Marine Pollution Bulletin xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

# The implications of recurrent disturbances within the world's hottest coral reef

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A R T I C L E I N F O

*Article history:*
Received 1 July 2015
Received in revised form 25 September 2015
Accepted 6 October 2015
Available online xxxx

*Keywords:*
Coral composition
Stress-tolerant
Environmental variation
Resilience
Stability
Novel ecosystems

A B S T R A C T

Determining how coral ecosystems are structured within extreme environments may provide insights into how coral reefs are impacted by future climate change. Benthic community structure was examined within the Persian Gulf, and adjacent Musandam and northern Oman regions across a 3-year period (2008–2011) in which all regions were exposed to major disturbances. Although there was evidence of temporal switching in coral composition within regions, communities predominantly reflected local environmental conditions and the disturbance history of each region. Gulf reefs showed little change in coral composition, being dominated by stress-tolerant Faviidae and Poritidae across the 3 years. In comparison, Musandam and Oman coral communities were comprised of stress-sensitive Acroporidae and Pocilloporidae; Oman communities showed substantial declines in such taxa and increased cover of stress-tolerant communities. Our results suggest that coral communities may persist within an increasingly disturbed future environment, albeit in a much more structurally simple configuration.



## 1. Introduction

Coral reefs are one of the worlds' most biodiverse ecosystems, and provide coastal populations with economically valuable goods and services (Moberg and Folke, 1999; Sheppard et al., 2009). However, coral reefs are in global decline. The combined effects of eutrophication, sedimentation, overfishing, outbreaks of disease and predation, and recurrent bleaching events associated with elevated sea temperatures are having a marked effect on the structure and functioning of reef systems (Hoegh-Guldberg, 1999; Hughes et al., 2003; Riegl et al., 2009). The capacity for reefs to resist change and/or recover from these escalating threats (i.e., resilience, sensu Walker et al., 2004) will be, in part, determined by the localised environmental context in which communities occur (Coles and Riegl, 2013; Hoegh-Guldberg, 1999). Abiotic factors, in particular temperature, salinity, and light, can strongly influence the growth, mortality, fecundity, and settlement of corals (Baird and Marshall, 2002; Hoegh-Guldberg, 1999; Riegl and Purkis, 2012b), and hence their capacity to re-assemble following disturbance (Glynn, 1996; Hoegh-Guldberg et al., 2007). Corals and associated organisms that occur in highly variable physical environments are physiologically acclimated and/or genetically adapted to the extreme conditions to which they are exposed, allowing them to persist in environments that are often outside the physiological thresholds for most communities (Hoegh-Guldberg, 1999; Rowan, 2004; Sheppard, 2003). Understanding how benthic communities in extreme environments respond to disturbances may therefore provide important insights into how reefs in other regions may respond to future disturbance under increasing climate change and anthropogenic pressure (Brown, 1997; Burt et al., 2011a).

The Persian Gulf is among the most physically hostile environment in which coral reefs currently exist (Coles and Riegl, 2013; Sheppard et al., 1992). The Persian Gulf is a small, shallow sea (mean depth <30 m) that has relatively restricted water exchange with the wider Indian Ocean (Riegl and Purkis, 2012a). As a result, the physical environment is characterised by thermal extremes, with sea surface temperatures (SSTs) ranging over 22 °C every 6 months; from < 13 °C in winter to > 35 °C in summer (Coles, 2003). This is the largest thermal range and highest maximum temperature experienced by extant coral reef communities (Coles, 2003; Sheppard et al., 1992; Sheppard and Loughland, 2002). In addition, limited freshwater input and the arid nature of the surrounding landscape causes high evaporation, and as a result salinity regularly exceeds 42 psu on reefs in the region (Coles, 2003; Riegl and Purkis, 2012b). Despite these extreme conditions, there are extensive reef systems in shallow coastal areas throughout the Persian Gulf, and these offer a 'natural laboratory' in which to study the impact of extreme and variable environmental conditions on the structure and function of coral reef fauna (Foster et al., 2012; Sheppard et al., 2012).

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http://dx.doi.org/10.1016/j.marpolbul.2015.10.006

The Gulf of Oman is biogeographically connected to and at the same latitude as the Persian Gulf. The Gulf of Oman is deep (mean depth > 1000 m) and well mixed with the wider Indian Ocean, resulting in relatively benign environmental conditions (SST: 22–32 °C, salinity: 35–37 psu; Böhm et al., 1999; Coles, 1997, 2003), making these regions ideal for comparative studies of the role of environmental extremes in structuring reef communities (Burt et al., 2011b; Feary et al., 2010).

Coral communities around the Arabian Peninsula, like reefs in other regions, have been subject to an increasing frequency and/or intensity of disturbances in recent years (Burt et al., 2011a; Riegl and Purkis, 2012a; Sheppard et al., 2012). In 2007, category 5 cyclone Gonu, the strongest cyclone ever recorded for the Arabian Peninsula, caused extensive damage to reefs in the Gulf of Oman (Coles et al., 2015; Foster et al., 2011; Fritz et al., 2010). This was followed by a widespread harmful algal bloom (HAB) in 2008/2009 that resulted in mass coral mortality in both the Persian Gulf and Gulf of Oman (Bauman et al., 2010; Riegl et al., 2012c), and recurrent large-scale bleaching events in 2010 and 2011 (Riegl and Purkis, 2012b). The objective of this study was to examine temporal changes in benthic reef communities in three locations around the Arabian Peninsula: the Persian Gulf (Abu Dhabi), the Gulf of Oman (Fujairah), and the Straits of Hormuz (Musandam Peninsula, which connects the two Gulfs). By comparing benthic assemblages over a period that included several large-scale disturbances this study may provide insights into how reefs may respond to disturbance under environmental extremes associated with future climate change.

## 2. Methods

Benthic coral reef communities were surveyed at six sites around the Arabian Peninsula, with two sites surveyed at each of three locations; the Gulf of Oman (Al Aqa, Dibba), Persian Gulf (Saadiyat, Ras Ghanada) and Musandam Peninsula in the Straits of Hormuz (Al Harf, Coral Garden) (Fig. 1). Sites within each location were separated by 13–33 km. All sites were initially surveyed in September/November 2008, at the start of a widespread harmful algal bloom (HAB) event, and resurveyed 3 years later (2011). The HAB started at Dibba in the Gulf of Oman in August 2008 and lasted until May 2009, initially expanding north to the Straits of Hormuz, before spreading westward and southward through coastal areas of Iran, Qatar, and the United Arab Emirates (Richlen et al., 2010). A total of 1200 km of coastline was affected by the HAB, with extensive fish kills and/or coral damage recorded in Oman, Fujairah, Iran, Dubai, Abu Dhabi, and Ajman (Bauman et al., 2010; Coles et al., 2015; Richlen et al., 2010). In 2010, a major bleaching event was also observed in the Persian Gulf, where corals were exposed to the highest temperatures recorded in the region (>35 °C) for a period of 3 weeks (Riegl et al., 2011, 2012a). A second major bleaching event was recorded in coastal UAE reefs in 2011 (Riegl et al., 2012c).

At each site the benthic community was quantified along six randomly placed 30-m transects at depths of 2–8 m. The depth of the surveys was determined by the reef topography and available hard substrata at each site, and depths surveyed were consistent between years. Transects were placed parallel to each other with a minimum of 3 m between adjacent transects. Along each transect eleven 0.5 × 0.5 m (i.e. 0.25 $m^2$) quadrats were placed at 3 m intervals and photographed ($n = 66$ quadrats per site per year). The substratum-type and coral composition within each quadrat was quantified under 50 random points using Coral Point Count with Excel Extensions (CPCe) software (Kohler and Gill, 2006). Substratum type was categorised into seven broad groups: (i) live scleractinian coral, (ii) fleshy and turf algae, (iii) crustose coralline algae (CCA), (iv) other live organisms (which encompassed all live benthic organisms that do not belong to the former groups; primarily barnacles, bivalves, sponges, and urchins), (v) dead coral framework, (vi) terrestrial derived rock, and (vii) unconsolidated substrata (i.e., sand and rubble). To quantify the composition of coral assemblages all live corals recorded were identified to genus (Riegl et al., 2012b; Veron, 2000). Percent cover of all benthic categories were then pooled to the transect level, and the relative abundance for each transect within each site calculated.

Two non-metric multi-dimensional scaling (nMDS) analyses and Permutational Multivariate Analysis of Variance (PERMANOVA, Anderson et al., 2008) were used to investigate variation in (i) benthic community composition and (ii) scleractinian coral composition among regions (Persian Gulf, Musandam, Gulf of Oman) and years (2008 vs. 2011). The analyses were based on the mean proportion of each substratum category and coral family, respectively at each site

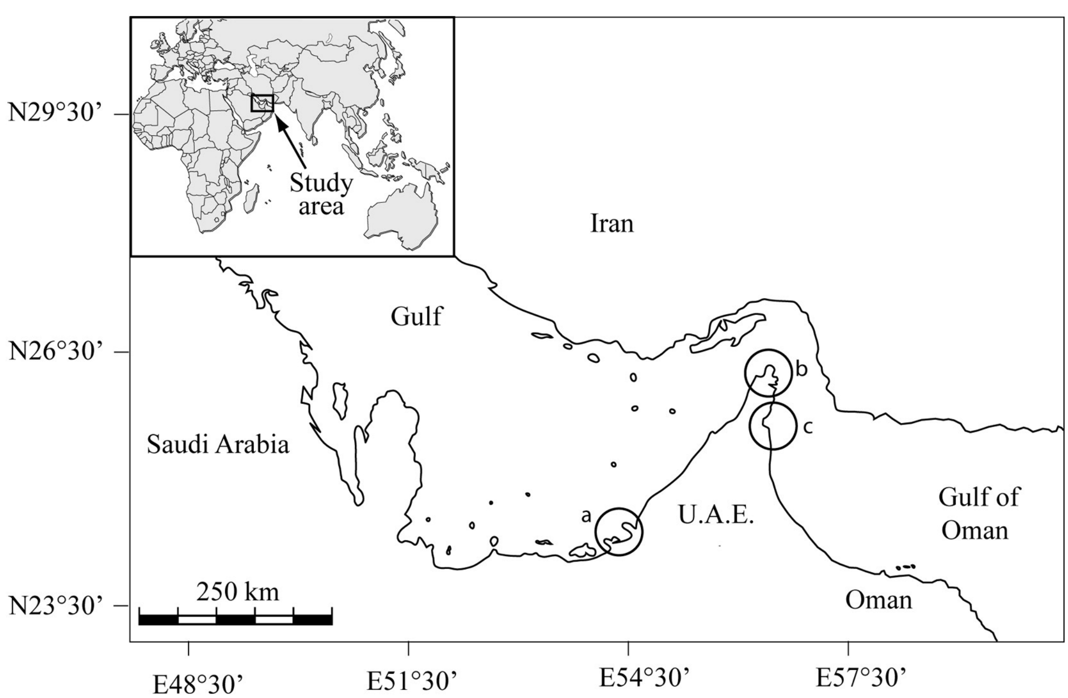


**Fig. 1.** Map of the Arabian Peninsula showing the geographic position of the three locations where the benthic communities were surveyed. a) Persian Gulf (Saadiyat and Ras Ghanada), b) Musandam (Al Harf and Coral Garden), and c) Gulf of Oman (Dibba and Al Aqa).

Please cite this article as: Bento, R., et al., The implications of recurrent disturbances within the world's hottest coral reef, Marine Pollution Bulletin (2015), http://dx.doi.org/10.1016/j.marpolbul.2015.10.006