Assessing resilience in a coral reef seascape

Bleaching Responses and Recovery in the Lakshadweep Archipelago

Nature Conservation Foundation

Status Report

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Summary

Low lying coral atolls are among the first natural systems to face the direct impacts of climate change, and have, over the last decade, emerged as potent indicators of what we can expect of the world's ecosystems in an environment of increasing uncertainty and change. They are also valuable laboratories to further our understanding of how socio-ecological systems respond to surprising events, and how we can best conserve these systems at scales relevant to regional management. We surveyed the reefs of the Lakshadweep Archipelago, a chain of 12 coral atolls in the northern Indian Ocean after a major El Niño anomaly in 2010 caused widespread coral bleaching, setting back more than a decade of recovery since a similar event in 1998. We assessed the present status of the ecosystem, surveying a total of 42 reefs across entire archipelago, including several locations at submerged coral banks. Our results show a mixed picture of impact across the archipelago, with few clear geographical patterns evident in coral mortality after the bleaching. While many locations saw significant reductions in coral cover, others appeared to have sustained the bleaching much better. This was particularly true of reef locations in the enclosed shallow lagoons, where there was considerable evidence for local acclimation of corals to high temperatures. We evaluated the resilience of each

reef location based on a range of parameters that either support or weaken the inherent buffer capacity of the reef. This analysis indicated that reef aspect and depth played very important roles in determining the predicted resilience of reef locations. In addition, ponded lagoon reefs scored higher on the resilience index than similarly shallow outer reef sites, indicating that these locations may be crucial to protect for their potential to recolonize the reef with stock that may be putatively better able to resist future bleaching events.

Introduction

Few natural systems are as susceptible to the forces of global change as low-lying coral atolls. Ocean warming events (associated with anomalous El Niño currents), sea level rise and ocean acidification act in concert with coastal development, fishing and other local pressures to create a cocktail of stressors that seriously threaten the existence of these systems (Hughes et al. 2003b, Lesser 2007, Carilli et al. 2009). What makes this particularly worrying is that these systems are among the most diverse and productive ecosystems in the world, performing a range of vital ecosystem functions, and sustaining the livelihoods of local communities (Done et al. 1996, Moberg & Folke 1999).

It is becoming increasingly clear that, given the scale and pace of global climate change, the goal of local management has to shift from attempting to control the forces of change, to one of prophylaxis in the face of an environment increasingly characterised by inevitable surprise. Determining the inherent ability of these critical ecosystems to sustain change when it does happen is the first step towards a management based on principles of resilience rather than control (Hughes et al. 2003a, West & Salm 2003). Beyond this initial assessment of buffer capacity is the even more vital task of determining the specific drivers and mechanisms of ecosystem resilience or susceptibility in the face of change. This will hopefully lead to a spatially explicit predictive framework of resilience that will enable a science-based prioritisation of coastal management. In its broadest formulation, this will help determine which areas and ecosystem processes are most fundamental to protect in order to enhance the overall buffer capacity of the system. This project takes the first step towards developing and validating a predictive resilience framework for the Lakshadweep Islands, an archipelago of low-lying coral atolls in the northern Indian Ocean.

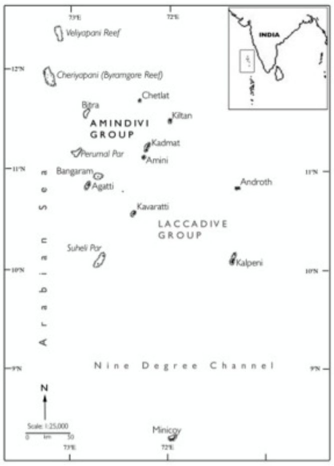

Figure 1

The Lakshadweep atolls (Figure 1) are high diversity coral formations that appear to be particularly vulnerable to changes in sea surface temperatures. The pan-tropical 1998 El Niño resulted in a coral mass mortality of between 80-90% in most surveyed reefs (Arthur 2000), and my work over the last decade in this island group has focused on tracking the further decline and recovery of these systems from that event (Arthur 2005, Arthur et al. 2005, Arthur et al. 2006, Arthur 2008). The last 12 years have witnessed a mixed reef recovery in the Lakshadweep, including some surprisingly rapid rates of coral recolonisation and growth at some locations, and very shallow recovery at others. The summer of 2010 saw another major El Niño-related bleaching event in these waters, and our initial assessments indicated that its impact could be as wide as the 1998 event. The repeated coral die offs that these systems are subject to raises the question of how resistent and/or resilient individual reefs in the face of change, and serves as an ideal natural experiment to test the buffer capacity of these ecosystems.

This project aimed to conduct a comprehensive archipelago-wide survey to assess the impact of the 2010 bleaching event on these atolls. Our goal was to evaluate the current benthic status of reefs, document impacts to fish communities, and measure a range of potential environmental and anthropogenic drivers that could help determine the overall resilience of these reef systems.

Project Update and Methods Employed

From Novemeber 2010 to April 2011, our team visited atolls across the Lakshadweep Archipelago and intensively sampled a total of 42 reef locations across 12 coral atolls (Figure 1). With the exception of Androth (a lagoonless island with fringing reefs) and Suheli (an uninhabited atoll), we surveyed every location in the archipelago including two submerged banks (Perumal Par and Cheriyapani). At each atoll we conducted in-water diving surveys, varying the number of reef sites we surveyed according to the size of the atoll. In addition, where substantial reef formations were present inside the lagoon, we also surveyed these lagoon sites.

At each location we sampled reefs at two depths (where possible), between 10-18 m (deep) and between 5-10 m (shallow). Benthic condition was assessed using 1 m^2 photographic quadrats established every 10 m along a 50 m free swim transect (5 quadrats per transect). Data on fish species was collected along this transect using a fixed width visual assessments for all non-cryptic individuals larger than 5 cm. In addition, we used scaled vertical photographs of the reefscape to assess the structural complexity of each transect (5 measures per transect). In addition, we collected a range of other reef- and island-based parameters that were used to assess the relative resilience of the reef location. We used a modification of Obura and Grimsditch's (2008) Resilience Indicator protocol to evaluate the relative resilience of each location (Obura & Grimsditch 2008).

Preliminary Results and Outcomes

Benthic status: assessing the impact of the 2010 bleaching event

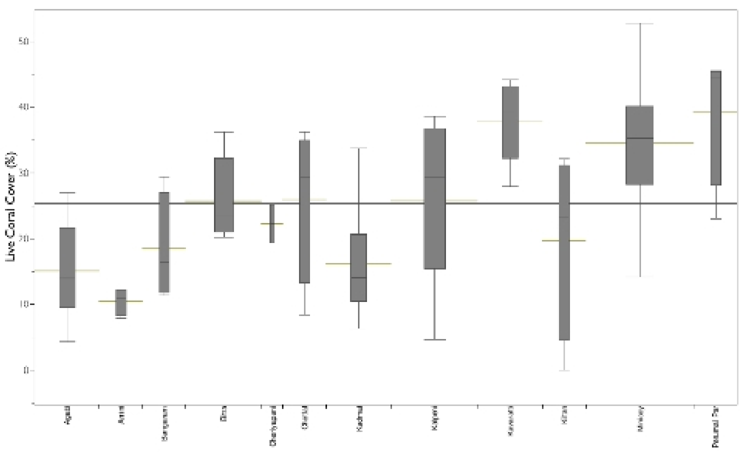

Figure 2

Our initial results paint a mixed picture of the benthic status of the Lakshadweep reefs. Post-bleaching mortality was evident in most surveyed reefs, and many shallow areas were dominated by recently dead *Acropora* tables and a mixture of dead massive genera, colonised by turfing algae. Although shallow reefs were the worst impacted, bleaching related mortality was recorded in many deep locations as well, up to 20 m. However, live coral cover varied considerably between locations, and, at some outer reefs we surveyed, coral cover was, on average, more than 40% of the benthic substrate (Figure 2), dominated by massive genera like *Porites*, *Goniastrea* and *Montipora*, among others, known to be less susceptible to bleaching.

In contrast, reefs once dominated by branching and tabular species appeared to have sustained the most significant damage, and many were reduced to rubble banks, with a major loss of reef structure. This was, in all probability, due to the combined impacts of bleaching related mortality (that peaked between April and May 2010), and the subsequent monsoon storms (that begin in mid May and continue until September). This rapid loss of coral structure could have major flow-on consequences for a host of ecological processes dependent on the complexity the reef framework provides, and our ongoing studies will focus on examining the impact of this structural loss on key ecosystem processes like predation, coral recruitment, and post-recruitment survival. Our initial attempts to quantify post-bleaching mortality based on standing recent dead coral (Figure 3) is likely to be a gross overestimation because of the quick turnover of dead structures on these reefs due to the monsoon. This is particularly true for *Acropora*-dominated reefs.

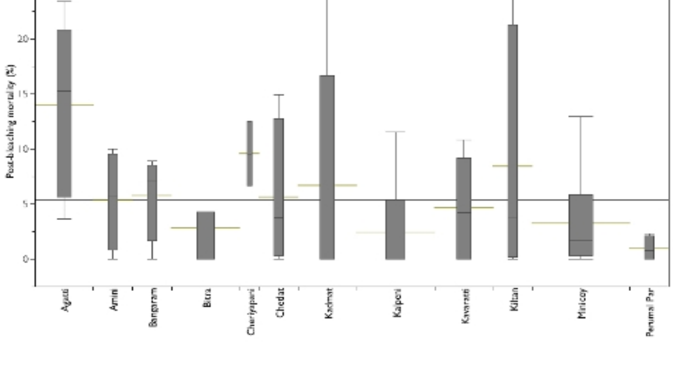

Figure 3

While most branching coral were particularly susceptible to the mass bleaching, *Pocillopora verrucosa* showed an opposite trend. This one species, from comprising less than 5% of the coral composition after 1998, is beginning to take over as the dominant species of branching coral in many shallow Lakshadweep reefs. Interestingly, this species has an entire retinue of facultative and obligate associates, and their numbers are also increasing considerably as this species gains ground in these post-bleached reefs. However, *P. verrucosa* has a branching structure very different from the *Acropora* species that once dominated these reefs, and it is unclear what the consequences of this change in the structural character of the benthos will be on the associations and processes in the reef.

Lagoon reefs: Getting used to change

There has been much debate about the potential adaptive capacity of corals and entire reefs to cope with repeated bleaching events (Kinzie et al. 2001, Brown et al. 2002, Coles & Brown 2003, Thompson & van Woesik 2009). One line of evidence for the potential for corals to 'learn' from their environment comes from lagoon reef sites in the Lakshadweep. At most lagoon sites (apart from Agatti), coral cover was significantly higher than the outer reef sites, and these locations were among the only surveyed locations where bleaching susceptible genera like *Acropora* were thriving. Interestingly, these locations experienced high levels of bleaching in April and May of 2010, but corals appear to have recovered since then. These shallow locations are highly entrained or ponded, and are typically subject to higher temperatures through the year, often climbing to 31ºC during the peak of a normal summer. Coral populations in these lagoon locations are potentially better able to cope with anomalous temperature events because of a longer period of acclimitisation. Lagoon reefs are typically small patch formations, but, in the context of repeated mass mortality events on outer reefs, these may serve as potentially vital source areas for recolonisation. Whether potential reseeding from lagoon reefs is sufficient to compensate the large losses experienced by the outer reefs remains to be seen. Another intriguing possibility is that these populations could transfer their acquired temperature plasticity to the newly seeded reefs, leading to new colonisation that is better able to resist future sea surface temperature increases. Given their importance, these shallow lagoon reefs need particular protection, since these locations among the most susceptible in the Lakshaweep to the combined effects of bait fishing, anchor and keel damage, nutrient pollution, etc.

Predicting relative resilience in the Lakshadweep

We used a modified version of Obura and Grimsditch's (2008) resilience assessment to derive an index of relative resilience across the Lakshadweep archipelago. We used a set of 12 positive resilience parameters and 9 negative resilience parameters which were assessed at every reef location. These included parameters that are assumed to to either facilitate or reduce the resilience of reef locations. The normalised parameters were combined to generate a simple additive index of relative resilience between locations. Crucial fish community variables have yet to be included along with several other key parameters, but the present index enables an initial examinination of trends in the potential resilience of these reefs.

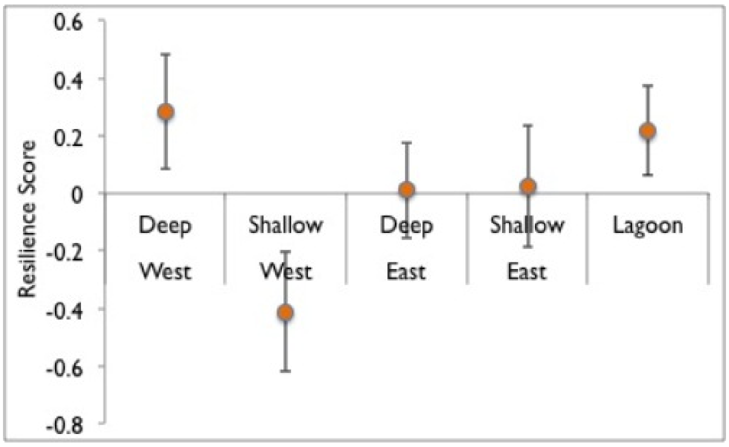

Figure 4

Aspect and depth play important roles in influencing resilience across this atoll chain (Figure 4). While for eastern reefs, there is not too much of a difference between resilience scores for shallow and deep reefs, resilience on eastern reefs tended to be low. In contrast, western reefs differed widely between deep and shallow locations, with deep reefs scoring highest in the resilience index, while the shallow western reefs scoring significantly lower than all other reef locations (Figure 4). The differences in resilience behaviour between reef aspects is most likely because of the clear hydrodynamic constrasts between eastern and western faces of these atolls. The south-west monsoon influences the western front of these atolls profoundly, while eastern reefs generally tend to be less exposed to four months of continuous monsoon battering. In a post-bleaching scenario, this makes the shallow western reefs particularly susceptible to a rapid loss of dead structure, while on the east, this structure is not eroded as quickly (Arthur et al. 2006). However, shallow western reefs also saw the most rapid rates of recovery after the bleaching of 1998. Their recovery was dominated by fast-growing branching and tabular *Acropora*, which is also highly susceptible to bleaching mortality. These shallow western reefs score very low on the resilience index, but represent potentially very dynamic sites. Thus while the resilience index, as currently constructed, may be effective in identifying sites with large buffer capacity (the ability to withstand disturbance events without changing), it may be less sensitive to a location's ability to recover from major disturbances.

In addition to large differences between aspects, lagoon sites, despite being shallow, scored higher on the resilience index than all but the deeper western sites on the outer reef (Figure 4). The lagoon reef of Agatti is a noteable exception which scored very low on the resilience index. The Agatti lagoon is peculiar in that it is not as enclosed (ponded) as other lagoon sites because of a very large break in the reef framework on its western front. This may result in a lower acclimation potential for this lagoon site, lowering its overall resilience. Table 1 provides atoll-wise characteristics for all surveyed locations: the relative resilience of an atoll appears not to be based on island connectivity, although large atolls with low to moderate fishing pressure appear to fare better in the resilience index. Although uninhabited atolls like Perumal Par and Bangaram had high resilience, merely having low population densities did not protect reefs from fishing pressure or from being vulnerable to climate related events. It has to be clarified that the fishing pressure characterisations are relative indications, and, in general, reef fishing in the Lakshadweep is low and limited to a largely non-commercial sustenance fishery. However, even at this relatively low level of fishery, it is possible for ecosystem-wide consequences to accrue to these reefs, and, in post-mortality reefs, could seriously compromise the overall resilience of the system.

In the next phase of this work, we will be examining fish communities in detail to determine the impacts on fish communities as well as to understand how changes in fish communities can influence reef recovery. After finalising the resilience index with the inclusion of all relevant parameters, we will choose representative locations across the gradient of relative resilience and establish permanent monitoring stations at these reef sites. Across this gradient we will conduct a series of socio-ecological studies over the next few years to tease apart the specific drivers of climate resilience to help us better understand the mechanisms that need the most attention while attempting to manage these climate challenged ecosystems.

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Table 1. Basic Atoll characteristics. Atolls are ordered based on their average resilience rank (low to high), based on our initial assessments.

Atoll	Resilience (Deep)	Resilience (Shallow)	Predicted Resilience	Atoll Size	Connectedness	Human Density	Fishing Pressure
Agatti	-0.66	-1.17	Vulnerable	Mid Size	High	High	High
Kadmat	-0.56	-0.46	Vulnerable	Mid Size	High	Moderate	Moderate
Amini	NA	-0.37	Vulnerable	Small	High	High	High
Kalpeni	0.16	-0.71	Low Resilience	Mid Size	Low	High	Moderate
Kiltan	-0.21	-0.27	Low Resilience	Small	Moderate	Moderate	Moderate
Bitra	-0.02	0.27	Low Resilience	Large	Moderate	Low	Moderate
Cheriyapani	0.14	NA	Moderate Resilience	Large	Moderate	Uninhabited	Moderate
Kavaratti	0.40	-0.08	Moderate Resilience	Small	Moderate	High	High
Chetlat	0.14	0.54	Moderate Resilience	Small	Moderate	Moderate	Low
Bangaram	0.62	0.08	High Resilience	Large	High	Uninhabited	Low
Perumal Par	0.68	0.03	High Resilience	Large	High	Uninhabited	Low
Minicoy	0.97	0.25	High Resilience	Large	Low	High	Moderate

References

Arthur, R. (2000). Coral bleaching and mortality in three Indian reef regions during an El Niño southern oscillation event. *Curr. Sci. (Bangalore)*, 79, 1723-1729.
Arthur, R. (2005). title. James Cook University pp. 135.
Arthur, R. (2008). title. In: *Ten years after bleaching-facing the consequences of climate change in the Indian Ocean* (eds. Obura, D., Tamelander, J. & Linden, O.). Coastal Oceans Research and Development in the Indian Ocean/Sida-SAREC, Mombasa, pp. 39-44.
Arthur, R., Done, T.J., Marsh, H. & Harriott, V. (2006). Local processes strongly influence post-bleaching benthic recovery in the Lakshadweep Islands. *Coral Reefs*, 25, 427-440.
Arthur, R., Done, T.J., Marsh, H. & Harriott, V.J. (2005). Benthic recovery four years after an El Niño-induced coral mass mortality in the Lakshadweep atolls. *Curr. Sci. (Bangalore)*, 89, 694-699.
Brown, B.E., Dunne, R.P., Goodson, M.S. & Douglas, A.E. (2002). Experience shapes the susceptibility of a reef coral to bleaching. *Coral Reefs*, 21, 119-126.
Carilli, J.E., Norris, R.D., Black, B.A., Walsh, S.M. & McField, M. (2009). Local stressors reduce coral resilience to bleaching. *PLoS One*, 4, e6324.
Coles, S.L. & Brown, B.E. (2003). Coral bleaching--capacity for acclimatization and adaptation. *Adv. Mar. Biol.*, 46, 183-223.
Done, T.J., Ogden, J.C., Wiebe, W.J., Rosen, B.R. & Mooney, H.A. (1996). title. In: *Functional Roles of Biodiversity: A Global Perspective*. John Wiley and Sons, London, pp. 393-429.
Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B., Kleypas, J., Lough, J.M., Marshall, P., Nystrom, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B. & Roughgarden, J. (2003a). Climate change, human impacts, and the resilience of coral reefs. *Science*, 301, 929-933.
Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Nyström, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B. & Roughgarden, J.D. (2003b). Climate change, human impacts, and the resilience of coral reefs. *Science*, 301, 929-933.
Kinzie, R.A., 3rd, Takayama, M., Santos, S.R. & Coffroth, M.A. (2001). The adaptive bleaching hypothesis: experimental tests of critical assumptions. *The Biological Bulletin*, 200, 51-58.
Lesser, M.P. (2007). Coral reef bleaching and global climate change: can corals survive the next century? *Proc. Natl. Acad. Sci. U. S. A.*, 104, 5259-5260.
Moberg, F. & Folke, C. (1999). Ecological goods and services of coral reef ecosytems. *Ecol. Econ.*, 29 215-233.
Obura, D. & Grimsditch, G. (2008). title. In: *Ten years after bleaching - facing the consequences of climate change in the Indian Ocean. CORDIO Status Report 2008* (eds. Obura, D., Tamelander, J. & Linden, O.). Coastal Oceans Research and Development in the Indian Ocean/Sida-SAREC, Mombasa, pp. 249-260.
Thompson, D.M. & van Woesik, R. (2009). Corals escape bleaching in regions that recently and historically experienced frequent thermal stress. *Proc Biol Sci*, 276, 2893-2901.
West, J.M. & Salm, R.V. (2003). Resistance and resilience to coral bleaching: implications for coral reef conservation and management. *Conserv. Biol.*, 17 956-967.