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Research

Wicked Social–Ecological Problems Forcing Unprecedented Change on the Latitudinal Margins of Coral Reefs: the Case of Southwest Madagascar

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ABSTRACT. High-latitude coral reefs may be a refuge and area of reef expansion under climate change. As these locations are expected to become dryer and as livestock and agricultural yields decline, coastal populations may become increasingly dependent on marine resources. To evaluate this social–ecological conundrum, we examined the Grand Récif of Toliara (GRT), southwest Madagascar, which was intensively studied in the 1960s and has been highly degraded since the 1980s. We analyzed the social and ecological published and unpublished literature on this region and provide new data to assess the magnitude of the changes and evaluate the causes of reef degradation. Top-down controls were identified as the major drivers: human population growth and migrations, overfishing, and climate change, specifically decreased rainfall and rising temperature. Water quality has not changed since originally studied, and bottom-up control was ruled out. The identified network of social–ecological processes acting at different scales implies that decision makers will face complex problems that are linked to broader social, economic, and policy issues. This characterizes wicked problems, which are often dealt with by partial solutions that are exploratory and include inputs from various stakeholders along with information sharing, knowledge synthesis, and trust building. A hybrid approach based on classical fishery management options and preferences, along with monitoring, feedback and forums for searching solutions, could move the process of adaptation forward once an adaptive and appropriately scaled governance system is functioning. This approach has broad implications for resources management given the emerging climate change and multiple social and environmental stresses.

Key Words: *adaptation; climate change; governance; marine resources; migration; solutions*

INTRODUCTION

> *Some problems are so complex that you have to be highly intelligent and well-informed just to be undecided about them* (Conklin 2006).

Coral reefs have been undergoing unprecedented rates of change during the past decades, and more change is expected as climate change and human disturbances continue (McClanahan 2002, Aronson et al. 2004, Pandolfi et al. 2011). Multiple forces of change are impinging on reefs and these are potentially undermining key reef ecological services, particularly fisheries, which represent critical sources of food where people heavily depend on such services (Castilla and Defeo 2005). Environmental change and human use of reefs and associated watersheds are creating novel social–ecological conditions that are both difficult to fully understand and solve because of the inherent social–ecological complexity and constant change.

These types of problems have been named wicked problems by management scientists because they are value driven, complex, multi-scale, persistent or reoccurring, and challenging to solve (Rittel and Webber 1973). Tame problems, in contrast, require technical and often single-discipline solutions that are not obviously value driven or socially contentious. Wicked problems are not just local but embedded and linked in broader social, economic, environmental, and policy issues and associated values, which can create a set of nested problems within problems. In a wicked problem situation, solutions to one aspect or one scale of the problem may even reveal or create a problem at another. For example, in a coral reef context, policy actions to reduce overfishing may involve alternative livelihoods in agriculture and tourism. Yet this solution leads to problems at larger scales: increased agricultural intensification may lead to land clearing and fertilizer use, which cause sedimentation and eutrophication in coastal areas. Increased tourism may result in more physical damage to reef ecosystems, whereas increased demands for seafood and curios can potentially add to the ecological pressures.

Competing mindsets and inflexible positions about the nature of the problem and potential solutions often reinforce wicked problems. For example, scientists, depending on their

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disciplines and available data, and stakeholders, depending on their livelihoods and economic needs, may develop very different views of the problems and solutions. This further challenges the potential for defining the problem in the first place, what the causes are, and the steps needed to resolve them, even in relatively data-rich environments (Jentoft and Chuenpagdee 2009). In most cases, cause and effect are not that well understood, despite claims from some disciplines.

Wicked problems, being complex and multi-factored, may not be tractable by reductionist scientific methods in traditional ways that can rigorously establish a few key variables needing attention. This complexity means that the proof needed to achieve consensus among scientists, let alone the larger group of stakeholders, is often difficult to obtain. Finally, the larger community may be paralyzed into inaction, not simply because of poor understanding and agreement, but social organization and incentives that block possible changes in behavior and implementation of potentially agreeable activities and pathways. Super wicked problems can arise when time to enact solutions is running out, there is no central authority to catalyze change, stakeholders are both the problem and the solution, and hyperbolic discounting behavior occurs along with fatalism (Lazarus 2009).

A coral reef example for this is in the Caribbean where, in spite of extensive time series data on reef state and environmental conditions, considerable debate persists about the causes and consequences of ecological change, for both fish and fisheries (Baisre 2010, McClenachan et al. 2010) and reef ecology (Pandolfi et al. 2005, Aronson and Precht 2006, Schutte et al. 2010). As time passes, the system continues to change, and solutions that existed in the early stages of the change may no longer be applicable at later stages (McClanahan et al. 2011a). Ecologically, this can occur because the species that cause the change may not be those that can reverse it (Bellwood et al. 2006), and the larger seascape and social context may have changed so fundamentally that there are other arising limits that were not previously present (Mora 2008, Paddack et al. 2009). Ecosystems and societies can be expected, at times, to pass through one-way gates where old issues and solutions are no longer useful, and the result can be social–ecological hysteresis if not perceived and acted on early (Roberts 2000, Biggs et al. 2009).

We address this issue in a coral reef ecosystem at its latitudinal limit, namely southwest (SW) Madagascar. Coral reefs at their latitudinal limits offer particularly important case studies. During the coming era of climate change, it may be expected that these reefs represent refugia and areas of reef expansion if the environmental conditions promoting reef survival and growth are present (Riegl and Piller 2003, McClanahan et al. 2007, Ateweberhan and McClanahan 2010). This possibility is reasonable and seen in the geologic past (Precht and Aronson 2004, Greenstein and Pandolfi 2008) but will depend on socioeconomic as much as on environmental conditions (McClanahan 2002). Although these latitudes may have oceanographic conditions suitable for reef development, they are also expected to see continuing drying as Hadley circulation is strengthened (Hansen et al. 2005) and high rates of ocean warming (McClanahan et al. 2009).

Where people are highly reliant on agriculture and other terrestrial resources, climate drying is expected to create greater dependency on marine resources and become a critical factor in the ecology and changes in these reefs. The social–ecological outcomes and the potential for reef refugia and expansion may be quite different based on socioeconomics. Natural resource dependent countries, such as Madagascar, will face considerable challenges as this change continues to emerge. In this evaluation, we explore the larger environmental change in SW Madagascar and ask if changes in reef state and services can be managed. Focusing on the Toliara region, we evaluate the contributions of different drivers of reef change and address the question whether these issues are amenable to tame or wicked problem solving and what specifically can be done to address the problem.

METHODS

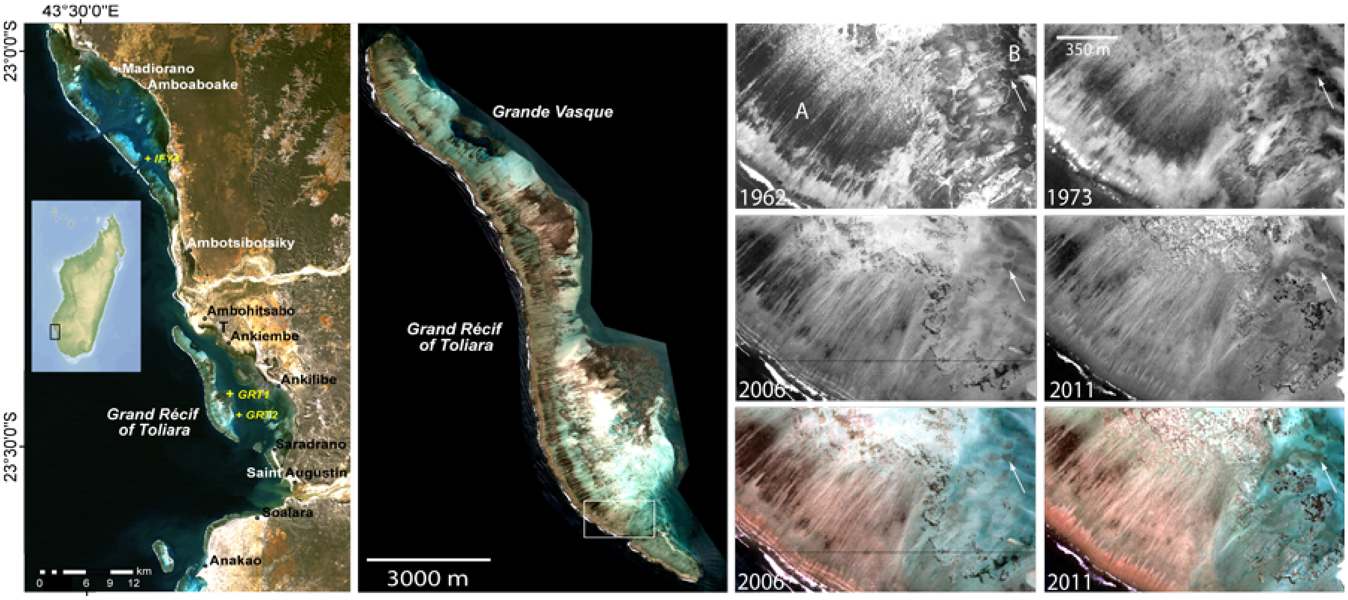
Study Site and Socioeconomic Context

The Grand Récif of Toliara (GRT), located <2 km seaward of Toliara town, is a major barrier reef system of the SW Indian Ocean. It stretches over 19 km (23°20–23°30 S), between the Fiherenana River in the North and the Onilahy River in the South (Fig. 1) and represents approximately 33 km² of structurally diverse shallow reef area. This reef system was studied intensively by French scientists between 1961 and 1972, focusing mainly on reef morphology (Clausade et al. 1971) and on the inventory and distribution of flora and fauna —in particular key taxa such as corals (Pichon 1978) and fish (Harmelin-Vivien 1979). Over 6000 species were identified (B. Thomassin, personal communication), still the highest biodiversity recorded for an Indian Ocean reef system.

With a human population of >200,000, Toliara is a major regional commercial and administrative center. The town and surrounding villages (Toliara district) have the highest population density in SW Madagascar. The population has been growing rapidly since the 1960s, increasing by 53% between 1993 and 2008, and is projected to increase further over the next decade (Institut National de Statistique (INSTAT) 2007). High population growth of ca. 3.5% y^{-1} (Vasseur et al. 1988, Laroche et al. 1997) is boosted by migration from inland tribal groups to the coast and along the coast to Toliara (Chaboud 2006).

Agricultural and livestock production in SW Madagascar is low and declining (Minten et al. 2003, Rasambainarivo and Ranaivoarivelo 2003) due to increasing aridity, exacerbated by land degradation from overgrazing and deforestation (Dyoulgerov 2011). Along the coast, the Vezo community was traditionally the most numerous and the only one to practice

Fig. 1. Left panel: location of the GRT in the Toliara region. Toponymy refers to villages mentioned in the paper. IFY4, GRT1, and GRT2 correspond to the locations of coral cores used for environmental proxies. Middle panel: a modern satellite view (Quickbird 2006) of the GRT. The square is the location of an example of image time series, on the right panel. On the right, changes are shown across 50 years, with aerial black and white photographs from 1962 and 1973, and from satellite images shown in both black and white (for comparison with historical photographs) and natural color on the lower panels. “A” indicates the habitat showing the most dramatic changes: reef flat with live coral strips has shifted to rubble and boulders covered by algae. “B” indicates the location of seagrass beds that have disappeared in the southern part of the GRT, being replaced by sand in 2006. Category 4 cyclone Boloetse, passing near Toliara early 2006, may be responsible for redistributing loose sediments and temporary covering features that are visible on images before and after 2006. The arrow shows pseudo-invariant features that remain visible across time (here, patch of low relief hardground). Images SGM (1962); SAG 464 (1973), Quickbird (2006), WorldView-2 (2011).



fisheries. More recently, several agriculturalist or pastoralist ethnic groups (e.g., the Mahafaly, Antandroy, Tanalana, and Masikoro) have turned to fisheries. Industrial or artisanal fisheries (boats with engines <50 HP) are not practiced on the GRT. Therefore, small-scale traditional fisheries provide the main source of protein and income (Laroche and Ramananarivo 1995) on which the coastal populations of the Toliara region have become increasingly dependent (Chaboud 2006).

Biophysical Changes: Climate, Reef Morphology, and Ecology

Available biophysical data were compiled and compared, aiming to improve our understanding of the drivers and consequences of the degradation of the GRT. Temporal trends in environmental conditions on the GRT, in Toliara, and in the region were assessed over a period of ca. 50 years, based on available historical records, recently collected data, and environmental proxies from coral cores taken in Ranobe lagoon off Ifaty, north of Toliara (Zinke et al. 2004, 2009; Fig. 1, Table 1). In 2008, additional coral cores were drilled from the GRT lagoon to reconstruct the Ba/Ca ratios, a proxy of sediment runoff from terrestrial discharge (McCulloch et al. 2003), with laser-ablation ICP-MS at the Max-Planck-Institut für Chemie in Mainz (Germany) following the method of Mertz-Kraus et al. (2009). Flow regimes, nutrients, pigments, and suspended matter were monitored weekly in and outside the GRT lagoon from January 2007 to November 2008 (Arfi et al. 2007, 2008). Changes in reef morphology were inferred by comparing historical sets of black and white aerial photographs from 1962 and 1973 with recent high spatial resolution (2.0–2.4 m), multispectral, satellite images from 2006 and 2011 (Andrefouët et al., accepted). Diversity and compositional changes of benthic and fish communities were assessed by comparing results of recent field surveys (2007–2009) at multiple outer reef slope, reef flat, and inner slope sites that were identical or close to those studied in the 1960s and 1970s (Pichon 1978, Harmelin-Vivien 1979).

Fisheries Status and Options for Management

Trends in fisheries practices and yields were analyzed by comparing historical data with those of recent surveys of

Table 1. Summary of environmental and ecosystem measurements and trends.

Data	1950–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	Trend
ENVIRONMENTAL							
In situ, local							
Air temperature (decadal mean of annual averages, ºC)[1,2]	24.3	24.0	24.3	24.5	25.0	25.4 [a]	Upward trend +0.023 ºC y^{-1} ($P <$ 0.001); Fig. 2a
SST (box 81, ºC)[3]	25.7	25.7	25.8	26.2	26.4	26.5 [b]	Upward trend +0.0186 ºC y^{-1} ($P <$ 0.001); Fig. 2a
Rainfall (decadal mean of cumulated annual, mm)[1,2]	504	539	414	361	347	384	High variability, downward tendency -1.30 mm y^{-1} ($P >$ 0.05, ns); Fig. 2b
Turbidity (mean Secchi disk depth, m)[4,5]	-	8.1 / 5.2 [c]	-	-	-	12.0 / 6.0 [c]	At both stations, lower turbidity in 2007–2008 than in 1970s
Nutrients (means, µM)[5] Nitrate / Ammonia / SRP	-	-	-	-	-	0.37 / 0.09 / 0.19 [d]	Generally oligotrophic, occasionally mesotrophic conditions
Chlorophyll a (mean, µg L^{-1})[5]	-	-	-	-	-	0.28 / 0.66 [c]	Low concentrations for coastal area under estuarine influence
Proxies, local							
SST anomaly Ranobe lagoon relative to 1961–1990 mean ($\delta^{18}O$)[6,7]	-0.032	-0.196	-0.102	0.298	0.74	-	Upward trend 0.016ºC y^{-1} ($P <$ 0.001); SST rise of 0.72°C between 1950–1995
Sediment runoff (Ba/Ca, µmol mol^{-1})[7] GRT-1 / GRT-2	- -	- -	5.59 / 5.51	5.48 / 5.36	5.93 / 5.34	6.73 / 5.89	2-y upward trend GRT1 +0.045 µ mol mol^{-1} y^{-1} ($P <$ 0.001); GRT2: +0.012 µmol mol^{-1} y^{-1} ($P <$ 0.02); strong sediment pulses during peak river discharges; higher base level since 1998
Regional							
Onilahy River flow (decadal mean of annual average, m^3 s^{-1})[8,9]	123	154	79[e]	-	-	-	Downward trend ($P <$ 0.001) but data gaps post 1978 might inflate the trend; Fig. 2c
SST (decadal means of annual average in South Mozambique Ch., °C)[3]	24.8	24.8	25.2	25.3	25.3	25.4 [c]	Upward trend +0.0133ºC y^{-1} ($P <$ 0.001)
ENSO / IOD[10,11,12]	-0.30 / -	-0.18 / 0.09	-0.18 / -0.02	0.37 / 0.03	0.48 / 0.01	0.20 / 0.13	Strongly positive ENSO since 1980s; increasing climate variability due to 20th century mode shifts IOD
Tropical cyclones passing <100 km from GRT[13,14]	9	3	5	3	4	5	No trend in overall cyclone frequency
ECOLOGICAL							
Coral cover (%)[15,16,17] Outer reef slope (6–10 m) / Reef flat / Inner reef slope	-	30–100 / 50–100 / 80–100	-	-	-	15–30 / 1–2 / 2–20	Generalized loss of coral cover, most pronounced on reef flat
Number of coral genera[15,18] Outer reef slope (≤15 m) / Reef flat / Seagrass / *Grande Vasque* / Inner reef slope / Overall	-	31 / 38 / 26 / 39 / 52 / 56	-	-	-	43 / 30 / 8 / 49 / 48 / 61	Loss of coral generic diversity from shallow habitats

(con'd)

SOCIOECONOMICS							
Human population Toliara town and suburbs[19,20,21]	-	37,000	46,000–60,000	81,000–100,000	140,000	>200,000	Increasing by 3–4% per year. After 1980, rural exodus from SW Madagascar results in >40% growth of Toliara population[25]
Human population Toliara district[22,23]	-	-	-	130,000[f]	-	190,000[f]	Strong increases in coastal population Strong increases in fishing pressure
Number of fishermen Toliara district[22,23,24]	-	ca. 800	-	1556	-	1715	
CPUE (kg d^{-1})[21,25,26] Line / Gillnet / Seine	- / 50–100 / ≤1000	-	-	4–6/ 12.5–27.7/ 25.6–39.7	-	2.5–2.6 / 6.5–7.4 / 14.5–18.0	Strong declines in fisheries yields since the 1950s; between 1989 and 2009, yield per fisherman per day fell by ca. 50% regardless of gear
CPUE(kg d^{-1}fisherman^{-1})[21,26] Gillnet/ Seine	-	-	-	5.2–8.2 / 5.9–10.6	-	2.9–3.6 / 5.4–5.5	

[a] Average 2001–2007 period; [b] Average 2001–2005 period; [c] Stations: North passage / lagoon; [d] Lagoon; [e] Average 1971–1978 period; [f] Includes communities Besakoa, Mahavatse II, and Mahavatse I, Ankilibe, Sarodrano, and St. Augustin; [g] Catches in respectively cool and hot seasons.

[1] ASECNA 1950–2007; [2] IRD 2007–2008; [3] HadISST1 monthly SST; [4] Gaudy 1973; 5 Arfi et al. 2006, 2007; [6] Coral core from Ifaty covering 1660–1995 (Zinke et al. 2004); [7] Four cores from Ifaty and GRT covering 1975–2008 (Maina et al. 2012; J.Z., unpublished results); [8] ORSTOM Laboratoire d'Hydrologie (1950–1960); [9] Direction de la Météorologie et de l'Hydrologie of Madagascar (1961–1978, 1987, 1995, 1996, partial data for 1990, 1992, 1993); [10] http://www.esrl.noaa.gov/psd/enso/mei/; [11] Abram et al. 2008; [12] Nakamura et al. 2009; [13] http://australiasevereweather.com/tropical_cyclones [14]; Kuleshov et al. 2010; [15] Pichon 1978; [16] Harris et al. 2010; [17] FMAR and JHB, unpublished results; [18] MMMG, MP, FMAR and JHB, unpublished results; [19] Salomon 1986; [20] Vasseur et al. 1988; [21] Laroche et al. 1997; [22] Laroche and Ramananarivo 1995; [23] Randriambololona 2009; [24] Bellemans 1989; [25] Lagouin 1959; [26] FR and JHB, unpublished results

Erratum: After publication of this manuscript, changes were made to the author affiliations, acknowledgments, and Table 1. The changes were made on 17 January 2013.

traditional fisheries conducted during the cool (2009) and hot (2010) seasons at five villages that exploit the GRT (Fig. 1), following similar methods as those used by Laroche and Ramananarivo (1995). In short, during 60 days per season, 15 fishing boats were sampled in each village, recording vessel type, number of fisherman, time spent at sea, capture location, gear types used, average size and total weight per species, and total weight of catch. In total, 6872 fish landings were analyzed during these recent surveys. Traditional organization and contemporary regulations of fishing practices on the GRT were inventoried concomitantly.

To better understand stakeholders' perceptions about different options for managing marine resources, we surveyed 270 resource users and four managers across 10 fishing villages north and south of Toliara (see Fig. 1) using a previously described questionnaire (McClanahan et al. 2008a). Respondents were asked to use a five-point scale (disagree strongly, disagree, neutral, agree, agree strongly) to indicate the degree to which they agree or disagree with the ability of restrictions on space, effort, time, gear, and species to maintain sustainable fisheries. We evaluated the similarity in responses between villages by cluster analysis (Ward method) and then plotted the village respondents' mean agreement with the six restrictions for the two clusters formed from the similarity analysis.

RESULTS

Climatic and Hydrological Trends

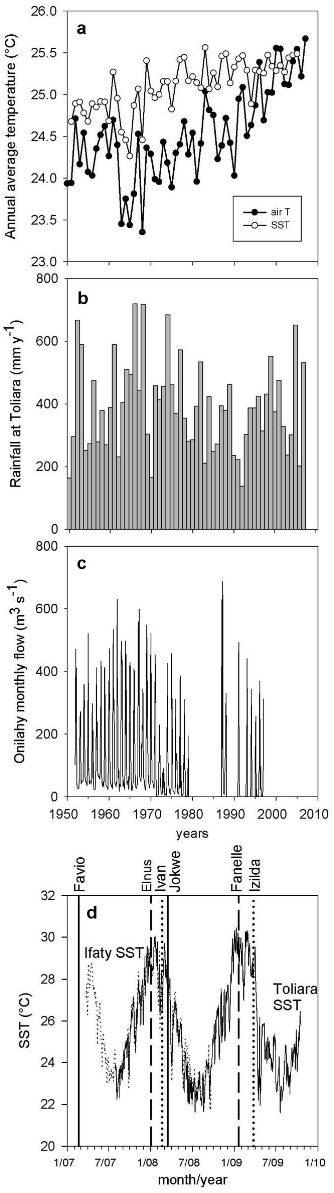
Temperature

Mean air temperatures at Toliara are presently >1°C higher than those recorded between 1950–1962 due to a distinct warming trend that started in the late 1960s (Fig. 2a, Table 1). Regional gridded sea surface temperature (SST) shows a similar pattern, comprising a general warming trend of 0.018° C y^{-1} from 1950 to present, with an abrupt warming since the early 1970s (Fig. 2a, Table 1; McClanahan et al. 2009). A >300-year temperature record (1658–1995) based on $\delta^{18}O$ analysis from three coral cores taken off Ifaty and Toliara show the highest SSTs of the entire record since the early 1970s superimposed over a more gradual SST rise over the 20th century (Zinke et al. 2004, 2009). The coral $\delta^{18}O$ SST trend between 1950 and 1995 was 0.016°C y^{-1} (Table 1), in close agreement with the rise reported from gridded SST (McClanahan et al. 2009). This record further revealed a strengthening of the correlation with the El Niño-Southern Oscillation (ENSO) between 1960 and 1995 (Richard et al. 2000). ENSO events lead to higher SST and evaporation in Ranobe lagoon (Zinke et al. 2004).

Rainfall

High inter-annual variability characterizes rainfall at Toliara. Years with relatively high rainfall (500–700 mm y^{-1}) alternate with dryer ones (200–500 mm y^{-1}), punctuated by years with very low rainfall (< 200 mm y^{-1}, in 1950, 1970 and 1992) (Fig. 2b). Mean number of rain days (>1 mm precipitation) is only 32 y^{-1}, irregularly distributed over the rainy season (December–March). Over the period 1950–2008, there is a tendency for decreasing rainfall (Table 1) which, if continued, may become insufficient (<200 mm y^{-1}) for agriculture by 2050.

Fig. 2. Compound figure of temporal change: (a) annual average for air and seawater temperature; (b) annual rainfall at Toliara airport; (c) annual Onilahy River outflow at Tongobory; (d) daily average in situ SST 2007–2009 at Ifaty and Toliara, from hourly records at 3 m depth (Hobo Water Temp Pro logger, accuracy: 0.2°C, Onset Computer Corporation, Pocasset, USA), completed with cyclone events. Data: air temperature and rainfall: courtesy of ASECNA Madagascar (23° 23’S, 43° 44’E); annual mean SST: Hadley Centre SST; river flow: courtesy of ORSTOM and DMHM; daily SST Ifaty: WCS; daily SST Toliara: UR/MNHN.



River flow

The Onilahy River flow shows a clear seasonal pattern, with flood events comprising several consecutive peaks occurring during the warm seasons (Fig. 2c). Although river flow continued throughout the cool dry seasons (20–50 m^3 s^{-1}) until 1972, this baseline flow decreased strongly after two consecutive years of very low floods (1972 and 1973). No continuous record exists after the late 1970s. Nevertheless, a decreasing trend is perceptible from the mid-1960s, both in floods and baseline flows (Table 1). The punctual records available for the Fiherenana River indicate a wadi flow regime, with absence or low flow during the dry seasons (subterranean flow may continue) and sporadic extreme floods that may be devastating, such as during the inland passage of cyclone Angele in 1978.

Water quality

Lagoon waters of the GRT are characterized by high turbidity. However, a recent survey revealed higher Secchi depths at the same two stations monitored during the early 1970s (Table 1). This indicates that water transparency in the GRT lagoon has slightly increased over the last 50 years.

Coral cores from the GRT show high flood peak Ba/Ca values, indicating high sedimentation during the wet season (Maina et al. 2012). Both cores agree in showing an upward trend and higher baseline levels for a period between 1998 (strong ENSO event) and 2002 (Table 1). Different absolute values in Ba/Ca between the two cores point to heterogeneous sediment supply within the GRT lagoon.

GRT waters are further typified by generally low nutrient concentrations (Table 1), corresponding to oligotrophic conditions. Temporary increases in nutrient concentrations corresponded to flood events during the warm season, sometimes reinforced by cyclone-induced mixing (Fig. 2d, see sudden drops in SST). Other transient rises in nutrient levels (mainly nitrate) corresponded to low-intensity cooling events reported during the cool season that might reflect the occurrence of a crypto-upwelling near the GRT, as proposed by Gaudy (1973).

Tropical cyclones

The impact of tropical cyclones on the GRT depends on their track, moving speed, and intensity. No trend in cyclone numbers passing <100 km from the GRT was detected in the historical records (Table 1). In the southern Indian Ocean, the total number of cyclones and number of cyclones with minimum central pressure of ≤970 hPa did not change over the period 1980–2006 (Kuleshov et al. 2010). These authors did, however, detect a significant increase in the occurrence and number of days of severe cyclones with minimum central pressure of 945 hPa.

Changes in Reef State

Habitat changes

For three wide swaths across the GRT, significant loss of coral habitats was evidenced. These habitats were formerly described as "reef flat with transverse strips" (Fig. 1, zone "A"), "reef flat with scattered coral growth," and "compact reef flat" (Clausade et al. 1971) and reported as dominated by living corals in the late 1960s (Pichon 1978). Between 1962 and 2011, the loss of transverse coral strips ranged from 80% to 40% depending on location (Andréfouët et al., accepted). These are conservative estimates because the images only show structural losses and not necessarily changes in coral cover, as both live coral and macroalgae appear very dark on historical black and white images. The recent field surveys revealed that these former coral zones are now mainly composed of loose rubble and boulders overgrown by macroalgae (see below). Seagrass beds on inner reef flats display a variable pattern of loss and recovery (Fig. 1, zone "B,", compare 2006 and 2011), depending on the location on the reef, but appear stable at the scale of the GRT.

Coral cover and diversity

Our surveys revealed drastic losses in coral cover in all reef zones compared with the 1960s. Shallow reef flats are most affected (presently ≤5% coral cover), reflecting the deeply modified habitat structure of this zone. For all reef flat coral habitats combined, coral diversity declined from 38 to 30 genera, whereas seagrass beds alone lost 18 coral genera over the past 40 years (Table 1). Remarkably, the Grande Vasque, a large semi-enclosed basin in the north of the GRT (Fig. 1), still maintains high coral diversity (49 genera) and large stands of *Acropora* spp. Inner reef slopes that harbored the highest coral diversity in the 1960s maintain rich coral communities, comprising 48 scleractinian genera, clustered in small patches, but overall representing merely 5% coverage (Table 1). On upper outer reef slopes, pocilloporids and acroporids may reach 30% cover but are replaced locally by macroalgae. Lower slopes contained more diverse coral communities. Surprisingly, the phase shift from corals to macroalgae on the GRT is not hitherto accompanied by a generalized loss in coral diversity (Table 1). *Gyrosmilia interrupta* is the only species abundant in the 1960s that seems to have disappeared from the revisited sites.

Algal cover and communities

The present low coral cover is offset by high cover and biomass of macroalgae. Whereas summer blooms of canopy-forming macroalgae (*Sargassum* spp., *Turbinaria* spp.) were already reported on inner reef flats in the 1960s (Pichon 1978), hard substrates are now dominated by macroalgae at all times of year. In summer, the canopy-forming species *S. latifolium* and *T. ornata* reach 70% cover, and in winter foliose algae (*Ulva* sp., *Padina* sp.) dominate, reaching 60% cover. The cover of algal turfs and crustose corallines is higher on the outer reef slope (ca. 40%) than on the reef flat (20–30%). On the outer slope, cover of canopy algae does not exceed 42%, and foliose algae are more diverse and abundant than on the reef flat.

Reef fish communities

Visual surveys in shallow reef zones in 2008–2009 compared with inventories made in the 1970s suggest that species richness decreased in several families of reef fishes. Minor losses occurred in Acanthuridae (two species) and Siganidae (one species), but the diversity of Scarinae (parrotfishes) declined from 13 to seven species. Chaetodontidae and Serranidae, formerly comprising 20 species each, have lost six and seven species, respectively, over the past 30 years. Keystone functional groups that can consume canopy algae (e.g., Ephippidae, Kyphosidae) were not observed in visual surveys but are occasionally caught in seine nets.

Earlier studies were oriented toward inventories and provide no information on density or biomass of reef fishes. Today, the standing stock of reef fishes is extremely low. Total biomass of the 11 families included in the recent surveys averages 159 kg ha^{-1} but is distributed unevenly across reef zones: highest biomass is found on the reef front (ca. 249 kg ha^{-1}), whereas inner reef slopes have lowest fish biomass. Detritivores are the dominant trophic group, representing 57% of total biomass. Herbivores attain ca. 40 kg ha^{-1} or 25% of total fish biomass, with slightly higher values on the reef front. These standing stocks are among the lowest recorded in the Indian Ocean (McClanahan et al. 2007, 2011b).

Changes in Fisheries and Their Management

Changes in traditional fisheries practices and yields

During the 1970s, engine-powered boats were used for fishing inside and outside the GRT lagoon. These had disappeared by 1984 due to high fuel costs and the poor economic situation (M. P., personal observation). Today, fisheries are operated on foot, from small canoes, or from 4–7 m long pirogues that are sail or hand powered. Fishing zones are not segregated by community, thus fishers from different villages may (and do) operate anywhere on the GRT. Earliest reports on finfish catches indicated high yields (>50 kg d^{-1} and >1000 kg d^{-1} for hand lines and seine nets, respectively; Lagouin 1959). Between 1972 and 1988, the number of fishermen increased by 57% in the Toliara province (Bellemans 1989; Table 1). Reported decreases in yield and fish sizes (Vasseur et al. 1988) led to a more detailed analysis of the fisheries in 1989. Yields averaged 4.8–10.6 kg fisherman^{-1} d^{-1}, depending on gear type and season, values that were lower than for most other artisanal fisheries in the southwest Indian Ocean (Laroche and Ramananarivo 1995). Our survey, conducted 20 years later in the same villages, showed that yields had further decreased by >50%, regardless of gear type (Table 1). Gear use shifted toward increased use of beach seines that allow slightly higher catches per fisherman (~5.5 kg fisherman^{-1} d^{-1}). Seine nets, used near shore or on the reef flats, now represent 43% of the catch by weight.

Women and children are traditionally the main people collecting shellfish and octopus during extreme low tides. However, for several decades, young men have used bars and wooden wedges to pry loose and overturn coral heads to catch octopus, shellfish, and fish hidden in crevices (Koechlin 1984). Salimo (1997) estimated that this destructive fishing practice, including the trampling of corals, annually destroys ca. 1 km^2 of coral habitat on GRT reef flats. This field estimate is compatible with the rate of disappearance of coral habitat as quantified from images (see above). Recent field observations indicate that this practice persists, likely contributing to the continual loss of habitat structure, evidenced by the satellite image from April 2011 (Fig. 1).

Past and present management practices

Madagascar has two types of customary rules that may have implications for conservation of both marine and terrestrial ecosystems: “fady” and “dina” (Cinner 2007, Cinner et al. 2009). A “fady” is a taboo that regulates specific activities in a particular location. A “dina” is a locally developed law that is based on and enforced by Malagasy social norms.

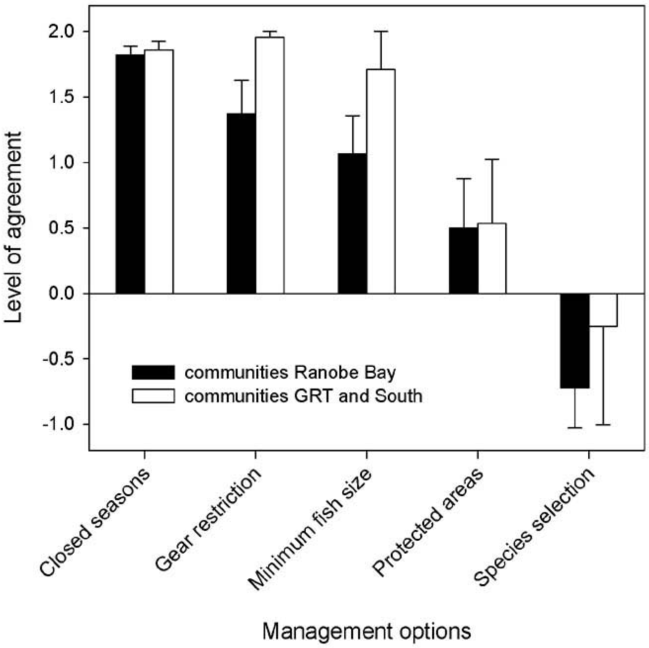
The northern part of the reef flat surrounding the island Nosy Ve, off Anakao (Fig. 1), is a fady zone and reputedly protected from fishing. Field surveys during 2008–2009 did indeed reveal higher biomass of reef fishes and coral cover at the Nosy Ve “fady” site than on GRT sites (fish biomass: $\text{ANOVA}_{\text{reef flats}}$, $F_{1,89} = 2.286$, $P = 0.000$; $\text{ANOVA}_{\text{outer reef slopes}}$, $F_{1,89} = 6.160$, $P = 0.015$; coral cover: $\text{ANOVA}_{\text{reef flats}}$, $F_{1,71} = 112.328$, $P = 0.000$; $\text{ANOVA}_{\text{outer reef slopes}}$, $F_{1,71} = 6.573$, $P = 0.013$). This indicates that customary “fady” regulations contribute to improve ecological conditions.

In 1996, the first system of community-based organization known as “Gestion locale sécurisée” (Gelose) was created (Antona et al. 2004). The law and institution allow communities to define their own goals and develop local resource use regulations as long as they do not conflict with national laws. This regulation was applied to marine resources for the first time for a mangrove social–ecological system in Toliara in 1999. Some communities in the country, including Anakao and Velondriake to the southwest of Toliara, have been practicing community-based marine resources management but without the Gelose legal status. This arrangement is supported by the Government and conservation NGOs, but there are contractual and legal gaps that create weaknesses with enforcement and compliance (see below; Cinner et al. 2009).

Acceptance of regulations

Responses to the questionnaire concerning the respondent’s views that certain restrictions promote sustainability or not indicated that about one-third of the people could not answer the questions for specific restrictions. Those that did answer, however, scaled their responses for high agreement with the six restrictions (Fig. 3). The restrictions: closed areas, closed seasons, gear restrictions, minimum sizes, and marine protected areas were scaled toward positive agreement by all villages, whereas species restrictions were consistently scaled negatively. The main difference in the responses was that three communities located in Ranobe Bay scaled gear restrictions and minimum sizes of fish lower than the villages along the GRT and further south (McClanahan et al., unpublished results).

Fig. 3. Scaled preferences for management restrictions from the 10 fishing villages studied in SW Madagascar. The northern communities at Ranobe Bay had less positive responses and clustered separately from the seven villages along the GRT and further south.



DISCUSSION AND CONCLUSIONS

Biophysical Drivers of the Historical Changes

A popular view of the causes of GRT degradation is that changes in water quality are responsible, in particular increases in nutrients and suspended sediments (Vasseur et al. 1988, Gabrié et al. 2000, Harris et al. 2010). Pollution and nutrient increases are hypothesized to derive from population growth in the Toliara district and are associated with the absence of wastewater treatment, agricultural practices, and harbor traffic. However, the measured low nutrient and chlorophyll *a* concentrations reflect oligotrophic conditions. Moreover, the low residence time of GRT lagoon water (C. Chevalier, personal communication) enhances flushing and disfavors potential nutrient enrichment. The dominant algae in the summer, when runoff is highest, are those taxa that often do not respond well to increased nutrients (McClanahan et al. 2003). Based on these field data, we believe that nutrient availability is unlikely to have contributed to the coral–algal phase shift of the GRT system or to promote macroalgal development today.

The permanent high turbidity of lagoon waters is often attributed to large-scale deforestation of river catchments. River discharge has decreased, however, whereas water transparency in the GRT lagoon has increased slightly over the last 50 years (Fig. 2c, Table 1). Due to the geomorphological setting and local wind and current fields, a large part of the sediment loads carried by the Fiherenana and the Onilahy rivers (mainly the larger-sized particles, such as sands) does not reach the reef, either because it sinks in the Onilahy River canyon or is carried out to sea. Sediments that reach GRT reef zones during peak river flows are primarily composed of small-sized particles, such as clays and silts. The shallow morphology of the GRT lagoon, comprising large intertidal zones, favors resuspension of fine sediments driven by the strong tidal currents and sea breezes. High turbidity is, therefore, typical of the GRT lagoon.

Seasonal Ba/Ca peaks in coral cores indicate high sedimentation during the rainy season. Increased baseline levels in the late 1990s, possibly triggered by the 1998 ENSO event, are correlated with increased sediment runoff in the vast Onilahy River catchment, the latter driven by population growth, deforestation, and changes in rainfall (Maina et al. 2012). However, habitat change detection spanning 50 years did not reveal continuing increases in sediment cover in shallow reef zones (Andréfouët et al., accepted). Consequently, there is no conclusive evidence that sediment runoff has contributed to the strong decline in coral cover.

The available temperature records (land-based, gridded SST and coral proxies) all indicate significant warming since the 1970s (Table 1). In 1983, higher than average temperatures were recorded in northwest Madagascar, corresponding to severe coral bleaching observed at Reunion Island (Guillaume et al. 1983) and in Mayotte (Faure et al. 1984). Although Toliara records show higher than average air temperatures and SST for 1983 (Fig. 2a), which may have affected corals of the GRT, we did not find a report of coral bleaching that year. Fast SST rises combined with high SST variability linked to ENSO and IOD systems have resulted in high heat stress for corals in southwest Madagascar since the 1998 temperature anomaly (McClanahan et al. 2009). Although not well documented, possibly due to a lack of trained observers, coral bleaching is likely to have contributed to the decline of the shallow coral communities.

Cyclones may act as co-stressors contributing to the demise of coral communities. Although the frequency of severe cyclones has increased significantly in the southern Indian Ocean (Kuleshov et al. 2010), no data are available on their impacts on the GRT. Climate records also revealed a clear trend of decreasing rainfall in Toliara (Fig. 2b). Rising air temperatures and diminishing rainfall contribute to decreased viability of agriculture and livestock production in the region (USAID 2008), which is likely to have increased human dependency on the GRT for food, particularly protein and micronutrients (see below).

Social–Ecological Causes of Change

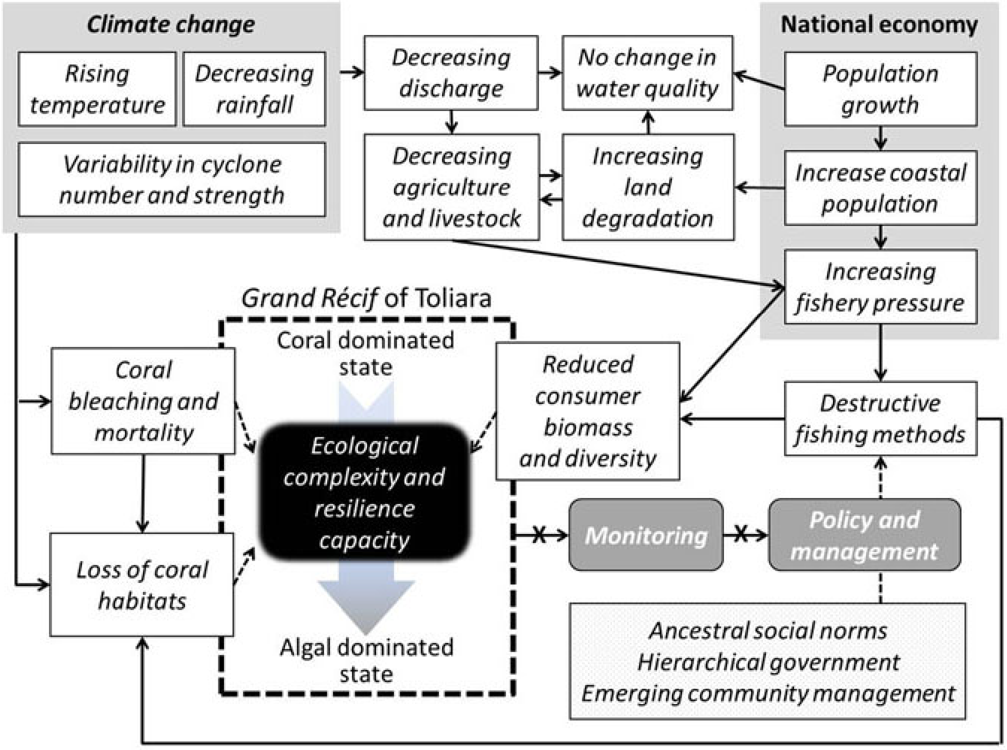
Based on the synthesis of the environmental context and trends summarized in Table 1 and our current understanding of the processes leading to phase-shifts in coral reefs, we consider bottom-up processes for the large-scale degradation of the GRT unlikely. Instead, our evaluation of the socioeconomic changes during the past ca. 40 years point toward top-down effects, particularly human population growth, increasing reliance on the GRT for food and survival, and technological change that concentrated fishing effort near shore (i.e., the demise of motorized boats).

Coastal population increases are the combined result of natural growth and migration from increasingly arid hinterlands that compromise options for land-based food production. The poor infrastructure (roads and refrigeration facilities) has contributed to concentrating coastal populations around Toliara, where fishermen can sell their products (Chaboud 2006). Cascading effects and causes include increased fishing pressure, loss of fish biomass including herbivores, and coral habitat destruction by increased destructive fishing on the reef flats. These have increased available space for the proliferation of macroalgae throughout the year.

Tame or Wicked Problem?

The key mechanisms that we believe are eroding the resilience capacity of the GRT, leading to its present degraded state, are synthesized in a conceptual flow diagram (Fig. 4). Direct climatic impacts on the reef are intimately linked to the socioeconomic changes they bring about. Some of the problems and social–ecological linkages in the data and associated conceptual model are reasonably understood by some disciplines. Nevertheless, when combined into a larger scheme and embedded in the national economic and local cultural and governance contexts, the responses to standard management recommendations are much more difficult to implement and predict. More practically, recognizing the inherent wickedness of the social–ecological problems is more likely to lead to some successes. Taming the problem to simple or isolated causative models and management recommendations

Fig. 4. Flow diagram of the key processes and interactions influencing coral reef state. Arrows with X indicate absence of information flow.



may lead to no or futile actions and then blame when they fail to be implemented or achieve the desired goals. Below, we discuss the results and recommendations, first in terms of the more traditional management tools and then in terms of the wicked problems that require other approaches, and argue for a hybrid path forward.

Management Tools and Selection for the Tame Problems

A hopeful finding of the management preference surveys is that the perceptions of management restrictions are generally positive. The caveat, however, is that a significant portion of those interviewed were unable to answer questions about sustainability, which suggests that this concept may not be considered among a significant portion of resource users (Chaboud 2006). Among the restriction options, support for marine protected areas was weak, and restrictions on harvesting species not favored. These two options are among those most desired by international conservation NGOs and donors—restrictions on megafauna, top-level predators, keystone species and their large area requirements (Ray et al. 2005). We believe that implementing these two undesired restrictions could create weak support and tensions, and delay actions. The chances for success are probably higher if restrictions on gear, size, and rotational or periodic closures are the primary focus of initial efforts, as they will promote and implement values that are already widely shared. There is also a need to couple implementation with education concerning the concepts of fisheries management and sustainability.

A second hopeful finding for initiating successful actions is that the preferred restrictions in the studied villages cluster by their geographic location. This allows area-specific management to be developed and reduces the problems of conflicts between villages. A common problem of local-level management is that villages may not practice and honor the restrictions of their neighbors, which can undermine local restrictions (Horrill et al. 2000, McClanahan et al. 2008a). Here, problems are more likely to arise from individual differences among resource users within villages where villages lack control of individual decisions and behavior. These management preferences results, when shown to resource users, can lead to recognition that there is a consensus or democratic majority that agrees on restrictions, and this can catalyze the desired actions (McClanahan et al. 2008b).

Fishing gear recognized as destructive by GRT fishermen are mosquito net and fish poison (the latex of *Euphorbia laro*). Their use is prohibited but continues and has even increased (Vasseur et al. 1988, Chaboud 2006). Although small-mesh seine nets are considered harmful for corals and seagrass, this gear type generates >40% of the catches. Our synthesis further highlights the devastating impact on coral habitat structure of destructive reef gleaning (Salimo 1997). Sharing this information with stakeholders and showing their impacts on fisheries production may contribute to reaching consensus on the priorities for gear and minimum fish size restrictions to be put in place. Perhaps increasing the mesh size rather than banning this gear might be a preliminary and less contentious action.

Fisheries management initiatives from the 1990s include the installation of fish aggregation devices (FADs) outside the GRT to improve access to pelagic stocks. However, these FADs were not maintained by the fishing communities and disappeared rapidly (Rey-Valette and Cayré 2000). Temporary closure of octopus fishing grounds is emerging as a popular management tool in southwest Madagascar, where >100 such closures have been implemented since 2004. A recent analysis showed their success in terms of increasing CPUE and cash profits (Benbow and Harris 2011). Closed seasons are among the management tools most favored by GRT fishers. The fact that temporary closures have not been implemented on the GRT may be related to the high population density in the Toliara agglomeration and to fishers operating all over the GRT, which makes compliance and enforcement particularly problematic. These examples illustrate the difficulties in putting in place a coordinated management action for the GRT that receives continued support and compliance by fishermen.

Creating alternative livelihoods, when successful, may be an important part of fisheries management and contribute to boost income of coastal populations. For the GRT, these initiatives have included *Euchema* farming, macroalgal collection in the wild, and rearing of sea cucumbers and post-larval fishes. However, as with many alternative livelihood schemes (Pollnac et al. 2001, Hill et al. 2012), these initiatives have met with limited success, either because of poor adoption by fishing communities (particularly for seaweed farming) or due to diseases and theft (holothurian farming). The post-larval fish rearing for the aquarium trade is promising, but is only very recent (Mahafina et al. 2009). Wild seaweed collection is now practiced by women of the fishing communities, who sell their harvest to a Malagasy enterprise for exportation.

Tourism around Toliara has been developing in Ifaty and Anakao. The GRT does have a few attractive reef sites that could be developed for ecotourism and education, such as the Grande Vasque, which maintains high coral and fish diversity. This site merits a targeted conservation effort to protect it from further destructive fishing practices.

Governance for the Wicked Problems

Solutions to wicked problems result from the interaction of many and possibly opposing perspectives on what the problems are and how they should be resolved, and requires a great number of people to exchange and possibly change their attitudes and behavior (Lazarus 2009). Here, we use the cultural viability framework (Verweij 2000) to help understand the nature of the varying perspectives on the wicked problem facing the GRT.

Cultural viability theory suggests that there are four primary ways of organizing, perceiving, and justifying social relations: (1) egalitarianism, whereby benefits from ecological goods and services need to be equitably distributed, and the precautionary principle employed; (2) hierarchy, in which nature has limits that require experts (e.g., scientists and managers) to discover and promote regulatory activity to keep society within these limits; (3) individualism, whereby solutions to social problems lie in self-organization and unfettered markets; and (4) fatalism, in which actors tend to have a “not-my-problem” view toward solving dilemmas and will defect in commons situations because of a lack of mutual responsibility, trust, and faith in proposed solutions (Verweij et al. 2006). These viewpoints, in their extreme, are mutually incompatible, yet solutions to complex social and ecological problems often require a compromise that embraces multiple viewpoints.

Despite the positive findings from the management perceptions study, the results beg the question that if a significant portion of the people favor restrictions, why are more restrictions not in place and, when in place, why such poor compliance? Destructive and small mesh nets and prying loose corals are among the many destructive practices that have transformed the GRT into one of the most degraded reefs in the region. It might be expected that a breaking point would be reached where action on restrictions would be implemented, and yet it appears to be a very slow process.

One of the strongest values among the Vezo people is the individual right to fish (Iida 2005), and we suggest that this strong individualism may create challenges for the cooperation that is frequently necessary to maintain common property management systems. Additionally, high population growth and a strong influx of migrants have likely contributed to the breakdown of customary laws for management of marine resources, resulting in weak rules, monitoring, and policing (Cinner et al. 2007).

The positive views toward management restrictions may be constrained by the right-to-fish value and a lack of institutional and social capacity to implement effective governance. For example, the institutional design elements for successful common property management for Gelose have been evaluated, and several key elements were weak or absent (Cinner et al. 2009). These are: monitoring of monitors, nested enterprises, clear definitions of geographic boundaries, the ability of individuals to influence rules, graduated sanctions, and the monitoring of resource users. This suggests that the

Table 2. Heuristic framework describing the attitudes, social organization, and expected responses to common property design elements of resource management. The framework can assist decisions on direction for change among forums on common property management.

	Social organization		
Attitudes	Individualism	Egalitarian	Hierarchical
Deterministic	Strong competition and rule making, self monitoring and policing	Strong collaboration, strong rules, group monitoring and policing	Strong authoritative collaboration, strong rules, effective outside policing
Fatalistic	Weak competition, rules, monitoring, and policing	Weak collaboration, rules, monitoring, and corruptible group policing	Weak authoritative collaboration, rules, and corruptible outside policing

capacity to implement an “egalitarian”-oriented common property management system is challenged by these institutional weaknesses. Additionally, customary institutions also may constrain peoples’ capacity to engage in resource management (Cinner 2007, 2011).

In southwest Madagascar, behaviors—and peoples’ capacity to engage in new ones—are often influenced by historical “fady” (taboos) established by ancestors (Astuti 2007, Cinner 2007). These “fady” can be numerous and complex, but sometimes apply only to individuals or specific family lineages. The strong individualism of the Vezo fishermen combined with a fatalistic attitude toward actions and changing behavior may also contribute to weak monitoring and policing (Table 2). Fatalism may result from morality and cultural practices of ancestral control and worship and satisfying ancestors rather than one’s future (Astuti 2007) and may also arise from a difficult and unpredictable environment. It is arguable that until the fatalism is replaced with a more deterministic attitude, possibly shown through the results of monitoring yields under different management systems (McClanahan 2007), stronger compliance is not attainable. Although this may seem unrealistic to some, adaptive management experiences in Kenya fisheries forums found that fatalistic views were replaced by deterministic views among many once cause and effect were determined from fish catch monitoring programs under different management systems (McClanahan 2010, McClanahan and Hicks 2011). Similar changes are being observed around the octopus seasonal closure in the fisheries north of Toliara (Benbow and Harris 2011). Consequently, it may also be that more egalitarian and hierarchical social organization can result in improved compliance, which can be achieved by strengthening and adapting the Gelose system to these local marine management systems (Roberts 2000). Therefore, increasing forums and resource monitoring are seen as two of the stronger recommendations for beginning a dialog needed to navigate the wicked problems.

Back or Forward to the Future?

Natural scientists share a common normative view that fisheries management should rebuild stocks and return ecosystems to a prior state (Jackson et al. 2001, Worm et al. 2009) or that a healthy future requires us to return to past conditions (Pitcher 2001). This view provides goals for management, but they may be so unrealistic and unattainable that they could promote cynicism about the value of natural science and scientists (McClanahan 2011). This cynicism contributes to the post-normal social organization, where natural scientists’ ideas are seen as naïve and value laden or possibly only useful for tame but not the more critical wicked problems (Rittel and Webber 1973). The possibly strong path dependency, one-way social–ecological gates and hysteresis that may occur in social–ecological systems may eventually put this concept to rest.

From the perspective of social policy, the region is one where a purely scientific–rational approach can be applied to only a limited set of issues because of the lack of a clear problem definition, clear cause and effect, trade-offs, and differing perspectives of stakeholders. In the suggested governance forums invoked to solve wicked problems, the question of who benefits and for what reason is essential to establish a stewardship that involves natural resource users (Jentoft and Chuenpagdee 2009). Despite extremely low standing stocks of fish and decreased fisheries yields, the GRT does continue to provide fisheries resources and income by promoting small fish with high production and turnover, as can occur in heavily exploited fisheries (McClanahan et al. 2008b). This is more satisfactory to poor consumers than scientists, and may delay changes in fisher and consumer behavior.

Based on our review of existing data, we have argued for a hybrid approach with the standard suggestions for solving tame problems, those locally tailored to current perceptions to reduce value conflicts among forum participants, combined with forums that will be needed for discovery of the wicked problems and crafting solutions, preferably through the monitoring of resources and users and the broad sharing of this information. The information needed to understand the system is slowly being generated by a renewed interest in the region since the early studies by the French scientific community, which established the important baseline. Although objective data gathering and analysis will never develop sufficient information to fully understand a wicked problem, the collective failure to recognize this may be delaying the needed response. The wicked problem approach to the degradation and management of the high-latitude GRT may apply more generally to other social–ecological systems in the context of climate change, including low-latitude coral reefs in areas with drying climates.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/5300

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