef ecosystems and to minimize, cope with, and recover from the consequences of a loss in fisheries production.Not fully considering these 3 factors can lead to poor support or compliance with any proposed management that restricts resource use, often resulting in closures that do not differ ecologically from fished areas (McClanahan et al. 2006b).

Simultaneously studying environmental, ecological, and social systems is difficult because each of these systems is complex and hierarchically organized such that there is considerable interdependence within and between systems (Odum 1988). Knowing what, how much, and which part of the hierarchy of the 3 systems to compare is a challenge because of theory and the trans-disciplinary nature of the investigations. Studying the foundation of systems is a good starting place because the hierarchies are built on and depend on these foundations. Key environmental parameters in the oceanographic environment are water temperature, light, and currents. In coral reef ecosystems, coral-algal relationships are the foundation of the ecology, productivity, and architectural complexity that support many fish and invertebrates used by people. Fish provide the main link between the ecology of coral reefs and coastal households. The fundamental unit of social organization is the household, where individuals produce and share resources, and actions that destabilize the household are likely to meet with considerable resistance (Jentoft et al. 1998).

In a previous paper (McClanahan et al. 2008a), we developed a framework for conservation action based on different combinations of environmental and social parameters. Here we add a third consideration, ecology, and evaluate it on the basis of our study of coral reefs in the western Indian Ocean to better contextualize the inferences. Our framework for conservation priorities and actions is that the appropriate response depends on elements of environment, ecology, and society, which can each be described by an axis (Fig. 1). We examined the physical oceanographic environment that creates conditions for coral bleaching, ecological aspects of corals and fishes that link physical oceanography to human food, and coastal households that can be vulnerable to the condition of their resources and influence the success of coral reef management actions. To develop a basis for contextualizing management needs in the western Indian Ocean, we compared the susceptibility of the physical environment to coral bleaching, nearness of sites to an undisturbed state (pristineness), and the adaptive capacity of adjacent coastal communities in 24 sites across 5 countries of the western Indian Ocean.

Methods

Study Sites

Data were collected from 24 human communities around 27 coral reef sites that spanned 5 regions in the western Indian Ocean (Fig. 1): southern Kenya, Tanzania, granitic Seychelles, Mauritius, and Madagascar. We collected 3 types of data at each site: environmental susceptibility (ES), or the conditions that create stress for corals, where oceanographic data were extracted from an Indian Ocean scale stress model (Maina et al. 2008); people were interviewed and their answers at each site were used to construct a social AC index; and, lastly, the abundance of fish and benthic cover variables in fished and unfished reefs, were measured by standard field methods.

Environmental Susceptibility Model

Existing data on coral bleaching and oceanographic conditions at selected sites were used to map thermal stress throughout the 5 regions (Maina et al. 2008). The model and map were based on 10 environmental variables in which 4 were derived from sea surface temperature (mean, maximum, coefficient of variation, and degree heating weeks), photosynthetically active radiation, ultraviolet radiation, chlorophyll, surface currents (zonal and meridional), and wind velocity . The model used in situ coral bleaching data collected between 1998 and 2005 from 216 sites (www.reefbase.org) and data collected in 2005 from 91 sites (McClanahan et al. 2007a) to correlate the environmental factors with bleaching intensity at these specific sites and times.

Environmental data that were significantly correlated with bleaching were used in a GIS fuzzy logic process and spatial principal component analysis (SPCA) to yield susceptibility relationships and models. These were then synthesized into a single environmental susceptibility map by summing 7 principal components weighted by their relative contribution. We used coral mortality across 1998 El Niño Southern Oscillation (ENSO) for 16-reef locations in the western Indian Ocean to test the model, and model fit was reasonable fit (r^2 = 0.27 and 0.50 when removing 2 outliers, Maina et al. 2008).

Social Adaptive Capacity Index

We used the social adaptive capacity index (McClanahan et al. 2008) to scale the community's tolerance to disturbance. To develop this indicator, we conducted household surveys and key informant interviews in 24 sites (Table 1). We determined 8 indicators of adaptive capacity on the basis of the socioeconomic surveys: (1) recognition of causal agents influencing marine resources (measured by content- organizing responses to open-ended questions about what affects the number of fish in the sea); (2) capacity to anticipate change and develop strategies to respond (measured by organizing responses to open-ended questions relating to a hypothetical 50% decline in fish catch); (3) occupational mobility (indicated as whether the respondents changed jobs in the past 5 years and preferred their current occupation); (4) occupational multiplicity (the total number of jobs people in the household had; (5) social capital (total number of community groups the respondent belonged to; Pretty & Ward 2001); (6) material assets (15 factors, e.g., whether a respondents had a vehicle or electricity and the type of walls, roof, and floor in the house, McClanahan et al. 2008a): (7) technology (measured as the diversity of fishing gears used); and (8) infrastructure (20 factors, such as whether the community had a hard-top road and medical clinic [Pollnac 1998]).

Our index of adaptive capacity was calculated as the weighted average of the 8 indicators. We used the analytic hierarchy process to determine the weightings for each indicator (Saaty 1980). The process provides a framework used to derive ratios from simple pair-wise comparisons and produces a continuous response variable that weights responses on the basis of known information or expert advice (Forman & Gass 2001). For adaptive capacity, 10 social scientists individually conducted pair-wise comparisons of all 8 indicators. Bray-Curtis similarity indices between researchers' weightings ranged from 73-92% (mean 80%). We used an average of the scientists' weightings to calculate adaptive capacity for each community (Table 1) (see McClanahan et al. [2008a] for indicator weightings).

Ecological Field Studies

Field sites were most frequently selected so we could compare the ecology of managed and unmanaged areas, and we selected unmanaged areas that would be as similar to the managed areas as possible in terms of reef structure, depth, and dominant substratum (McClanahan & Graham 2005). Four types of ecological data were collected at each site, including hard coral cover, coral community susceptibility to bleaching, fish biomass (>10 cm), and numbers of fish species in selected families.

Percent cover of live hard coral (expected to reflect mortality and recovery from coral bleaching in 1998) was quantified with line intercept transects at each location in

2005. At each site a genus-level survey of corals was used to calculate the susceptibility of the coral community to anomalous temperatures. The bleaching susceptibility (*S*) index of each site was based on the relative density of each coral genus at each site and a bleaching response index of each genus, derived from the responses of ~37,000 coral colonies in 49 taxa to warm water at 91 Indian Ocean sites (McClanahan et al. 2007a [see erratum for correct equation]). A more susceptible community is relatively undisturbed by warm water anomalies and is composed of corals sensitive to climate disturbances that have frequently had their numbers reduced by previous climate impacts (McClanahan et al. 2007a). Fish species richness per 500 m^2 (*R*) was calculated for the families Chaetodontidae, Labridae, Scaridae, and Acanthuridae, which we selected because they respond differently to habitat and coral mortality (Graham et al. 2006; Wilson et al. 2006). We calculated overall fish biomass >10 cm (*F*, kilograms per hectare) at each site as an indicator of the effects of fishing and years of closure from fishing (Jennings & Polunin 1997; McClanahan & Graham 2005).

We normalized these 4 variables to scales of 0-1 and combined them into a common metric with the analytic hierarchy process (AHP) to create a weighted average. Variables known to display the greatest response and slowest recovery to the disturbances, fishing and climate change were weighted according to their known response. Two pristineness indices were calculated, one weighted toward the large-scale climate disturbance in which coral cover and bleaching susceptibility were given more weight (coral prinstineness [CD]) and the other toward local fishing disturbances in which fish species richness and biomass were attributed more weight (fish pristineness [FD]). Having 2 indices distinguished the impacts of large climate-mediated coral bleaching disturbances from those of small-scale fishing-related disturbance. Mean site CP was calculated as italicize S, C, R, and F; fix all, remainder not marked

$$\mathrm{CD} = \mathrm{S} \times 0.35 + \mathrm{C} \times 0.35 + \mathrm{R} \times 0.19 + \mathrm{F} \times 0.10 \text{ and } \quad \textbf{(1)}$$

mean site FP was calculated as

$$\mathrm{FD} = \mathrm{S} \times 0.20 + \mathrm{C} \times 0.12 + \mathrm{R} \times 0.20 + \mathrm{F} \times 0.49 \text{ , } \quad \textbf{(2)}$$

where *S* is the coral-bleaching-susceptibility index (McClanahan et al. 2007a), *C* is coral cover, *R* is fish species richness, and *F* is fish biomass, each multiplied by their respective weightings. These ecological weights did not require expert advice because they were derived from known disturbance sensitivity and recovery values from fishing and large-scale bleaching (McClanahan et al. 2005, 2007c).

Data Plotting

We sought to evaluate our field sites in terms of environmental vulnerability, ecology, and social adaptive capacity (Fig. 1). Consequently, we plotted environmental susceptibility values for a site against respective pristineness values (CP and FP) to assess the reefs' dispersion patterns. These dispersion patterns were used to project the reefs long-term status derived from the climate-change environmental stress model. The social AC metric was also plotted against both CP and FP to assess AC in relation to the ecological measures.

Use of *disturbance* in results will change the way the variable is described…i.e., Mauritius had the lowest CP, as opposed to the highest pristineness.

Results

Environmental susceptibility (ES) of the study sites ranged from 0.22 to 0.66. Mauritius and eastern Madagascar had the lowest, Tanzania moderate, and Kenya, Seychelles, and western Madagascar the highest ES levels. Coral pristineness indicated considerable scatter, but the low ES sites were generally the most pristine and a site in Mauritius had the highest CP value of all (Fig. 2a). Two sites in Tanzania, 2 protected areas in Kenya, and the sites in western Madagascar also had high CP. Sites with low values included Kenya, Seychelles, and 2 Tanzanian sites. Fish pristineness had an equally high scatter, but most fished sites had lower values than unfished sites (Fig. 2b). The highest FP was in Kenya's marine protected areas at the high end of ES. FP values were moderate for one Tanzanian site (the oldest managed site in the Tanga Coastal Zone Conservation and Management Programme) and western Madagascar. Most other sites, including a number of protected areas in Mauritius and Seychelles, had low FP, and Kenya's fished reefs had among the lowest values.

Mean social adaptive capacity (AC) of the sites ranged from 0.28 to 0.53. The mean AC for all sites was 0.41 (SD 0.07). On a national level, Madagascar had the lowest, Kenya and Tanzania low to moderate, and Mauritius and Seychelles moderate to high AC levels (Fig. 3).

Discussion

Many ecological or biodiversity surveys are intended to scale sites along axes of uniqueness or abundance and diversity of key taxa. These scales or ranks can then be used to develop priorities for conservation (Roberts et al. 2002; Leslie et al. 2003). We add 2 additional and pertinent dimensions to this scaling that further separate sites with similar ecological characteristics across oceanographic and socioeconomic environments. These axes are seldom considered or quantified despite being important for management efforts because they indicate potential effects of future climate change (ES) and the ability of people to anticipate and respond to changes in coral reefs and fishery resources (McClanahan et al. 2008a). Several factors influence these axes, and we believe the position of the sites along these axes suggest the most plausible management options (Fig. 1).

There are 2 key methodological issues to consider when using aggregated indicators. First, the practical significance of observed differences in aggregate indicators can make it difficult to identify those specific factors that most influenced the responses. Second, indicator weighting on the basis of expert advice can be subjective. With our adaptive-capacity scores we attempted to address this by using a structured method (AHP) to average weighting of indicators by multiple scientists that had done social survey work in the region. The ecological pristineness values were based on ecological surveys with good time series responses to disturbances and were probably applicable to the region, but some measures were based only on Kenyan studies.

Pristineness Axis

Coral and fish pristineness values showed different patterns. Coral pristineness most likely reflected large-scale environmental pristinenesss, such as the 1998 ENSO and bleaching event (McClanahan et al. 2007a). Reefs with high CP were in the southern Indian Ocean, notably Mauritius and eastern Madagascar, that appear to have either escaped massive mortality in 1998 and other large-scale climatic disturbances or were quick to recover from them (Obura 2005; McClanahan et al. 2007a). Tanzanian CP was intermediate, and comparisons with Kenyan reefs indicated they either had greater acclimatization or adaptations that give them resilience to climate change or the ability to recover more quickly from these disturbances (McClanahan et al. 2007a,b).

Fish pristineness most likely indicated the effects of local-scale fishing pressure and management, including the effectiveness of protection from fishing. Kenya's no-take protected areas stood out among the few sites that maintained conditions most representative of fish communities undisturbed by heavy fishing and indicated that approximately 10 years of protection were required for the recovery of fish diversity, whereas ≥ 40 years may be needed for full recovery of biomass and community structure (McClanahan & Graham 2005; McClanahan et al. 2007c). Consequently, the variable with the longer length of time for recovery was given a proportionally higher weight. Kenyan protected areas were of modest size (~10 km^2), embedded in areas with heavy fishing, and unlikely to represent the large-scale pristine conditions characteristic of remote unpopulated areas (Stevenson et al. 2007; S.A. Sandin et al. 2008. Baselines and degradation of coral reefs in the Northern Line Islands. Public Library of Science ONE **3**:e1548) (see comment on p. 17), which indicates that all our studied sites, including protected areas, experienced human influences.

When composite indices are used, it can sometimes be difficult to ascertain the driver of patterns. Although an index may be weighted to one measure, the response can be driven by other measures for which differences between measures are large. It is therefore important to identify cases in which interpretation of the plot may be obscured by weighting effects. In both CP and FP indices, the fished area of western Madagascar had higher values than the protected area. Although fish biomass was higher in the protected than fished area, the effect was modest and the 3 other measures that contributed to the pristineness scores were greater in the fished area. Similarly, the Kenyan protected areas had much higher CP values, when only one of the PAs had higher coral cover. This is because the great differences in fish biomass and diversity between fished and unfished areas in Kenya enhanced the CP scores of the protected sites. A similar, but weaker, effect also occurred in the Seychelles protected areas. For Mauritius, higher coral cover in the protected areas was not heavily reflected in the CP value due to low fish variables. However, the use of these composite variables including measures related to both fish and corals was justified here because fishing has an impact beyond fish (McClanahan et al. 2006a) and coral bleaching has an impact beyond corals (Graham et al. 2006; N.A. J. Graham et al. 2008. Climate warming and the ocean-scale integrity of coral reef ecosystems. Public Library of Science ONE DOI: 30310.31371). (We don’t cite PLoS ONE publications in Literature Cited because the review process of these papers is inconsistent and is still being debated.)

Environmental Susceptibility Axis

The ES axis model had the highest stress scores in the northern Indian Ocean, mostly in a belt from northern Kenya to the Maldives (Maina et al. 2008), where coral reef communities have been substantially transformed (McClanahan et al. 2007a). Greater seawater temperature variability and lower light intensity in the southern Indian Ocean helped explain the lower ES values there, and the sites were among those most likely to persist without major ecological transformations. Large and possibly irreversible changes have already been reported for the Seychelles and some Kenyan sites (Graham et al. 2006, 2008; McClanahan et al. 2007a). Western Madagascar had among the highest ES levels, but there is little evidence for any permanent changes in these sites, which maintain high coral biodiversity (Veron & Turak 2005). This may represent an error in the predictive capacity of the model or some other aspect of the reef ecology, such as high coral acclimatization and recovery rate, as has been suggested for Tanzania (McClanahan et al. 2007b). Potential weaknesses in the ES model result from not including potentially important variables, such as light absorption from factors other than chlorophyll, tides, and small-scale upwelling and eddies, and factors associated with the coarse spatial resolution that cannot account for fine-scale environmental conditions that may influence our specific sites. Improved resolution of the satellite data and collecting the above measurements will be needed to improve the model's predictive capacity. The current ES model only partially predicts the ES of sites to warm-water bleaching and is not useful for predicting disturbance recovery rates. The predictions of the model for low ES and persistence of Mauritian reefs were supported by results of bleaching and biodiversity surveys that show intact coral communities contain highly susceptible taxa (Moothien Pillay et al. 2002).

Social Adaptive Capacity Axis

The AC variable creates a proxy for a communities' ability to anticipate and adapt to changes in coral reef ecosystems. In general, communities in Kenya, Tanzania, and particularly Madagascar will struggle to cope with disruptions to the flow of ecosystem goods and services that coral reefs provide. These disruptions can arise from ecosystem degradation or the restriction of resource use through management interventions designed to conserve coral reefs. Consequently, conservation initiatives in areas with low AC should seek to minimize the impacts of management on local livelihoods and build AC through poverty alleviation, infrastructure development, and building social capital.

Despite broad national-level differences in AC, we also found a considerable spread within countries. Urbanized areas with higher levels of economic development and a greater range of livelihood options tended to have higher levels of AC. For example, the periurban sites in Kenya and Tanzania had similar AC to some sites in Seychelles and higher AC than several Mauritian sites. We believe this is a novel metric that can be used to improve and tailor conservation policies and strategies that measure intra-country differences in the ability of communities to anticipate and cope with environmental change.

Integrating social, environmental, and ecological axes

Incorporating these social, environmental, and ecological dimensions into conservation planning can assist local and national management institutions and donors to develop more nuanced policy and management options for coral reef sites in the region

(McClanahan et al. 2008a). The approaches to management and conservation priorities will differ in the countries studied because of the differences in the interplay between pristineness, ES, and social AC, and we suggest 8 possible strategies for the 3 gradients established by the 3 axes, of which 2, adaptive capacity and pristineness, are locally manageable (Fig 1). Social organization can affect adaptive capacity and requires either relieving or building it when it is low and when it is high using it to protect, preserve, adapt, or transform the ecology depending on environmental susceptibility and pristineness. Resource management can also potentially manage pristineness, which means restoration when it is low and preservation when it is high and environmental susceptibility is low. When both ES and AC are high, ecosystems are likely to be transformed and humans will need to be involved in engineering or reorganizing unique forms of biodiversity and ecosystems that will potentially replace the ecosystem services lost by climate disturbances. Examples of appropriate management strategies from our study region follow.

Sites with high levels of pristineness that are likely to persist unchanged through climate change are typically considered a high priority for protective conservation strategies (Sanderson et al. 2002; West & Salm 2003). Among our locations, coral reefs in Mauritius and eastern Madagascar are expected to survive better than elsewhere due to their oceanographic characteristics. However, AC and pristineness differed considerably between the locations and therefore in appropriate management strategies. Higher AC in Mauritius suggests that local communities should be able to adapt and take advantage of the opportunities arising from a system of protected areas. In this country, if local fishing effort is reduced, luxury, eco- and local tourism are likely to be the larger impacts that will require managing (Hunter & Shaw 2006). Mauritian marine protected areas (MPAs) exist in an essentially urbanized seascape and consequently have considerable potential for beach tourism and revenue generation among the many other economic alternatives provided by urbanization. However, due to the small area under protection and intense fishing pressure, they are not likely to approach undisturbed or pristine ecological conditions and, based on the currently low FP index, require increased efforts to close areas to fishing and possibly stock fish populations. Marine protected areas (MPAs) in Mauritius are not notably different from unmanaged areas and restoration will require actions to increase both their size and management effectiveness.

Management systems for MPAs have been established in eastern Madagascar through the efforts of international donors and are currently directed by the national government with NGO technical assistance (Kremen et al. 1999). However, low AC of local communities suggests that it will be challenging for them to cope with changes in access to resources or to take advantage of opportunities generated through protected areas. Simultaneous efforts to enhance the AC of people and encourage self-compliance among those affected may be the most likely long-term solution. In the interim, management systems that require less coping by communities than entailed by the establishment of full closures, including gear restrictions and periodic closures, should be pursued (Cinner 2007; McClanahan et al. 2008b).

Sites with high ES, low pristineness, and low AC are of a lower priority for conservation efforts focused on protecting biodiversity. Efforts to preserve areas with high ES and protect them from climate change (have sites already been affected by climate change?) are potentially futile, but even in these sites there are opportunities to reorganize socioecological systems and reduce adverse impacts of change on resources and societies. Enhancing AC in these situations may require adapting and restoring ecosystems, allowing sustainable resource extraction of species that will not be adversely affected by climate change, reevaluating the sustainability for those species most affected by climate change, and decoupling local economies from natural resources. People or countries in this situation will require strategies that balance production and consumption of natural resources and management systems that do not accelerate adverse environmental or socioeconomic conditions. These societal transformations will likely include development assistance, such as poverty alleviation measures and disaster relief, to avoid mass emigration or evacuation from these sites, a phenomenon that has already begun in some regions and has been highlighted as a significant threat to human security (Adger et al. 2005).

Kenya's MPAs are highly disturbed and are influenced by high ES, but they have the most undisturbed fish communities due to a successful urban or periurban protected-area system that generates significant tourism revenue. Despite intense fishing pressure around the MPAs and high ES, Kenya's MPAs have produced among the most pristine conditions in this region, largely due to the failure of other countries in the region to implement and successfully manage fisheries closures. Kenya has achieved this with moderate AC. This may be largely due to the high levels of tourism in Kenya and may explain the strong differential support between resource users and managers (McClanahan et al. 2005). Although this system has been successful for increasing (increasing fish populations? meaning unclear) fish, a loss in tourism or increased climate-change effects has a high potential to jeopardize their future. Tanzania fell in an intermediate position on most measures of ES, AC, and ecological pristineness and requires a mix of management strategies and efforts.

Conclusions

The use of social and economic factors in prioritizing conservation efforts in response to loss of biological diversity and global climate change is important (Donner & Potere 2007). We present a way to combine environmental, ecological, and social factors in the process of planning future management efforts in a region where people depend heavily on coral reef resources and where differential responses to climate change are expected. We differentiated sites with 2 measures or scales of human disturbance and with environmental susceptibility and social adaptive capacity. The heterogeneity that sites displayed along these 3 axes supports our contention that further contextualization will improve the chances of making decisions with realistic chances of success in both the social and ecological spheres.

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Literature Cited

Adger, W. N. 2000. Social and ecological resilience: are they related? Progress in Human Geography **24**:347-364.

Adger, N. W. 2006. Vulnerability. Global Environmental Change **16**:268-281.

Adger, W. N., T. P. Hughes, C. Folke, S. R. Carpenter, and J. Rockstrom. 2005. Social-ecological resilience to coastal disasters. Science **309**:1036-1039.

Berkes, F. 2004. Rethinking community-based conservation. Conservation Biology **18**: 621-630

Berkes, F., and C. Folke 1998. Linking social and ecological systems. Cambridge University Press, Cambridge, United Kingdom.

Chapin, M. 2004. A challenge to conservationists. World Watch Magazine **Nov/Dec**: 17-31.

Christie, P., K. Lowry, A. T. White, E. G. Oracion, L. Sievanen, R. S. Pomeroy, R. B. Pollnac, J. M. Patlis, and R. L. V. Eisma. 2005. Key findings from a multidisciplinary examination of integrated coastal management process sustainability. Ocean & Coastal Management **48**:468-483.

Cinner, J. E. 2007. Designing marine reserves to reflect local socioeconomic conditions: Lessons from long-enduring customary management systems. Coral Reefs 26: 1035-1045.

Clark, J. S., et al. 2001. Ecological forecasts: an emerging imperative. Science **293**:657-660.

Coles, S. L., and B. E. Brown. 2003. Coral bleaching - capacity for acclimatization and adaptation. Advances in Marine Biology **46**:183-223.

Donner, S.D. and Potere, D., 2007. The inequity of the global threat to coral reefs. BioScience **57**: 214-215.

Folke, C. 2006. Resilience: the emergence of a perspective for social-ecological systems analysis. Global Environmental Change **16**:253-267.

Forman, E. H. and S. I. Gass. 2001. The analytic hierarchy process - an exposition. Operations Research **49**: 469-486.

Graham, N. A. J., S. K. Wilson, S. Jennings, N. V. C. Polunin, J. P. Bijoux, and J. Robinson. 2006. Dynamic fragility of oceanic coral reef ecosystems. Proceedings of National Academy of Science, USA **103**:8425-8429.

Henry, G. 1990. Practical sampling. Sage Publications, Newbury Park, California.

Hunter, C., and J. Shaw. 2006. Applying the ecological footprint to ecotourism scenarios. Environmental Conservation **32**:294-304.

Jennings, S., and N. V. C. Polunin. 1997. Impacts of predator depletion by fishing on the biomass and diversity of non-target reef fish communities. Coral Reefs **16**:71-82.

Jentoft, S., B. J. McCay, and D. C. Wilson. 1998. Social theory and fisheries co-management. Marine Policy **22**:423-436.

Kremen, C., V. Razafimahatratra, R. P. Guillery, J. Rakotomalala, A. Weiss, J. S. Ratsisompatrarivo. 1999. Designing the Masoala National Park in Madagascar based on biological and socioeconomic data. Conservation Biology **13**:1055-1068.

Leslie, H., M. Ruckelshaus, I. R. Ball, S. Andelman, and H. P. Possingham. 2003. Using siting algorithms in the design of marine reserve networks. Ecological Applications **13**:S185-S198.

Maina, J., V. Venus, T. R. McClanahan, and M. Ateweberhan. 2008. Modelling susceptibility of coral reefs to environmental stress using remote sensing data and GIS models in the western Indian Ocean. Ecological Modelling **212:** 180-199.

McClanahan, T. R., J. Davies, and J. Maina. 2005. Factors influencing resource users and managers' perceptions towards marine protected area management in Kenya. Environmental Conservation **32**:42-49.

McClanahan, T. R., and N. A. J. Graham. 2005. Recovery trajectories of coral reef fish assemblages within Kenyan marine protected areas. Marine Ecology Progress Series **294**:241-248.

McClanahan, T. R., J. Maina, P. Herron-Perez, and E. Dusek. 2005. Detriments to post-bleaching recovery of corals. Coral Reefs **24**:230-246.

McClanahan, T. R., E. Verheij, and J. Maina. 2006a. Comparing management effectiveness of a marine park and a multiple-use collaborative fisheries management area in East Africa. Aquatic Conservation: Marine and Freshwater Ecosystems **16**:147-165.

McClanahan T. R., M. J. Marnane, J. E. Cinner, and W. Kiene. 2006b. A comparison of Marine Protected Areas and alternative approaches to coral reef management. Current

Biology **16**:1408-1413.

McClanahan, T. R., M. Ateweberhan, N. A. J. Graham, S. K. Wilson, C. R. Sebastian, M. M. M. Guillaume, J. H. Bruggemann. 2007a. Western Indian Ocean coral communities, bleaching responses, and susceptibility to extinction. Marine Ecology Progress Series **337:** 1-13.

McClanahan, T. R., M. Ateweberhan, C. Muhando, J. Maina, and S. M. Mohammed. 2007b. Climate change and spatio-temporal variation in seawater temperature effects on coral bleaching and mortality in East Africa. Ecological Monographs **77:** 503-525.

McClanahan, T. R., N. A. J. Graham, J. M. Calnan, and M. A. MacNeil. 2007c. Toward pristine biomass: reef fish recovery in coral reef marine protected areas in Kenya. Ecological Applications **17:** 1055-1067.

McClanahan, T. R., et al. 2008. Conservation action in a changing climate. Conservation Letters 1: 53-59.

McClanahan, T. R., C. C. Hicks, and E. S. Darling. 2008b. Malthusian overfishing and efforts to overcome it on Kenyan coral reefs. Ecological Applications **18:** 1516-1529.

Moothien Pillay, R., H. Terashima, and H. Kawasaki. 2002. The extent and intensity of the 1998 mass bleaching event on the reefs of Mauritius, Indian Ocean. Galaxea **4**:43-52.

Nowlis, J. S., and C. M. Roberts. 1999. Fisheries benefits and optimal design of marine reserves. Fishery Bulletin **97**:604-616.

Obura, D. O. 2005. Resilience and climate change: lessons from coral reefs and bleaching in Western Indian Ocean. Estuarine Coastal and Shelf Science **63**:353-372.

Odum, H. T. 1988. Self-organization, transformity, and information. Science **242**:1132-

1139.

Pollnac, R. B. 1998. Rapid assessment of management parameters for coral reefs. University of Rhode Island, Coastal Resources Center, Narragansett.

Pretty, J., and H. Ward. 2001 Social capital and the environment. World Development **29**: 209-277.

Roberts, C. M., et al. 2002. Marine biodiversity hotspots and conservation priorities for tropical reefs. Science **295**:280-284.

Saaty, T. 1980. The analytic hierarchy process. McGraw-Hill, New York.

Sanderson, E.W., M. Jaiteh, M. A. Levy, K. H. Redford, A. V. Wannebo, and G. Woolmer. 2002. The human footprint and the last of the wild. BioScience **52**:891-904.

et al. Stevenson, C., L. S. Katz, F. Micheli, B. Block, K. W. Heimen, C. Perle, K. Weng, R. Dunbar, and J. Witting. 2007. High apex predator biomass on remote Pacific islands. Coral Reefs 26:47-51.

Veron, J. E. N., and E. Turak. 2005. Zooxanthellate scleractinia of Madagascar. Pages 23-25 in S. A. McKenna, and G. R. Allen, editors. A rapid marine biodiversity assessment of the coral reefs of northwest Madagascar. Conservation International, Washington, DC.

West, J. M., and R. V. Salm. 2003. Resistance and resilience to coral bleaching: implications for coral reef conservation and management. Conservation Biology **17:**956-967.

Wilkinson, C., editor. 2004. Status of coral reefs of the world: 2004. Global Coral Reef Monitoring Network, Townsville, Australia.

Wilson, S. K., N. A. J. Graham, M. S. Pratchett, G. P. Jones, and N. V. C. Polunin. 2006.

Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? Global Change Biology **12**:2220-2234.

Wooldridge, S., and T. Done. 2004. Learning to predict large-scale coral bleaching from past events: a Bayesian approach using remotely sensed data, in-situ data, and environmental proxies. Coral Reefs **23**:96-108.

Table 1. Countries, study sites, measurements, and sample sizes of environmental, ecological, and social surveys. Use letters for footnotes

Country	Social Site	Communities	No. Surveys[a]	No. Fisher Interviews[b]	Adaptive capacity	Ecological site	Management
Kenya	Vipingo	1	63	13	0.36	Kanamai/Vipingo	fished
	Mijikenda	1	34	32	0.45	Malindi	protected
	Shela	1	31	11	0.47		
	Bamburi	1	31	18	0.37	Mombasa	Protected
						RasIwatine	Fished
	Kuruwitu	1	32	4	0.31	Vipingo	Fished
	Mayungu	1	29	16	0.34	Watamu	Protected
Tanzania	Mazizini	1	43	43	0.43	Changu/Chapwani	Fished
	Stone Town	1	44[c]	44	0.43		
	Buyu	1	44	18	0.37	Chumbe	Protected
	Nyamanzi	1	49[c]	26	0.44		
	Mtangata	3	143	66	0.33	Makome/Unfunguni	Fished
	Dar Es Salaam	2	59	43	0.42	Mbudya/Bongoyo	Fished
W Madagascar	NW Madagascar	3	70	33	0.28	Sakatia/Ambaritelo	Fished
						Tanikely	Protected
E Madagascar	Tanjona	5	52	38	0.33	Cape Est	Fished
						Tanjona	Protected
	Ambodilaitry Area	3	50	22	0.31	Masoala	Protected
Mauritius	Pointe des Lascars	1	65	18	0.41	Anse la Raie	Fished
	Pointe aux Piments	1	87	16	0.49	Balaclava	Protected

						Balaclava buffer	Fished
	St Martin	1	59	13	0.42	Belombre	Fished
	Blue Bay	2	57	5	0.45	Blue bay 1	Protected
						Blue bay 2	Fished
	Le Morne	1	40	11	0.49	Le Morne	Fished
Seychelles	Grand Anse	1	46	6	0.48	Cousin	Protected
						SW Praslin	Fished
	Anse Volbert	1	23	4	0.48	NE Praslin	Fished
	Belombre	1	89	13	0.53	NW Mahe	Fished
	Roche Caiman	1	85	7	0.51	St Anne MP	Protected

[a]Systematic random sample of households that may have included fishers

[b]Total fisher interviews from household survey or targeted sampling of fishers.

[3]Only fishers were interviewed in Nyamanzi and Stone town so adaptive capacity is calculated for fisher households only.

Figure legends

Figure 1. Model of conservation priorities and action where sites and appropriate actions lie within the 3 axes of environment, ecology, and society. Our suggested prescriptive response for each octet is presented with examples from the studied region.

Figure 2. Map of study sites (black dots and sample sizes per country given in parentheses) overlaid on the model predictions of environmental susceptibility to climate change for the region.

Figure 3. Predicted bleaching susceptibility and ecological pristineness where ecological parameters are weighted toward more importance with (a) coral measures and (b) fish measures. Filled symbols (and star and long dash for Tanzania and western Madagascar respectively) are fished sites, open symbols (and cross and short dash for Tanzania and western Madagascar respectively) are unfished or protected closures. Axes have different scales.

not much difference between long and short dash

Figure 4. Social adaptive capacity index and ecological disturbance where ecological parameters are weighted toward (a) coral measures and (b) fish measures. Filled symbols (and star and long dash for Tanzania and western Madagascar respectively) are fished sites, open symbols (and cross and short dash for Tanzania and western Madagascar respectively) are unfished closures. Axes have different scales.

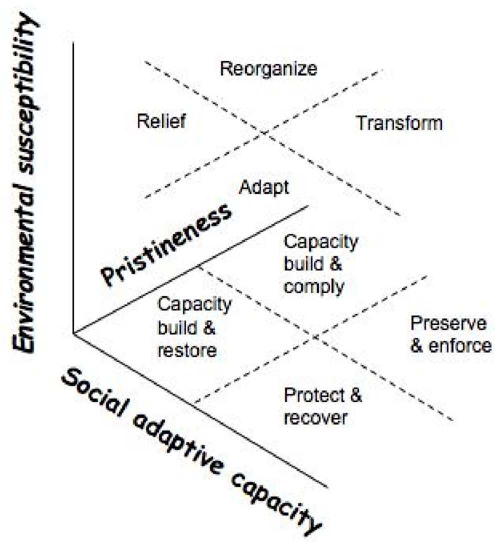

Environmental susceptibility
Reorganize
Relief
Transform
Adapt
Pristineness
Capacity
build &
comply
Capacity
build &
restore
Preserve
& enforce
Protect &
recover
Social adaptive capacity

Figure 1

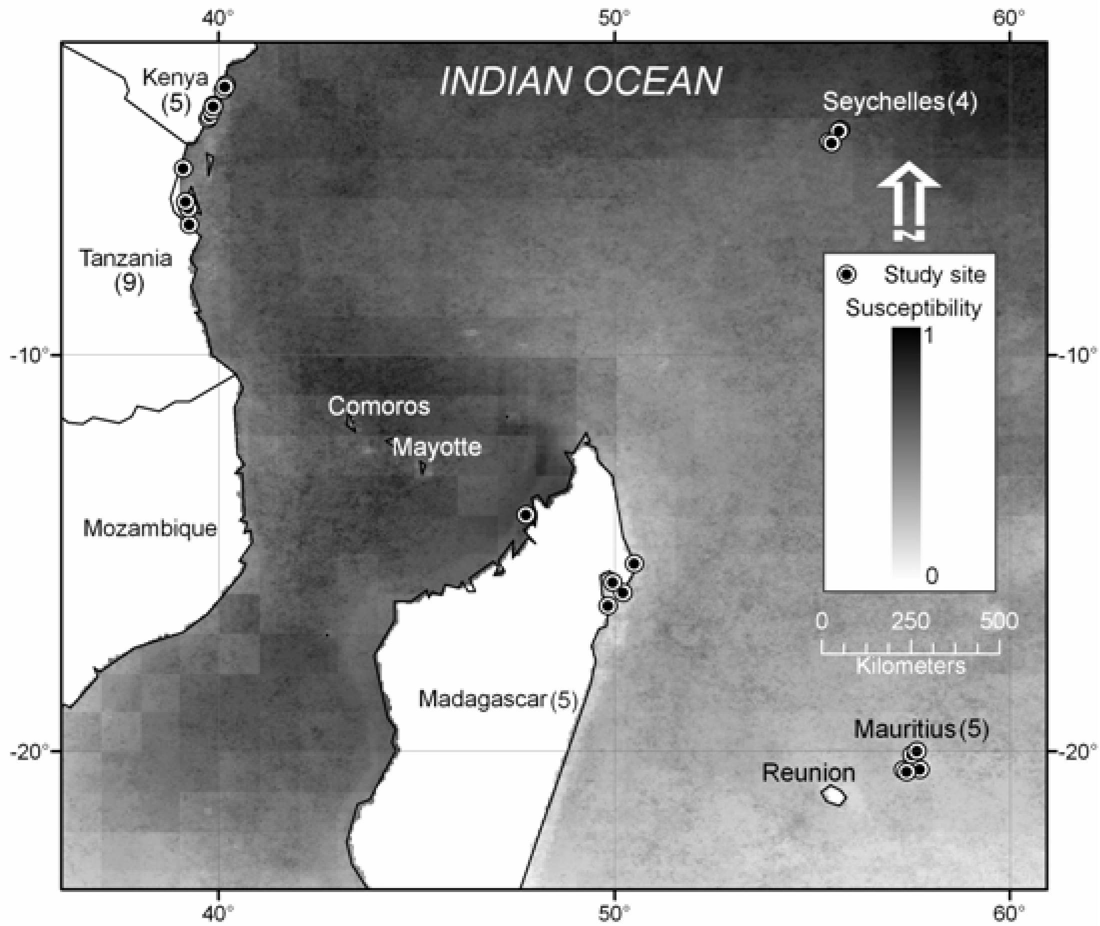

40°
50°
60°
INDIAN OCEAN
Kenya
(5)
Seychelles(4)
Tanzania
(9)
Study site
Susceptibility
1
0
-10°
-10°
Comoros
Mayotte
Mozambique
0
250
500
Kilometers
Madagascar(5)
Mauritius(5)
-20°
-20°
Reunion
40°
50°
60°

Figure 2

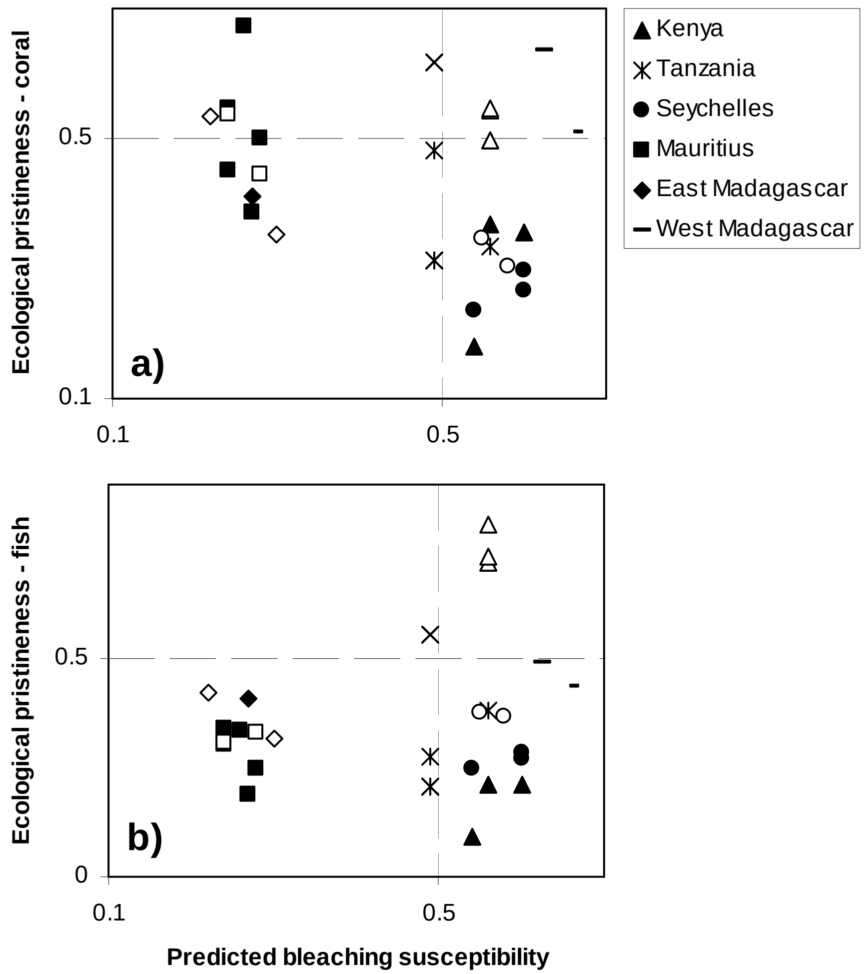
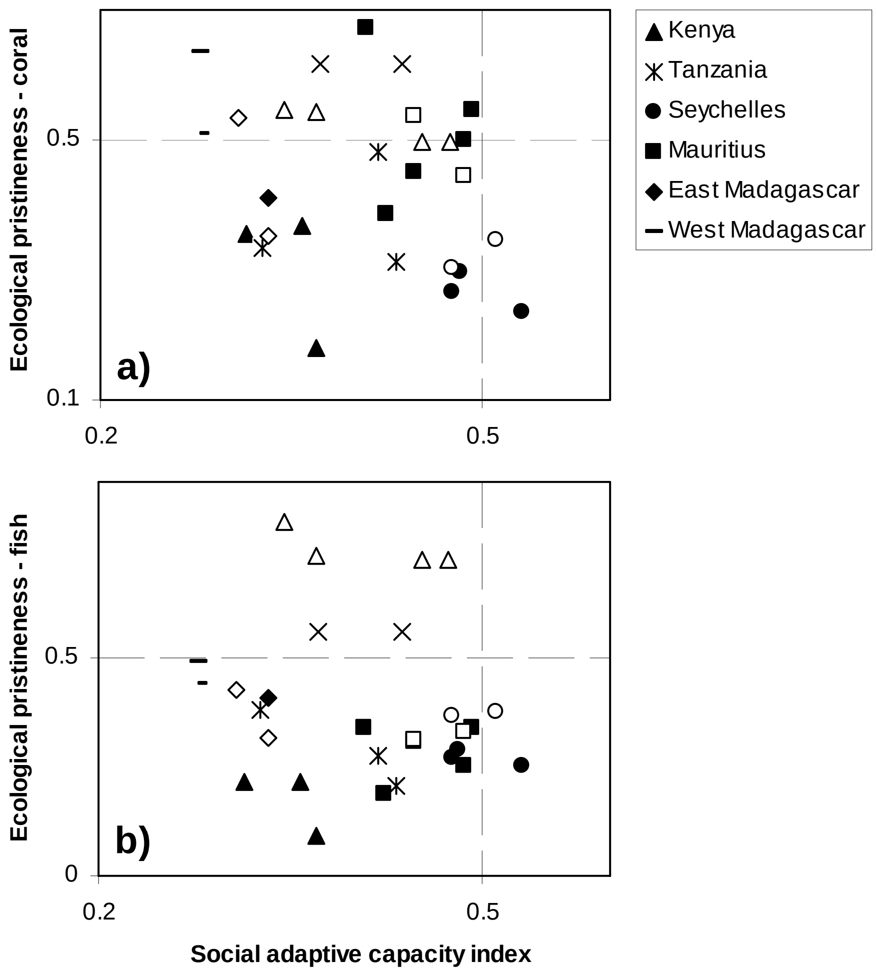

Ecological pristineness - coral
0.5
0.1
0.1
0.5
a)
Kenya
Tanzania
Seychelles
Mauritius
East Madagascar
West Madagascar
Ecological pristineness - fish
0.5
0
0.1
0.5
b)
Predicted bleaching susceptibility

Figure 3



Kenya
Tanzania
Seychelles
Mauritius
East Madagascar
West Madagascar
Ecological pristineness - coral
0.5
0.1
0.2
0.5
a)
Ecological pristineness - fish
0.5
0
0.2
0.5
b)
Social adaptive capacity index

Figure 4