

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

T.R. McCLANAHAN,* J.E. CINNER,† N.A.J. GRAHAM,‡§§ T.M. DAW,‡‡ J. MAINA,§** S.M. STEAD,‡ A. WAMUKOTA,** K. BROWN,††‡‡ V. VENUS,§ AND N.V.C. POLUNIN‡

*Wildlife Conservation Society, Marine Program, Bronx, NY 10460–1099, U.S.A., email tmclanahan@wcs.org

†Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4811, Australia

‡School of Marine Science and Technology, Newcastle University, Newcastle upon Tyne NE1 7RU, United Kingdom

§International Institute for Geo-Information Science and Earth Observation, Enschede, The Netherlands

**Coral Reef Conservation Project, Mombasa, Kenya

††Tyndall Centre for Climate Change Research, University of East Anglia, East Anglia, United Kingdom

‡‡School of Development Studies, University of East Anglia, East Anglia, United Kingdom

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 [ES]), and capacity of human communities to cope with and adapt to change (social adaptive capacity [AC]). We studied 24 human communities and adjacent coral reef ecosystems in 5 countries of the southwestern Indian Ocean. We used ecological measures of abundance and diversity of fishes and corals, estimated reef pristineness, and conducted socioeconomic household surveys to determine the AC of communities adjacent to selected coral reefs. We also used Web-based oceanographic and coral mortality data to predict each site's ES to climate warming. Coral reefs of Mauritius and eastern Madagascar had low ES and consequently were not predicted to be affected strongly by warm water, although these sites were differentiated by the AC of the human community. The higher AC in Mauritius may increase the chances for successful self-initiated recovery and protective management of reefs of this island. In contrast, Madagascar may require donor support to build AC as a prerequisite to preservation efforts. The Seychelles and Kenya had high ES, but their levels of AC and disturbance differed. The high AC in the Seychelles could be used to develop alternatives to dependence on coral reef resources and 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 were 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.*

Keywords: adaptive management, coral bleaching, global climate change, marine protected areas, resilience, socioecological systems

Identificación de Arrecifes de Esperanza y Acciones Esperanzadoras: Contextualización de Parámetros Ambientales, Ecológicos y Sociales para Responder Efectivamente al Cambio Climático

§§Current address: Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4811, Australia

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Resumen: *Las prioridades de conservación, manejo y actividades asociadas serán diferentes con base en la interacción entre la cercanía de los ecosistemas a la recuperación total de una perturbación (pristinidad), la susceptibilidad al cambio climático (susceptibilidad ambiental) y la capacidad de las comunidades humanas para soportar y adaptarse al cambio (capacidad adaptativa social). Estudiamos 24 comunidades humanas y los ecosistemas de arrecife coralino adyacentes en cinco países del suroeste del Océano Índico. Utilizamos medidas ecológicas de abundancia y diversidad de peces y corales, estimamos la pristinidad de los arrecifes y realizamos muestreos socioeconómicos para determinar la capacidad adaptativa de las comunidades adyacentes a los arrecifes coralinos seleccionados. También utilizamos datos oceanográficos tomados de la Web y de mortalidad de arrecifes para estimar la susceptibilidad ambiental de cada sitio al calentamiento climático. Los arrecifes coralinos de Mauricio y este de Madagascar tuvieron baja susceptibilidad ambiental y, consecuentemente, se predijo que no serían afectados por agua caliente. La mayor capacidad adaptativa en Mauricio puede incrementar las posibilidades de una recuperación auto-iniciada y un manejo protector de arrecifes en esta isla. En contraste, Madagascar puede requerir el soporte de donadores para construir capacidad adaptativa como un prerrequisito de esfuerzos de conservación. Las Seychelles y Kenia tuvieron susceptibilidad ambiental alta pero sus niveles de capacidad adaptativa y perturbación fueron diferentes. La alta capacidad adaptativa en las Seychelles puede ser utilizada para desarrollar alternativas a la dependencia en recursos de los arrecifes coralinos y reducir los efectos del cambio climático. La pristinidad enfocada en medidas para la recuperación de peces fue mayor en las áreas marinas protegidas de Kenia; sin embargo, la mayoría de las áreas protegidas en la región estaban lejos de ser prístinas. Las prioridades y acciones de conservación con posibilidades de éxito reales requieren conocer donde se encuentran los sistemas socioecológicos entre los tres ejes del ambiente, la ecología y la sociedad.*

Palabras Clave: áreas marinas protegidas, blanqueo de corales, cambio climático global, manejo adaptativo, resiliencia, sistemas socioecológicos

Introduction

A contemporary challenge for the 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 (ES) 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. 2006b, 2008a). Integrating these factors is becoming increasingly urgent for the 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. 2008a). These efforts are necessary and laudable, but they are based largely on environmental and biological attributes, without adequate consideration of the socio-economic context (Chapin 2004). This may leave little scope for management actions in areas that are consid-

ered 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; Adger 2006; Folke 2006). The common assumption among conservation biologists is that fisheries closures benefit people by improving or maintaining fish catch. Nevertheless, these net benefits may not be realized unless resource extraction is already beyond some maximum sustained yield (Nowlis & Roberts 1999), may not be equitably distributed among people, and may not be perceived by potential beneficiaries (Berkes 2004; McClanahan et al. 2005a). Additionally, people with low adaptive capacity (AC) 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* as a latent characteristic of people that reflects their ability to anticipate and respond to changes in coral reef ecosystems and 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

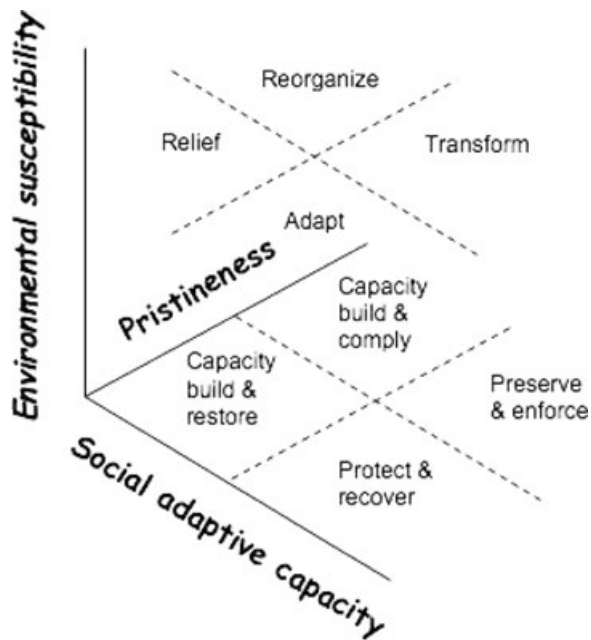


Figure 1. Model of conservation priorities and action where sites and appropriate actions lie within the 3 axes of environment, ecology, and society. Our suggested prescriptive response for each octet is presented with examples from the studied region.

resulting in closures that do not differ ecologically from fished areas (McClanahan et al. 2006a).

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 transdisciplinary 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 fishes 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 susceptibility of the physical environment to coral bleaching, nearness of sites to an undisturbed state (pristineness), and the AC 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. 2): southern Kenya, Tanzania, the granitic Seychelles, Mauritius, and Madagascar. We collected 3 types of data at each site: ES, or the conditions that create stress for corals, for which 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 abundance of fishes and benthic cover variables

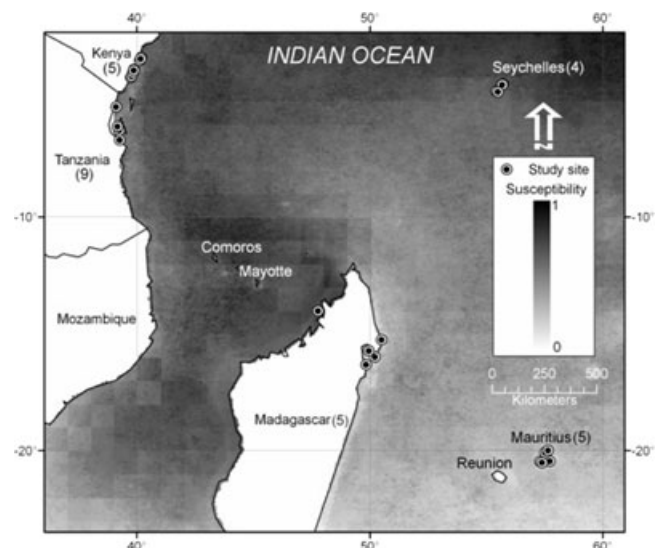


Figure 2. Map of study sites (black dots; sample sizes per country in parentheses) overlaid on the model predictions of environmental susceptibility to climate change for the region.

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

Country	Social site	Communities	No. of surveys ^a	No. of 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
Tanzania	Kuruwitu	1	32	4	0.31	RasIwatine	fished
	Mayungu	1	29	16	0.34	Vipingo	fished
	Mazizini	1	43	43	0.43	Watamu	protected
	Stone town	1	44 ^c	44	0.43	Changu/Chapwani	fished
	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
Mauritius	Ambodilaitry area	3	50	22	0.31	Masoala	protected
	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
The Seychelles	Le Morne	1	40	11	0.49	Blue bay 2	fished
	Grand Anse	1	46	6	0.48	Le Morne	fished
						Cousin	protected
	Anse Volbert	1	23	4	0.48	SW Praslin	fished
	Belombre	1	89	13	0.53	NE Praslin	fished
	Roche Caiman	1	85	7	0.51	NW Mahe	fished
					St. Anne MP	protected	

^aSystematic random sample of households that may have included fishers.

^bTotal fisher interviews from household survey or targeted sampling of fishers.

^cOnly fishers were interviewed in Nyamanzi and Stone towns, so adaptive capacity is calculated for fisher households only.

in fished and unfished reefs, which were measured with 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 (<http://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 geographic information system fuzzy logic process and spatial principal compo-

nent analysis (SPCA) to yield susceptibility relationships and models. These were then synthesized into a single ES map by summing 7 principal components weighted by their relative contribution. To test the model, we used coral mortality at 16 reef locations in the western Indian Ocean affected by the 1998 El Niño Southern Oscillation (ENSO). Model fit was reasonably good ($r^2 = 0.27$, and 0.50 with removal of 2 outliers; Maina et al. 2008).

Social Adaptive Capacity Index

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

duced by previous climate impacts (McClanahan et al. 2007a). Fish species richness per 500 m² (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 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 pristineness [CP]), and the other weighted toward local fishing disturbances, in which fish species richness and biomass were attributed more weight (fish pristineness [FP]). Having 2 indices distinguished the impacts of large climate-mediated coral bleaching disturbances from those of small-scale fishing-related disturbance. The mean site CP was calculated as:

$$CP = S \times 0.35 + C \times 0.35 + R \times 0.19 + F \times 0.10 \quad (1)$$

and the mean site FP was calculated as:

$$FP = S \times 0.20 + C \times 0.12 + R \times 0.20 + F \times 0.49, \quad (2)$$

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 & Graham 2005; McClanahan et al. 2007c).

Data Plotting

We sought to evaluate our field sites in terms of environmental vulnerability, ecology, and social AC (Fig. 1). Consequently, we plotted ES 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.

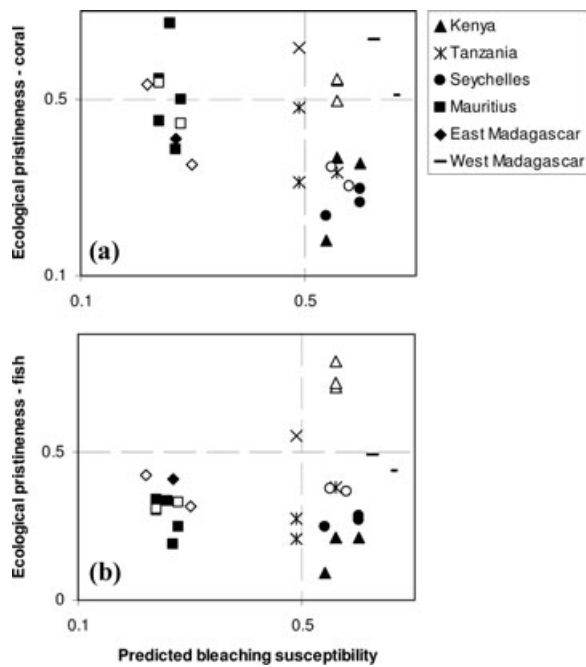


Figure 3. Predicted bleaching susceptibility and ecological pristineness, where ecological parameters are weighted toward more importance with (a) coral measures and (b) fish measures. Filled symbols (star and long dash for Tanzania and western Madagascar, respectively) are fished sites, open symbols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

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, the 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. 3a). Two sites in Tanzania, 2 protected areas (PA) in Kenya, and the sites in western Madagascar also had high CP values. Sites with low values included Kenya, the Seychelles, and 2 Tanzanian sites. Fish pristineness had an equally high scatter, but most fished sites had lower values than unfished sites (Fig. 3b). The highest FP was in Kenya's marine protected areas (MPAs) at the high end of ES. The values of FP were moderate for one Tanzanian site (the oldest managed site in the Tanga Coastal Zone Conservation and Management Programme) and one site in western Madagascar. Most other sites, including a number of PAs in Mauritius and the Seychelles, had low FP values, and Kenya's fished reefs had among the lowest values.

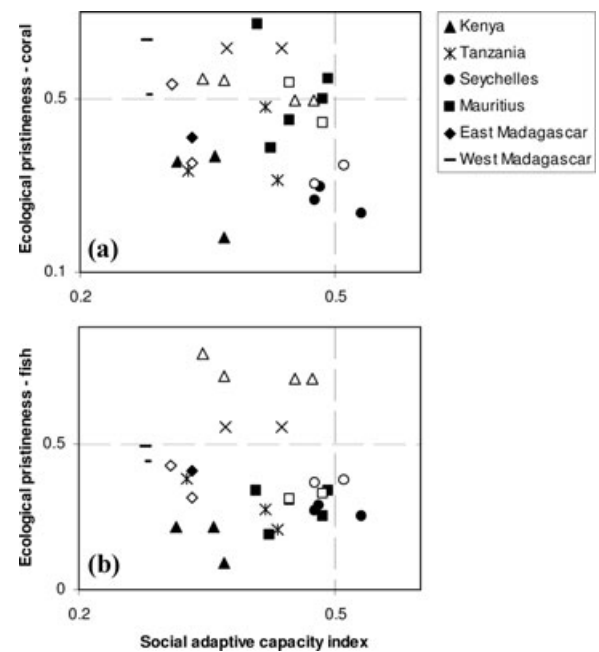


Figure 4. Social adaptive capacity index and ecological disturbance, where ecological parameters are weighted toward (a) coral measures and (b) fish measures. Filled symbols (star and long dash for Tanzania and western Madagascar, respectively) are fished sites, open symbols (cross and short dash for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

The mean social 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 the Seychelles moderate-to-high AC levels (Fig. 4).

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 added 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 suggests 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 AC scores we attempted to address this using a structured method (AHP) to average weighting of indicators by multiple scientists who 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 pristineness, such as the 1998 ENSO and bleaching event (McClanahan et al. 2007a). Reefs with high CP values 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 value was intermediate, and comparisons with Kenyan reefs indicated they either had greater acclimatization or adaptations that give them resilience to climate change or had the ability to recover more quickly from these disturbances (McClanahan et al. 2007a, 2007b).

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 PAs 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. The Kenyan PAs were of modest size ($\sim 10 \text{ km}^2$), embedded in areas with heavy fishing, and unlikely to represent the large-scale pristine conditions characteristic of remote unpopulated areas (Stevenson et al. 2007; Sandin et al. 2008), which indicates that all our studied sites, including PAs, 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 PA. Although fish biomass was higher in the protected than the fished area, the effect was modest, and the 3 other measures that contributed to pristineness scores were greater in the fished area. Similarly, the Kenyan PAs 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 PAs. For Mauritius higher coral cover in the PAs was not heavily reflected in the CP value due to low fish variables. Nevertheless, 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. 2006b), and coral bleaching has an impact beyond corals (Graham et al. 2006; Graham et al. 2008).

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 collection of 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 that intact coral communities contain highly susceptible taxa (Pillay et al. 2002).

Social Adaptive Capacity Axis

The AC variable creates a proxy for a community's 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 social capital building.

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 as that in some sites in the 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 intracountry 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, AC and pristineness, are locally manageable (Fig. 1). Social organization can affect AC 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 ES and pristineness. Resource management can also potentially manage pristineness, which means restoration when it is low, and preservation when it is high and ES 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 those elsewhere due to their oceanographic characteristics. Nevertheless, AC and pristineness differed considerably between the locations and therefore in appropriate management strategies. The higher AC in Mauritius suggests that local communities should be able to adapt and take advantage of the opportunities arising from a system of PAs. 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 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. Nevertheless, 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). Nevertheless, 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 PAs. 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 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).

Coral communities in 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 PA 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 large 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. 2005a). Although this system has been successful for increasing fish, a loss in tourism or increased climate change effects have 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 the 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 ecological disturbance and with ES and social AC. 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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