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Coral reef habitat mapping: A combination of object-based image analysis and ecological modelling

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ABSTRACT

Despite being one of the most important and well-studied coral reefs in the world, the full extent of coral habitat of the Great Barrier Reef (GBR) is not well mapped and there is no current and comprehensive map of the GBR's geomorphic zonation or benthic composition. This paper demonstrates an approach that integrates ecological coral habitat mapping with empirical modelling to map the geomorphic zonation and benthic composition of the "shallow offshore reefs" of the GBR, using the Capricorn Bunker Group (CBG) as a case study. The approach combined environmental data sets and geo-ecological rule sets to identify geomorphic zones. The benthic composition of individual geomorphic zones was mapped for: shallow reef flat zones, using object-based image analysis with context driven rules based on coral reef ecology; and reef slope zones, using levels of wave exposure to predict the distribution of coral types. The environmental data sets used were field-based benthic composition data, Landsat 8 OLI satellite image-derived bottom reflectance, water depth and slope (15 m × 15 m pixel size) data, reef impact data, and modelled wave exposure. The study showed that the combination of geomorphic-ecological rules and models with remote sensing imagery provided robust mapping results over a large (~2500 km^2) reef system, of which 245 km^2 was mapped as shallow coral reefs and 88 km^2 of that was mapped as areas containing coral. Most importantly, the method produced defined the geomorphic zones and benthic composition of a study area that is significantly larger than the majority of coral reef remote sensing mapping projects previously published. With some modifications, the methods presented have the potential to be applied to the full extent of the shallow offshore reefs of the GBR, or any large reef globally. Monitoring and management of coral reefs for conservation and other purposes, at regional to global scales will benefit from the ability to produce and use this type of essential information on a regular basis.

1. Introduction

The Great Barrier Reef (GBR) stretches for 2300 km, includes 3000 shallow reefs (~25,000 km^2) (Lewis et al., 2003) and is the largest coral reef ecosystem in the world. It was declared a World Heritage site in 1981 and provides an economic value of approximately AUDS$7 billion per annum from tourism and fishing alone (Economics, 2013; Marshall and Johnson, 2007). As such, the deteriorating health of the GBR has become a major national and international concern and is the subject of considerable investment. Between 1985 and 2010, coral cover declined by 51% on the reef slopes of the central and southern portions of the GBR due to a combination of cyclones, Crown Of Thorns Starfish (COTS) outbreaks and bleaching (De'ath et al., 2012). The recent 2016 mass global bleaching event devastated the relatively healthy northern third of the GBR, impacting over 90% of the 1156 surveyed reefs (Hughes et al., 2017). Despite growing threats to one of the most globally important and significant coral reef systems, the GBR at its full extent, is among the least comprehensively mapped coral reef system in the world.

Coral reef habitat maps that describe either geomorphic zonation (e.g. slope, crest, flat) at moderate spatial scale (100's–1,000's m) or benthic composition (e.g. cover type, coral type) at fine scale

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(10's–100's m) can assist with ecosystem-based management as habitat mapping does for terrestrial ecosystems (Kenchington and Hutchings, 2012; Sattler and Williams, 1999). The need for detailed mapping and classification was identified in the Reef 2050 Long Term Sustainability Plan, Actions 15 and 17 (Australia, 2015). Detailed habitat maps can provide the basis for multiple whole of reef estimates, e.g. total carrying capacity as habitats for fish (Knudby et al., 2010, 2011; Purkis et al., 2008), COTS distribution (Hock et al., 2014) and the degree of carbonate production (Hamylton et al., 2017). This type of derived information at individual reef scales for the full extent of the GBR would support responses to specific management actions (e.g. COTS eradication programs).

Benthic composition and geomorphic zonation maps for the full extent of the GBR are not presently available mainly due to: the large geographical extent of the GBR and the need for vast amounts of satellite imagery to cover the full extent; a lack of consistent and repeatable methods; available resources to access the remote sites for field data collection; and/or the volume of water covering the benthic features limiting mapping to shallow water areas (Purkis and Roelfsema, 2015; Robinson et al., 2011; Purkis, 2018; Hedley et al., 2016).

The lack of detailed spatially explicit benthic habitat mapping means that management, monitoring and research approaches for the GBR are often based on benthic information with limited spatial detail, or high detail, but not covering the entire GBR. Coarse scale maps describe gross morphological features such as water depth (100 m × 100 m grid) (Beaman, 2010), bioregions (Kerrigan et al., 2010), shallow reef areas (Lewis et al., 2003), and geomorphic reef types (e.g. platform reef) (Hopley et al., 2008). Habitat maps are available for some individual GBR reefs (Ahmad and Neil, 1994; Kutser and Jupp, 2006; Leon and Woodroffe, 2011), from reef-specific projects that were not designed for operationally mapping and monitoring the whole GBR. Extensive field programs (Beeden et al., 2014; De'ath et al., 2012; Marshall and Johnson, 2007; Sweatman et al., 2001) provide mostly detailed and accurate information on benthic composition and status at field sites. These are spatially limited as they represent a small portion (≪1%) of the GBR, making it challenging to resolve the complete picture for research and management questions (Madin and Madin, 2015; Phinn et al., 2010). This situation is in stark contrast to the management of terrestrial ecosystems where detailed mapping is available and extensively used in decision making (Neldner et al., 2012).

Coral benthic composition maps can be created using optical remote sensing approaches and/or ecological modelling (Hedley et al., 2016). High spatial resolution remote sensing imagery (< 10 m pixel), coincident field data and pixel- or object-based mapping, have been successfully applied to map benthic composition on small reefs (< 100 km^2) (Andréfouët et al., 2006; Phinn et al., 2012), with exception of some studies that covered larger area (Roelfsema et al., 2013; Rowland et al., 2012). However, this high spatial resolution imagery is limited as it is captured on demand for a significant cost and coverage is only available for half of the GBR. In contrast, moderate resolution imagery (> 10 m pixel), such as Landsat (30 m pixel, and 16-day revisit time) is free, providing extensive low cost worldwide coverage. Although Landsat imagery is less suitable for mapping variations in benthic composition within individual coral reefs, it can assist with predicting benthic composition when combined with detailed, fine spatial resolution ecological and environmental field data (Andréfouët et al., 2003). Coarser scale geomorphic zonation maps for global reefs have been created through manual delineation of Landsat imagery (Andréfouët et al., 2006) with the exception of the GBR.

Ecological modelling uses empirical evidence, such as different wave energy thresholds (Madin, 2005; Madin et al., 2006), to estimate the distribution of coral morphology (e.g. massive, branching, plate), to build benthic habitat maps. This type of approach, species distribution modelling, has been applied extensively for terrestrial vegetation for over 40 years, where physical and biological variables are used to drive empirical- and rule-based models to predict the spatial distribution of individual vegetation species and communities and their properties (Elith and Leathwick, 2009). In the context of coral reefs, we refer to this as ecological modelling, and it has been applied on a Belizean reef (256 km) to predict distributions of the dominant reef building coral species in the Caribbean (Chollett and Mumby, 2012), and also in the Red Sea to predict live coral cover from water depth, turbidity and wave exposure (Hamylton, 2012). Pacific reefs, such as the GBR, have a complex assortment of corals, and any empirical modelling method would need to account for this diversity.

In summary, it is evident that creation of detailed habitat maps that describe geomorphic zonation and benthic composition of the GBR is an enormous task. The GBR Marine Park occupies an area of 345,000 km^2 and the current modelling and mapping techniques are unsuitable for large expanse, highly detailed benthic habitat mapping due to lack of resources and suitable techniques. The aim of this paper was to integrate ecological mapping with empirical modelling to map the geomorphic zonation, benthic cover type and dominant coral type distribution for the "shallow offshore reefs" of the Capricorn Bunker Group (CBG) of the southern GBR. Our approach integrated remote sensing and ecological modelling (species distribution modelling) and was developed for the GBR by building upon existing methodologies described previously. The method had to be able to predict coral type (Chollett and Mumby, 2012), represent the complex diversity of GBR coral types (Ortiz et al., 2014), model relationships between coral type and environmental factors (Madin et al., 2006), and utilise Landsat imagery (Andréfouët et al., 2003) combined with object-based habitat mapping. Amalgamation of these aspects provided moderate scale benthic habitat mapping in the context of ecological/environmental parameters, which took into consideration the increased diversity of coral communities and geomorphic zones on the GBR (Done, 1982, 1983; Hopley et al., 2008).

Fundamentally, the methods were developed for the 20 reefs in this study area with a view to further development for application to all the shallow reefs of the GBR.

2. Methods

2.1. Study site and overview

This study was conducted for twenty "shallow offshore reefs" (~246 km^2) of the CBG (± 2500 km^2, 23.45 S, 151.95 E), located 70 km off the Australian coast in the most southern section of the GBR (Fig. 1). In the context of the GBR and for the purpose of this study, "shallow offshore reefs" are defined as coral reefs that are visible in optical remote sensing imagery down to a depth of 20 m Lowest Astronomical Tide (LAT) and do not include nearshore fringing reefs. The CBG is characterised by platform reef types, subject to predominant south-easterly winds and swell, with water depths reaching 40 m in the areas between reefs (Hopley et al., 2008).

The CBG was used as a case study because it is a relatively large and distinct section of the GBR, for which there was existing field data and extensive expert knowledge (Hamylton et al., 2016; Joyce et al., 2002; Phinn et al., 2012), important for input into this study.

To produce geomorphic zonation and benthic composition maps, an object-based and empirical modelling approach was applied. This approach used water depth (bathymetry) derived from satellite imagery to estimate reef slope angle, and in combination with historical wind data, to model wave exposure and fine scale benthic composition (Fig. 2).

Geomorphic zone definitions, based on previous studies (Phinn et al., 2012; Roelfsema et al., 2013), included deep lagoon, shallow lagoon, inner reef flat, outer reef flat, reef crest, fore-reef slope sheltered and fore-reef slope exposed (collectively reef slope to a depth of 10 m), deep reef and land area descriptors (Gourlay and Colleter, 2005; Neil et al., 2000; Syms and Kingsford, 2008). Benthic composition was