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Assessing coral reef health in the North Ari Atoll (Maldives) using the FoRAM Index

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ABSTRACT

Tropical marine ecosystems are richly diverse, but are experiencing growing pressure from coastal development and tourism. Assessing the status of coral reef communities along gradients of human pressure is necessary to predict recovery capacity of reefs exposed to acute events such as mass bleaching or storm destruction. Islands in the central Maldives Archipelago, which experience three different management regimes (four for each category: local community, uninhabited, and resort islands), were sampled during the International Union for Conservation of Nature (IUCN)-REGENERATE Cruise in 2015. Assessments were carried out using the FoRAM Index (FI), based on relative abundances of larger foraminiferal shells in reef sediments.

Overall, FI values (> 5) indicate that water quality currently should support active accretion by reef-building corals and larger benthic foraminifers. The highest median FI values (5.9) were recorded from sites associated with the uninhabited islands. Slightly, but significantly lower medians were recorded at sites near community and resort islands (FI = 5.3 and 5.1, respectively) that host permanent human settlement, indicating possible local deterioration of water quality by disposal of domestic wastes. Note that the FI was designed to assess suitability of local water quality and not to assess responses to regional to global changes associated with temperature stress or ocean acidification.

1. Introduction

Coral reefs are important ecosystems that are threatened worldwide. Their study can provide fundamental insights for their conservation and can drive management actions before it is too late. These ecosystems may appear healthy long after serious degradation has occurred (McClanahan et al., 2011), similar to forests that may appear healthy but have lost their ability to provide ecosystem services or have undergone changes in species composition (Millennium Ecosystem Assessment, 2005). Severely overfished reefs can be dominated by high live coral cover long after fish biomass has declined, then undergo a rapid phase shift following a major stress event (Hughes, 1994). Live coral cover is a widely used metric for coral reef condition, yet it has been shown not to differ between reefs exposed to different fishing pressure (Hughes, 1994; McClanahan et al., 2011). Thus, for sustainable management, additional approaches are essential to evaluate the condition of coral reef ecosystems (Sandin et al., 2008).

Defining reference conditions against which changes can be measured is often difficult because the different components of ecosystems often respond differently to changes in physical and biotic processes (Dayton et al., 1998). Coral reef condition greatly depends upon reef characteristics, ecological characteristics, disturbance regime, and anthropogenic influences (Sandin et al., 2008; Graham et al., 2011). Reefs exposed to high human pressure or in proximity to human population centers may be expected to show slower recovery due to pollution, terrestrial run off and exploitation (Sandin et al., 2008).

Much of the understanding of coral reefs and their resilience comes from the Caribbean and Australia's Great Barrier Reef (Hughes, 1994; Mumby et al., 2007; Sweatman et al., 2011; De'ath et al., 2012). In contrast, much less is known about the condition of coral reefs in the Indian Ocean. Coral reefs in the Maldives are some of the most diverse in the Indian Ocean, hosting > 250 species of corals and 1200 species of fish (Naseer and Hatcher, 2004). Their remote oceanic location, combined with a fishery that historically has not been based on reef fish, place them among the reefs with limited local anthropogenic disturbances worldwide.

Given the logistic and economic constraints for broad-scale environmental management, understanding the ecological factors driving reef resilience (i.e., recovery capacity) is of paramount importance for the appropriate management of Maldivian reefs, and in guiding

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investments in efforts aimed at enhancing resilience. Disturbances to Maldivian reefs have increased in the recent years as the consequences of crown-of-thorn starfish outbreaks and nutrification associated with disposal of human wastes (Morri et al., 2010), resulting in spatial variation in recovery and condition of reefs (McClanahan, 2000; Edwards et al., 2001; McClanahan and Muthiga, 2014; Morri et al., 2015). The extent to which current condition and recovery potential vary among Maldivian reefs is poorly understood, especially in the context of anthropogenic pressure.

Foraminifera, unicellular protists, are very sensitive to changing environmental conditions and their shells are a standard tool for paleo/oceanographic reconstruction. Hallock et al. (2003) developed the Foraminifera in Reef Assessment and Monitoring (FoRAM) Index (FI) to meet the need for bioindicators for coral reefs as expressed by the U.S. Environmental Protection Agency (Kurtz et al., 2001). Hallock (2012) summarized applications of this index in different habitats, reefs and countries, concluding that its applicability has proven far beyond that originally proposed, despite some regional limitations. Use of the FI has been also proposed as a low-cost approach to reef health assessment that could have application in countries with strong human resources and limited technological resources (Hallock et al., 2006).

The FoRAM Index is based on the observation that large benthic foraminifera hosting algal endosymbionts, which are abundant on healthy coral reefs, require water-quality conditions similar to those required by corals (e.g., Hallock, 1984; Hallock et al., 2003; Fujita et al., 2014). The input of nutrients into coral reef environments allows the proliferation of small heterotrophic foraminifera, whose shells numerically overwhelm those of symbiont-bearing taxa (Cockey et al., 1996). Under extreme local nutrification, where organic-rich conditions can result in intermittent hypoxia in the sediments (i.e., eutrophication), a few species of small, stress-tolerant foraminifera can become dominant (e.g., Alve and Bernhard, 1995; Carnahan et al., 2009). The advantage of benthic foraminifera as bioindicators is that their relatively short life cycles and sensitivity to changing environmental conditions allow them to respond more quickly than corals to changes in water quality. Therefore, foraminiferal-shell proportions in reef sediments provide a simple yet sensitive tool to differentiate between chronic reef decline and acute coral-specific mortality events (Cockey et al., 1996; Hallock et al., 2003). If chronic nutrification is present, it can reduce the potential for coral recruitment and thus reef resilience, such that a coral reef will be unlikely to recover and may continue to decline following an acute mortality event (Hallock et al., 2003; Ramirez et al., 2008).

This study evaluates the FI in islands from the North Ari Atoll in the Maldives, to assess spatial variation in current reef condition within the context of different human pressures. Specifically, the FI was determined for sediments in the vicinity of islands with different human population levels and under different management regimes, to test if it can predict reef resilience in the Maldives.

2. Materials and methods

2.1. Sampling sites and sample treatment

This study surveyed islands in the North Ari Atoll in the central Maldives archipelago from 22nd April–6th May 2015, including four community islands: Rasdhoo, Bodufolhudhoo, Feridhoo and Maalhos; four uninhabited islands: Gaathafushi, Alikoirah, Vihamafaru and Madivaru; and four resort islands: Velidhu, Kandholhudhoo, Maayafushi, and Madoogali (Fig. 1, geographical coordinates of each island are shown in Figs. 2–4). Community and resort islands are densely populated. For example, Rasdhoo, the capital of the North Ari Atoll, is 0.57 km long and 0.40 km wide, and hosts a permanent population of 867 people. Velidhu is 0.35 km long and 0.27 km wide, and may daily host several hundred tourists.

At each island reef, three sites were randomly chosen. Sediment samples (0–1 cm surface interval) were collected into 15 ml falcon tubes by SCUBA divers; collection sites were consistently at 10 m water depth in areas without coral or algal cover. Three replicate samples for each site were taken along reef slopes at 50 m distance one from another, for a total of 108 samples (Figs. 2–4). The islands of Vihamaafaru were sampled twice, first at 10 m depth on reef terraces and then at 10 m depth on the slope for comparison. Samples were treated with rose Bengal to ascertain that dead specimens had living counterparts. In the laboratory all samples were dried in open air and weighed.

2.2. Sediment texture

Subsamples of all samples were dry sieved, using standard mesh sizes of 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.063 mm, 0.040 mm and < 0.040 mm. Each fraction was weighed and the weight percentage of each fraction was calculated, allowing the median grain size to be determined for each sample (Table 1, Supplementary Material-1).

2.3. Foraminiferal investigations

Because cohesive mud-sized particles were scarce in the sediments samples, the subsamples for foraminiferal investigations were not sieved, thus retaining very small, stress tolerant taxa such as *Bolivina*. This procedure was adopted to investigate the complete foraminiferal assemblage. Subsamples were split using a standard splitter to acquire a split of approximately 1 g. The sediment from that split was placed on a gridded tray and examined under a binocular microscope; 150–200 foraminiferal specimens were picked following the standard protocol. Dix (2001) demonstrated that this amount provides a statistically valid compromise between the precision of larger samples and processing costs in low diversity samples, or when not identifying to species level (Hallock et al., 2003). The picked benthic foraminiferal specimens were classified to genus and into one of three functional groups (symbiont-bearing, stress-tolerant, or other smaller taxa) and counted (Supplementary Material-2).

The FI was calculated based on functional groups according to Hallock et al. (2003), as modified by Carnahan et al. (2009). For each sample, the FI was determined by the equation:

$$FI = (10 \times P_s) + (P_o) + (2 \times P_h)$$

where $Ps = N_s/T$, N_s represents the number of symbiont-bearing foraminifera and T is total fauna; $Po = N_o/T$, where N_o represents the number of stress tolerant foraminifera; and $Ph = N_h/T$, where N_h represents the number of other small foraminifera. FI values < 2 indicate ecological conditions unfavorable for calcifying organisms that host algal endosymbionts (and therefore not conducive to reef growth), values between 2 and 4 indicate marginal conditions, and values > 4 indicate ecological conditions generally favorable for calcifying organisms that host algal endosymbionts, and therefore that support reef growth.

During specimen counting, the degree of bioclast preservation was also evaluated (Barbosa et al., 2009; Hallock, 2012). For example bioclasts corroded or rounded may indicate prolonged reworking by currents (e.g., heavily broken specimens and missing or eroded tubulospines in calcarinids). Both means and medians of the FI were calculated, the latter to minimize the influence of local microenvironments that can result in an anomalously high or low FI values (Table 1, Supplementary Material-1).

2.4. Water samples

Water samples were collected into plastic bottles by divers, and were taken both at the sea surface and at the sea floor from the same locations where sediments were collected. Immediately after collection the pH, temperature and conductivity of the water samples were