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Tight coupling between coral reef morphology and mapped resilience in the Red Sea

Gwilym Rowlands [a,b,*], Sam Purkis [a], Andrew Bruckner [c]

[a] Nova Southeastern University, United States
[b] Rowlands Ecology Ltd., United Kingdom
[c] Khaled bin Sultan Living Oceans Foundation, United States

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ABSTRACT

Lack of knowledge on the conservation value of different reef types can stymie decision making, and result in less optimal management solutions. Addressing the information gap of coral reef resilience, we produce a map-based Remote Sensed Resilience Index (*RSRI*) from data describing the spatial distribution of stressors, and properties of reef habitats on the Farasan Banks, Saudi Arabia. We contrast the distribution of this index among fourteen reef types, categorized on a scale of maturity that includes juvenile (poorly aggraded), mature (partially aggraded), and senile (fully aggraded) reefs. Sites with high reef resilience can be found in most detached reef types; however they are most common in mature reefs. We aim to stimulate debate on the coupling that exists between geomorphology and conservation biology, and consider how such information can be used to inform management decisions.

1. Introduction

Coral reefs are among the most iconic of ecosystems, valued for their beauty, biological diversity, and productivity. Many human communities are economically tied to coral reefs in terms of the nutrition that reefs provide, the tourism and fishing industries that reefs support, and the shorelines that reefs protect. However, recent global assessments suggest that the health of coral reefs is on a downward trajectory (Burke et al., 2011; Wilkinson, 1999).

In an era of changing climate, management for coral reef resilience is an emerging approach to stewardship (Anthony et al., 2015). Where stressors such as anomalous temperature regimes, ocean acidification, fishing pressure, coastal development, nutrients, and sediments escalate and accumulate, the capacity of a coral reef to resist, recover, and adapt to disturbance is diminished; the reef is viewed as having reduced resilience (Nyström and Folke, 2001). However, where conditions remain benign, and sufficient time is allowed, there is ample evidence that reef ecosystems can recover following even the most severe disturbances (Done et al., 2010; Mumby and Harborne, 2010; Purkis and Riegl, 2005; Riegl et al., 2009; Wilkinson, 1999).

In complex, multi-impact scenarios where different groups and external environmental influences impact upon the same areas of reef resource. Facing this management challenge, Marine Spatial Planning (MSP) is a tool that has come to the fore. Through MSP, conflicts to a desired management goal can be proactively managed through a planning and mapping process. MSP may be conducted for local and community driven projects or, as is the focal scale of this paper, at archipelago or national scale. Data gaps and inconsistencies are particularly problematic when operating at larger spatial scales, and surrogates and proxies may be required. Regardless of the scope of interest, ultimately MSP requires the mapping of data. Motivated by this need, this paper advances a strategy for considering multiple impacts to reefs, develops an index that simplifies impacts and desirable properties of reefs, and considers how geomorphology may act as a general indicator of reef resilience.

Identifying what contributes to the relative resilience of one reef compared to another is a scientific and management priority (McClanahan et al., 2012). Surveys of the factors affecting coral reef resilience have been conducted at a number of spatial and temporal scales, including genetic and molecular assessments of organism traits (Pandolfi et al., 2011; Van Oppen and Gates, 2006), and field-based observation and monitoring (McClanahan et al., 2012; Mumby et al., 2012; Obura et al., 2009; West and Salm, 2003). An emerging area of research, driven by advances in several fields of spatial science including remote sensing, distribution modeling, and ecosystem simulation, allow simultaneous assessment of pressures to reefs across large geographic areas (Knudby et al., 2013; Knudby et al., 2014; Maina et al., 2011; Maina et al., 2008; Pittman and Brown, 2011; Rowlands et al., 2012; Wooldridge, 2009).

The close association between coral reef geomorphology, environmental drivers, and biological processes is well documented (Andréfouët and Guzman, 2004; Bellwood and Hughes, 2001; Blanchon,

* Corresponding author at: Nova Southeastern University, United States.
E-mail address: gwilym@rowlandsecology.com (G. Rowlands).

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2011; Falter et al., 2013; Goreau, 1959; Hopley et al., 2007). Considering biodiversity at large oceanic scales, Bellwood and Hughes (2001) suggest that reef type had a minimal role in determining biodiversity patterns, however as Andréfouët and Guzman (2004) note, the categorization of Bellwood and Hughes (2001) is limited to only oceanic and continental reef types and more refined morphological analyses are merited. Utilizing remote sensed data, relationships between habitat heterogeneity and benthic diversity have been established (Andréfouët and Guzman, 2004; Dalleau et al., 2010; Mumby, 2001), while geomorphology has been shown to be a robust predictor of habitat richness (Hamylton et al., 2012).

Different reef types, such as atolls, individual or groups of patch reefs, or sections of barriers and fringing reef incised by deep channels, can be rapidly identified by their clear land/sea boundaries and distinct morphological traits. Such reef types can therefore become the de facto 'management units' of MSP. It is advised that spatial planning targets are set to achieve a good representation, replication, and spread of sites between different reef morphologies, justified through the context of risk spreading (McLeod et al., 2009). The relative importance of different reef morphologies contributing to the management portfolio may however be poorly understood.

Through a study of coral reefs in the Red Sea, we seek a better understanding of the role of morphology in influencing reef resilience at local to regional scales. The diversity of reef morphology in the Red Sea has been well documented (Bosence et al., 1998; Dullo and Montaggioni, 1998; Guilcher, 1988; Montaggioni et al., 1986; Rowlands and Purkis, 2015; Rowlands et al., 2014; Sheppard et al., 1992; Sheppard, 1985), and recently mapped into sixteen end-member types (Rowlands et al., 2014). The Farasan Banks, the focus of the present study, has been shown to be the most morphologically diverse region of the Saudi Arabian Red Sea (Rowlands et al., 2014). A dazzling array of morphology is delivered through contemporary and historic tectonics of the rifting basin, subsidence and uplift from subsurface evaporites, variations in sea level and climate, differing degrees of terrestrial input, as well as growth of coral communities.

Utilizing maps of regional reef stressors and benthic biota, coupled to environmental remote sensing data, Rowlands et al. (2012) advanced the Remote Sensed Resilience Index (*RSRI*). While *RSRI* remains to be validated and its accuracy is not fully known, it provides a sound theoretical framework for investigating resilience at archipelago and national scales. The map-based index has an operational definition similar to West and Salm (2003) which describes areas likely to be inherently resilient either through lower rates of stress and disturbance, or increased functional redundancy.

To understand the distribution of coral reef resilience with respect to differences in reef morphology the goals of this paper are several fold. First, we assemble maps of coral reef morphology; second we develop *RSRI* maps for the Farasan Banks region of Saudi Arabia; and third, we relate maps of this index to mapped patterns of reef morphology. We discuss the patterns observed in the context of making informed decisions for the management of coral reef resources and wider implications for assessing coral reef resilience.

2. Methods

2.1. Farasan Banks geomorphology

This paper focuses on a morphologically diverse region of the eastern Red Sea, the Farasan Banks (Figs. 1, 2). The region boasts over 5000 km^2 of shallow coral and sedimentary habitat, almost a quarter of such habitat in the Saudi Arabian Red Sea (Rowlands et al., 2014). Coral reefs may be found up to 100 km offshore and exist as a series of shore-parallel banks, small isolated atoll-like systems, as well as fringing reef systems along the mainland coast and surrounding offshore islands. Patch reefs of varying sizes and shapes are located within the sheltered lagoons of offshore banks and atop the coastal shelf.

The geomorphology of coral reefs in Saudi Arabia was mapped to a sixteen member typology by Rowlands et al. (2014). Under this typology a reef type is defined as a shallow-water (<30 m) accumulation of both reef frameworks and their associated carbonate sediments. The typology takes the form of a decision tree and is built upon the visual interpretation of satellite and aerial imagery and georeferenced British and Saudi Arabian nautical charts. Criteria in the tree include differences in the spectral content and texture of satellite image pixels, measurements of the size and shape of coral reefs assessed in a Geographic Information System (GIS), and water depth assessed from nautical charts. On the basis of the typology, coral reefs of the Farasan Banks are mapped from satellite imagery and nautical charts using a 1 km × 1 km grid (Fig. 1b). This grid is hereafter referred to as being composed of 'GIS grid cells'.

Fourteen of the sixteen reef types mapped for Saudi Arabia are found within the Farasan Banks (Fig. 2); the exception being two types of attached reef, 'lineated' and 'dendritic', which are formed of elongate or reticulated patch reefs and are only found to the north (Rowlands et al., 2014). A reef is defined as attached if it has a land boundary, while detached if separated from land by water deeper than ~50 m, a depth chosen as the most appropriate contour consistently mapped in regional nautical charts and below which little coral growth occurs. If no nautical chart data could be sourced, the edge of a system was determined by the depth at which the seafloor could no longer be distinguished. Two types of narrow fringing reef are described, one with, and one without, embayments (Fig. 2, tiles A and B). The expansive 'unorganized' reef classes describe situations where reef frameworks and sediments extend outboard from the coastline as isolated or coalesced patch reefs punctuated by channels (Fig. 2, tile C). Detached coral reefs are first classified into either the 'tower group' which are circular in plan-view (Fig. 2, tiles K–N), or the 'platform group' (Fig. 2, tiles D–J).

Coral reefs were then classified within these two groups according to the degree and spatial distribution of reef aggradation. Whether reefs are aggrading in the center of the platform (Fig. 2, tiles D–F), or have an aggraded perimeter margin (Fig. 2, tiles G–J). This break down of reef morphology covers a spectrum of reef types which are consistent with Hopley's (1982) Great Barrier Reef categorization of reef maturity as reefs that are *juvenile*, *mature*, or *senile*. The approach however allows rapid classification of a reef system; however similarity of form does not necessarily imply similar developmental paths in the Great Barrier Reef and Red Sea, as different processes including the presence of subsurface evaporites influence reef development in the southern Red Sea (Rowlands et al., 2014).

Following Hopley's classification a reef evolves from a submerged platform (not represented in our classification). The progression of reef development may differ if primary growth is at the center of the platform (D–F) or on the margins (G–K). For example, if reef growth is patchy and across the center of the platform, a juvenile non-aggraded platform reef is categorized (D). These patches may grow laterally along topographic highs to form a mature ribbon platform reefs (E), and through infilling and further reef growth aggrade to the senile partially aggraded platform reefs (F). If reef growth is primarily on the margin a platform reef without lagoonal patches will form (G), through infilling of the lagoon and upward growth of lagoonal patch reefs the reef takes on the mature form of a lagoonal reef with patches (H), or a crescentic reef (I) with a fully aggraded windward margin and partially aggraded platform. Finally once the lagoon has filled and fully aggraded to sea level the reef becomes a senile planar reef (J).

2.2. Habitat, water depth, and wave height mapping

To assist with calculating resilience indices, GIS data layers describing benthic habitats, seabed topography and wave heights were assembled for the Farasan Banks region (Fig. 4a). The benthic mapping campaign is described in detail in Bruckner et al. (2011) and