Are Zanzibar's reefs undergoing ecological change? Foraminifera bio-indicators for monitoring and assessment of reef ecosystems in the west Indian Ocean

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Abstract The reefs of the Zanzibar Archipelago are highly diverse ecosystems, providing a resource base that generates fisheries and tourist revenue for subsistence-based coastal communities. Zanzibar's reefs remain some of the least studied in the world and face increasing pressure from rapid coastal expansion of urban areas, development of tourist facilities, overharvesting and daily boat/tourist visitations. Here, we provide the first foraminiferal community data and preliminary assessment of the response of foraminifers to wastewater pollution from the urban center, Stone Town, to the nearby fringing reefs (Changuu, Bawe and Chumbe) along western Zanzibar Island. Overall, we find: a high diversity assemblage (greater than 135 species) dominated by abundant symbiont-bearing, large benthic foraminifers (LBFs); high FORAM Index values ranging from 7.0 to 8.8. Communities at the Chumbe Island Coral Park Ltd. (CHICOP), Marine Protected Area, are more stable than at Changuu Reef, which has higher daily visitations. The concentration of nutrients (in seawater) is low (< 0.5 umolL^{-1}). However, an increase in sea urchins and predators such as Crown-of-thorns starfish (COTS) in reefs closest to Stone Town indicates that regular monitoring of benthic communities and management of water quality are needed to ensure long-term protection of Zanzibar's ecological integrity and natural resources. Foraminifera offer a good cost-effective monitoring tool for regular, effective assessments.

Keywords: bio-indicators, benthic foraminifera, water quality, nutrients, monitoring, conservation

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Introduction

Foraminifera as bio-indicators are a low-cost ecological assessment tool that can be easily and affordably integrated into existing monitoring programs in tropical developing nations that have limited technological resources, but sufficient means for capacity-building and an urgency for understanding the impacts of rapidly changing ecological conditions (Linton and Warner 2003; Hallock 2012). Bio-indicators, such as foraminifers, are excellent tools with a potential to facilitate the participation of a wide cross-section of individuals from scientists, marine managers, policy-makers to locals, in the communication of environmental status and in educational outreach (Linton and Warner 2003).

Foraminifers excel as bio-indicators as they are small, abundant in reef sediments, easy to sample with minimal damage to the environment, they indicate gradations in their response with respect to environmental stress and have a relatively stable taxonomy that can be taught to non-specialists (Hallock 2000; Bouchet et al. 2012). Furthermore, environmental stressors can induce relatively rapid quantitative and qualitative changes in foraminiferal community structure (composition, diversity and richness) and function (carbonate production, symbiont photosynthesis, growth and reproduction) (Murray 2006; Hohenegger et al. 2014). This paper presents preliminary data from an ongoing survey of the foraminiferal assemblages of the western reefs of Zanzibar. Foraminiferal assemblage composition and spatial distribution patterns are used to assess the current health of the shallow-water reefs of Zanzibar.

Study location

Coral reef ecosystems of the Western Indian Ocean (WIO) are exemplary in their high biodiversity but remain some of the least studied and characterized in the world (Veron 1995; Johnstone et al. 1998; Obura 2012). The Zanzibar Archipelago lies approximately 35 km from the Tanzanian mainland and is the largest reef system in East Africa. The main island of Zanzibar, “Unguja” (6.1333°S, 39.3167°E), is 85 km long, 35 km wide and encompasses 1530 km^2 (Figure 1 A-B) (Shaghude and Wannäs 2002). Several small coral cays and sand bars with compressed (about 200 m wide), shallow-water (10 to 15 m) fringing reefs occur on the protected, western side of Zanzibar. These reefs are easily accessed from the commercial and historic center, Stone Town. This UNESCO World Heritage site is also the location of the Institute of Marine Sciences (IMS), University of Dar Es Salaam. Stone Town’s population is growing rapidly and there are noticeable increases in coastal development, including port expansion and tourist facilities. Currently, an estimated 2.2 x 10^6 L d^{-1} of untreated sewage effluent is released into the sea surrounding Stone Town, with the dominant direction of current flow northwards towards popular coral reef sites (Moynihan et al. 2012).

Chumbe Island Coral Park Ltd (CHICOP) is located 12 km southwest from Stone Town. It has the highest genetic diversity of hard coral cover among the reefs of Zanzibar (Mbije et al. 2002). CHICOP was established in 1992 as a privately managed (non-profit) eco-tourist center and a registered marine protected area with the United Nations Environment Programme (UNEP) World Conservation Monitoring Center (Kloiber 2015). CHICOP is an example of successful management practices for biodiversity monitoring, conservation and

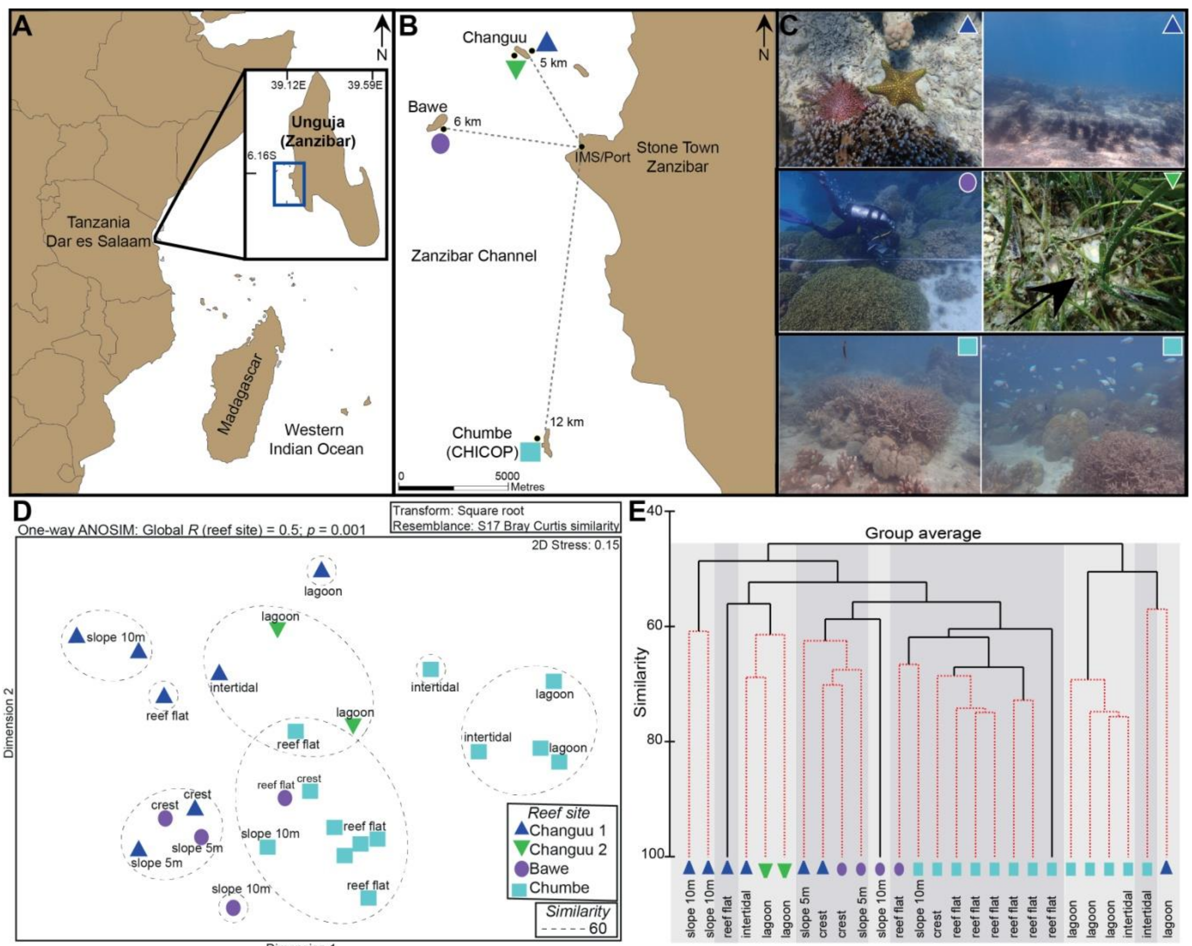

Fig. 1 A Location of Zanzibar Island, Tanzania. **B** The location of the western Zanzibar reefs sampled (in 2014). **C** Photographs of: Changuu 1 where there is evidence of predation by COTS and sea urchins. Visible, large benthic foraminifers (*Marginopora vertebralis*) are abundant in the shallow seagrass/patch reefs of Changuu 2. Coral cover assessments at Bawe. Chumbe supporting healthy reefs and fish

populations. Photographs by J. Schroeder and G. Narayan. **D** The nMDS plot of the foraminiferal community structure showing significant separation between the communities of Changuu and Chumbe reefs and overlapping differences with Bawe Reef. **E** Hierarchical cluster analysis dendrogram of reef samples showing separation into nine groups.

capacity-building in Zanzibar (Kloiber 2015). Eco-tourism and restricted access to the reefs for scientific study and monitoring are permitted on Chumbe.

The fringing reefs of Changuu (Prison) Island are located approximately 5 km NNW from Stone Town Harbour. Two sites were sampled. Changuu 1 is on the northeastern side, which is relatively protected from strong waves and currents and is the main fringing backreef area. This site is visited regularly by boaters, snorkelers and researchers from the IMS. There are clearly visible signs of boat anchor damage and overfishing at the reef. The rarely visited Changuu 3 site is a shallow-water (5 m) patch reef and seagrass meadow (*Syringodinum-Thalassia*) located on the southwestern sides of the island, respectively (Figure 1). Bawe Reef located approximately 6 km due west from Stone Town, is less popular than Changuu Reef and therefore less frequently visited by tourists and scuba-divers. During the spring tide, broad beaches and shallow reefs are exposed, bringing local people to the island's shores for harvesting of invertebrates and seashells. Our sample site was located on the southern side of the island (facing Stone Town), where waves and currents are stronger. Both Changuu and Bawe reefs are conservation areas. Nevertheless, extractive and destructive activities including fishing (including net, line and cage), shell harvesting and daily tourist visitations by boat and boat anchor damage are the major direct impacts to the reefs.

Methods

Three fringing reefs (Changuu 1, Bawe and Chumbe) and a patch reef/seagrass meadow (Changuu 2) off of western Zanzibar Island were sampled during the dry season, between September to November 2014 (Figure 1 A-C). Sampling was conducted during low-tide and replicate (3-5 per zone) surficial sediments were hand-collected by snorkeling or scuba diving along an approximately 200 m transect from the shoreline to the 10 m reef slope (two transects at Changuu 1, Bawe and Chumbe). Water depths did not exceed 10 m at our sampling sites. Water samples (including April 2015 samples) were collected and analyzed for: phosphate (PO_4^{3-}), ammonia (NH_4^+), nitrogen oxide (NO_x) and nitrite (NO_2^-) using the Skalar®, Alliance Flow System, Tecan® at ZMT in Bremen, Germany.

Standard sediment and foraminifer sampling methods were employed following previous studies (Narayan and Pandolfi 2010; Kelmo and Hallock 2013). Biodiversity analysis of the relative abundance data included Shannon-Wiener Diversity (H´), Fisher's α**,** Margalef Richness (d) and Pielou's Evenness (J´) indices. The FORAM Index (FI) was calculated as an indirect measure of water quality (Hallock et al. 2003; Hallock 2012). Foraminiferal relative abundance data were square root transformed and the Bray-Curtis Similarity Index calculated. Differences in community structure were visualized using a two-dimensional, non-metric multidimensional scaling (nMDS) ordination, for a group average, hierarchical cluster analysis. To test the relationship between species composition between reef sites, a one-way analysis of similarity (ANOSIM) was calculated. Assemblage analyses were performed using PRIMER 6.1.10 (Primer-E Ltd., UK) for Windows. Below, we present preliminary results of the differences in species composition and relative abundance from an assessment of 26 surficial samples from four reef sites.

Results and Discussion

A preliminary survey of foraminiferal species diversity, assemblage composition and abundance, FI values and nutrient concentrations consistently indicate that adequate water quality conditions, conducive to algal symbiosis, are maintained in Zanzibar's western reefs (Tables 1 and 2). The reefs harbor a diverse assemblage of large benthic foraminifers (LBFs) and foraminiferal tests are important contributors to reefal sediments, indicating their important role in carbonate production.

Foraminiferal assemblages at Chumbe had the highest average values in species diversity ($H'\log_2 = 3.6$) and richness ($d' = 7.3$) and Changuu 1 and 2 sites had the lowest (Table 1). Species composition and abundance between Changuu 1 and Chumbe reefs showed strong separation and there were significant differences in the foraminiferal assemblage structure (ANOSIM $R = 0.6$; $p = 0.01$) (Figure 1D). Differences between Changuu 2 and Chumbe were weak but significant (ANOSIM $R = 0.4$; $p = 0.01$), as were the differences between Bawe and Chumbe (ANOSIM $R = 0.3$; $p = 0.04$) (Figure 1D). Hierarchical cluster analysis revealed 9 major groups (Figure 1E). In Chumbe, foraminiferal assemblages in the "reef" habitats (reef flat, crest and slope) were significantly different (ANOSIM $R = 0.9$ to 1; $p = 0.01$ to 0.04) from the shallow-water, lagoonal and intertidal habitats (Table 1), which were dominated by *Thalassia hemprichii* seagrass communities and abundant *Peneroplis and Sorites* spp.

The FI was > 4 in all reef systems and LBF were dominant, indicating conditions conducive for symbiont-bearing assemblages (Table 1). The dominant LBF species, *Amphistegina lessonii* and *A. lobifera* (combined 65% to the foraminiferal carbonate tests), were the top ecosystem and carbonate sediment producers in the reef-top, back- and fore-reef sites. Other common LBFs including *Coscinospira* sp., *Heterostegina depressa*, *Marginopora vertebralis*, *Monalysidium* sp., *Sorites orbicularis*, *Peneroplis* spp., were found in greater abundances on the Chumbe Reef slope and in the very shallow-water patch reef and seagrass meadows of Changuu 2.

Nutrient flux has been implicated as a major factor controlling foraminiferal assemblages in previous studies (Reymond et al. 2012; Kelmo and Hallock 2013). Our faunal data (Table 1), complimented our preliminary nutrient results (Table 2), which indicate low average values (< 0.5 μM/L) in the reef sites (Table 2). The influence of strong daily tides and currents allows regular flushing around Stone Town, which is a likely explanation for low nutrient values in our water samples (Moynihan et al. 2012; Gouveia 2015). Alternatively, analysis of nutrient and trace metal concentrations in the sediments may be a more reliable indicator of micronutrient enrichment in high water energy locations (Rumisha et al. 2012; Gouveia 2015). Future monitoring is needed to address variability and/ increase in nutrient concentrations. Variability in nutrient flux (diurnal and seasonal) is currently being investigated by the authors and details will be presented in a future publication.

We found no foraminiferal response to water column nutrient pollution. However, continued discharge of wastewater from Stone Town may lead to reduced water quality, decreased light availability and chronic stress responses in benthic communities, that will result in decreased species richness (Björk et al. 1995) and an increase in opportunistic taxa. Long-term impacts would result in reduced LBF and coral generic diversity and a reduction in living reef framework to support economically important fish and invertebrates species (Johnstone et al. 1998; Wagner 2004). This would have devastating consequences for Zanzibar's rapidly growing island populations that depend on its marine resources for food and livelihood (Lange and Jiddawi 2009).

What's driving the differences in the foraminiferal community structure between Changuu 1 and Chumbe reefs? Changuu Reef, closest to Stone Town, is impacted by indirect (sedimentation and low to moderate level nitrification) and direct (tourist visitations and overfishing) human activities (Johnstone et al. 1998). Compared to Chumbe, reduced fish species, higher numbers of sea urchins, outbreaks of crown-of-thorn starfish and greater abundance of macro-algae are visible signs that the Changuu Reef ecosystem is stressed (Björk et al. 1995; Horrill et al. 2000; Moynihan et al. 2012; Kloiber 2015).

In contrast, the strictly protected, actively and effectively monitored reef ecosystems of the CHICOP (Kloiber 2015) (which are further removed from anthropogenic effects) provide an excellent baseline and reference site (for fishing, pollution and reef health) from which scientists and marine managers can gauge shifts in the other local reef systems (i.e Changuu 1). We recommend foraminiferal monitoring in CHICOP to provide necessary baseline data from which sound management decisions can be made regarding uses and maintenance of Zanzibar's vulnerable reef habitats.

Currently, high LBF abundance and FI values >4 in Zanzibar's reefs are positive indicators that local human influences on water quality are mediated by exchange with oligotrophic oceanic waters (Hallock 2012). However, can reef-dwelling LBF provide further clues of coming changes to the benthic communities? The dominance of amphisteginids, variable species diversity and comparatively low abundances of other LBF species including *Heterostegina depressa* and *Marginopora vertebralis* in Changuu's Reef (in sites 1 and 2) indicate that conditions there may be reducing the diversity of LBF assemblages that prefer well-lit and oligotrophic conditions. To further assess if Zanzibar's reefs are experiencing nitrification and to understand the variability in environmental conditions that influence the living LBF assemblages, faunal resilience and their ecological thresholds, we are carrying out further investigations which also include assessments of coral diversity, macroinvertebrates and sediment carbonate components. We recommend the implementation of regular monitoring of the reef-dwelling foraminiferal assemblages and regular application of the FORAM Index.

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