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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

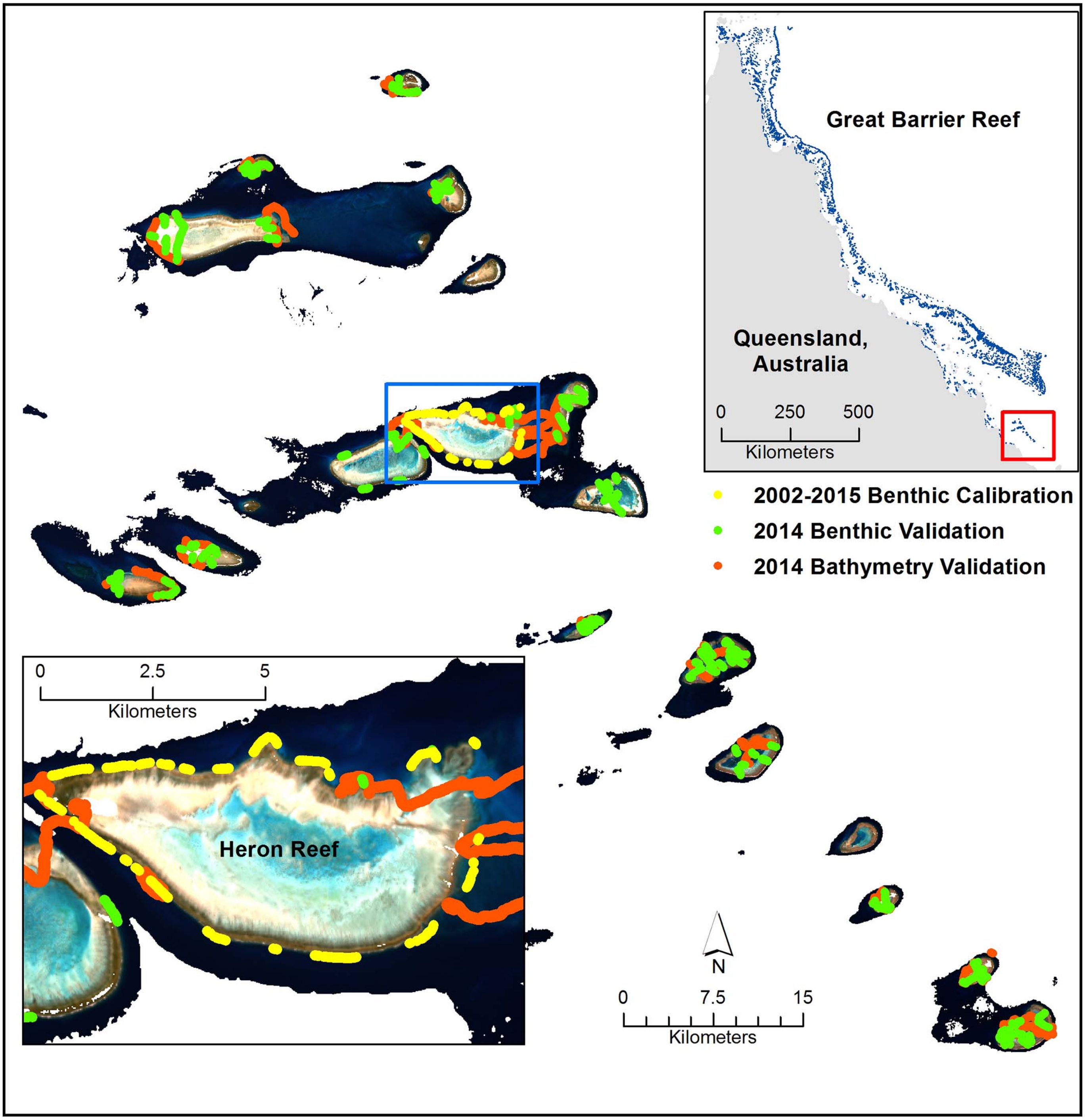

Fig. 1. Capricorn Bunker Group Reefs, Southern Great Barrier Reef, Australia. The coloured points represent sampling locations for video spot check and photo transect field data used for benthic calibration and validation, and water depth (bathymetry) measurements, projected on a Landsat 8 OLI (10th June 2014 and 3th September 2014) sub-surface reflectance image mosaic. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

defined differently for reef slope and reef top areas: (1) For the *Reef Slope*, benthic composition was defined as **dominant coral type** in regards to morphology (plate, branching, or massive/encrusting corals) (Chollett and Mumby, 2012; Done, 1982, 1983; Ortiz et al., 2014); and (2) for the *Reef Top*, benthic composition was defined more broadly as **dominant benthic cover type** (coral, algae, sand, rubble and rock) (Roelfsema et al., 2013). These distinctions between reef slope and reef top were due to the reduced capability of remote sensing data and methods to differentiate benthic cover type with increasing water depth, and the fact that wave exposure is unlikely to be a good predictor of coral community composition on the reef top due to dissipation of the wave energy beyond the reef crest.

2.2. Input data

2.2.1. Satellite products

Sub-surface and seafloor reflectance as well as tide-corrected water depth to LAT (Fig. S1) were derived from Landsat 8 Operational Land Imager (OLI) imagery, at 15 m × 15 m resolution, calculated using the Modular Inversion and Processing (MIP) system (Cerdeira-Estrada et al., 2012; Heege et al., 2004; Ohlendorf et al., 2011). The commercial- algorithms underlying the MIP system have been previously tested

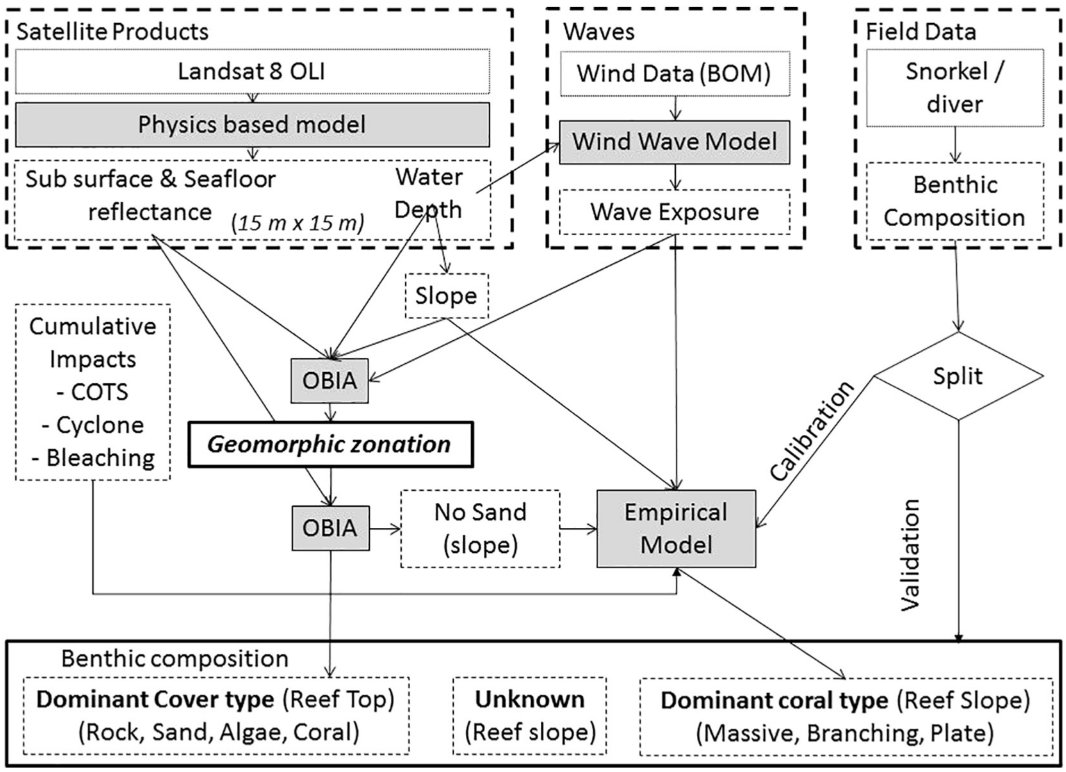

Fig. 2. The steps used to develop the method to map the geomorphic zonation and benthic composition of Capricorn Bunker Group Reefs, Southern Great Barrier Reef, Australia. OLI = Operational Land Imager, BOM = Bureau of Meteorology, OBIA = object based image analysis, COTS = Crown of Thorns Starfish. Bold dashed boxes describes input data sets, and bold boxes the output data sets.

and validated worldwide (EOMAP, 2016; Kobryn et al., 2013; Siermann et al., 2014).

2.2.2. Waves

Wave climate descriptors (18 different wave parameters; Table S1, Fig. S2) were determined using numerical modelling of wave generation and propagation throughout the CBG, and near-reef transformations using local wind data and Landsat 8 OLI-derived water depth. The approach we followed is described in detail in (Callaghan et al., 2015). Briefly, wave parameters were derived using a process-based wave model that included 16 grids ranging from 5 km to 50 km to model swell wave propagation from the Pacific Ocean and local wind-wave generation and propagation to each reef. The finer grids were used at reefs to model wave shoaling, refraction, diffraction and depth limited breaking (critical nearshore processes that control wave height). This model of 16 grids evaluated wave condition across each reef between 17-Jul-1994 and 31-Mar-2015. These temporal and spatial wave climate estimates were then used to estimate exceedance statistics for wave parameters listed in Table S1 at each spatial location by sorting each grid's temporal predictions in ascending order and empirically associating exceedance probability. Local winds were obtained from The Bureau of Meteorology (BOM) and Pacific Ocean swell was obtained from the European Centre for Medium-range Weather Forecasts' (ECMWF) ERA-Interim Project hindcast data for waves (Dee et al., 2011). The improvement of process-based over fetch-based wave predictions is that the former includes swell and shallow water processes of shoaling, refraction, diffraction and most importantly depth limited wave breaking. This provides a better estimate of wave exposure within shallow reef regions.

2.2.3. Field data

Coral type benthic information was derived from georeferenced benthic field photographs collected on dive and snorkel transects at Heron Reef in 2002, 2004, 2006, 2007, 2008 and 2015. See a detailed description of field methods in (Phinn et al., 2012; Roelfsema and Phinn, 2010). This was used to generate the empirical relationships (predictive models) between wave exposure and benthic community composition. Additional benthic composition field data, collected throughout the CBG in 2008 and 2014, were used to validate the dominant benthic cover on the *Reef Top* (935 sites) and dominant coral type maps on the *Reef Slope* (193 sites; Fig. 1). In this case, benthic composition was estimated for each photograph and video recording that was captured using drop camera surveys or georeferenced transect surveys (Hamylton et al., 2016). For qualitative assessment, The Australian Institute for Marine Science's Long Term Monitoring Program (AIMS-LTMP) data provided an estimate of dominant coral type for four zones (front (windward side), back (leeward side), flank1 (area clockwise from back to front) and flank2 (area clockwise from front to back; (Miller et al., 2009) along the perimeter of eight reefs. Water depth measures (n = 30,071) conducted in 2014 using a Garmin GPS echo sounder 550C and corrected to LAT (Hamylton et al., 2016) were used to validate the water depth maps (Fig. 1).

2.3. Mapping geomorphic zonation, dominant benthic cover type and predicted dominant coral type

2.3.1. Geomorphic zonation: object-based mapping

Object-based image analysis (OBIA) through Trimble eCognition 9.3 software was used to map geomorphic zones by adaptation of a protocol developed in Roelfsema et al. (2013), with the following additional attributes incorporated: water depth, slope (calculated from water depth), significant wave height and sub-surface reflectance. In this instance, sub-surface reflectance was considered a proxy for consolidated (dark e.g. reef matrix, coral, algae) or unconsolidated material (bright e.g. sand).

OBIA requires a spatial data set to be first segmented into groups of pixels with similar characteristics (e.g. colour or texture, or a physical property such as water depth), followed by segment labelling using a

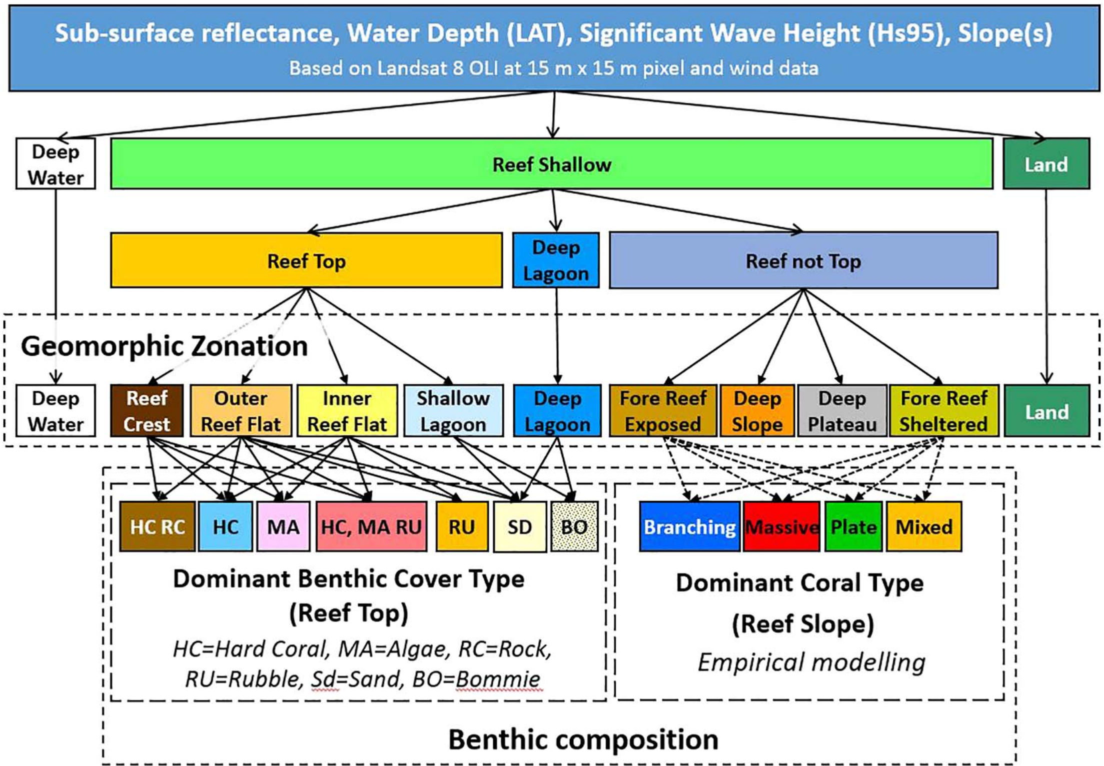

Fig. 3. Hierarchical classification scheme for the Capricorn Bunker Group Reefs. The geomorphic zonation (all reef) and dominant benthic cover type (reef top only) was defined using object-based analysis and integrated with empirical modelling to predict dominant coral type on the reef slope.

membership rule set (Blaschke, 2010). A hierarchical classification was first applied for the geomorphic zonation followed by benthic composition (Fig. 3).

For each geomorphic zone category, a rule set was developed to assign a label to each segment based on a set of biophysical attributes such as water depth (depth LAT > 0.75 m = *Reef Top*), colour (e.g. brightest = sand), slope derived from water depth (> 10 degree = slope) and neighbourhood relationships, e.g. Fore Reef Exposed is adjacent to reef crest (Table 1). Areas with a depth of > 20 m LAT were labelled *Deep Water*. Areas with a depth of 10 m–20 m LAT were labelled *Deep Slope* or *Deep Plateau*, dependent upon slope and water depth attributes. Areas 0.75 m–10 m LAT and neighbouring *Reef Top* were labelled *Not Reef Top*. *Not Reef Top* exposed to historically high significant wave heights (Hs95 > 2 m) were labelled as *Fore Reef Exposed*, while areas with low significant wave heights (Hs95 < 2 m) were labelled as *Fore Reef Sheltered* (Gourlay and Colleter, 2005). *Reef Top* was re-segmented into smaller segments and assigned *Reef Crest*, *Reef Flat*. *Outer Reef Flat*, *Inner Reef Flat* and *Shallow Lagoon* were assigned to segments based on: neighbourhood relationship, slope and brightness level within the blue, green and red bands, and whether they contained bright objects (a surrogate for sand). In the latter case, the brightest objects were assigned *Inner Reef Flat* as these areas commonly contain more sand (Table 1).

2.3.2. *Dominant benthic cover type: object-based mapping*

Dominant benthic cover type was determined for the *Reef Top* using OBIA, local knowledge of CBG reefs and rules from previous OBIA studies (Fig. 3) (Joyce et al., 2002; Phinn et al., 2012; Roelfsema et al., 2013). Membership rules to assign dominant benthic cover type labels to segments were based on the brightness of the segments, band ratios,

Table 1
Geomorphic categories and the core attributes and thresholds used to assign labels to the segmented satellite imagery using the object-based analysis approach for Capricorn Bunker Group Reefs. Sub-surface reflectance bands B = blue, G = green, and R = red.

Level	Mapping category	Relation ship	Depth (m) LAT	Slope (degrees)	Significant wave height (Hs95; m)	Sub-surface reflectance
Land/water/reef	Land/exposed	No data value + surrounded by reef	n.a.	n.a.	n.a.	No-data
	Very deep water	Remaining no data values	n.a.	n.a.	n.a.	No-data
	Deep Water	n.a.	> 20 m	n.a.	n.a.	0.01–1
	Shallow water	Not: deep, land or exposed	< 20 m	n.a.	n.a	0.01–1
Shallow water	Reef Top	Intermediate class	< 0.75 m	n.a.	n.a	0.01–1
	Not Reef Top	Intermediate class	> 0.75 m	n.a.	n.a	0.01–1
Reef Top	Reef Crest	Adjacent “not reef top”	< 0.75 m	0–10	n.a	Low B + G + R
	Outer Flat	Not inner, crest, adjacent reef crest	< 0.75 m	0–5	n.a.	Med B + G + R
	Inner Flat	Adjacent outer reef flat	< 0.75 m	0–5	n.a.	High B + G + R
	Shallow Lagoon		0.5–0.75 m	0–5	n.a.	High B + G + R
Not Reef Top	Fore Reef Exposed	Adjacent crest or inner/outer reef flat	0.75–10 m	5–90	> 2 m	n.a
	Back Reef Sheltered	Adjacent reef crest	0.75–10 m	5–90	< 2 m	n.a
	Deep Slopes		10–20 m	5–90	n.a.	n.a
	Deep Plateau		10–20 m	0–5	n.a.	n.a
	Deep Lagoon	Surrounded by reef top	0.75–20 m	0–90	n.a.	n.a

segment location within each of the geomorphic zones, expert knowledge and/or field data. Rules varied between geomorphic zones dependent upon the type of relationship and/or threshold value for a dominant benthic cover type. Dominant benthic cover type labels assigned included: Coral, Algae, Rock, Rubble, Sand and Mixed, where Algae is dominated by macro algae (> 2 cm), and Rock includes turf algae (< 2 cm) and crustose coralline algae (Steneck and Dethier, 1994). For *Deep Lagoon* and *Shallow Lagoon*, object brightness was used to differentiate between Sand and Bommie categories, where the latter represent small patch reefs (approximately 10 m–50 m diameter) that occur in sandy areas.

For water deeper than *Reef Top* (e.g. *Fore Reef Exposed*), due to increased bottom reflectance attenuation with increasing water depth, the only differentiation that could be made was between bright and dark objects. Bright objects were assumed to represent unconsolidated material (e.g. bright = sand), and dark objects consolidated material (e.g. dark = coral, rock or algae).

2.3.3. Dominant coral type: ecological modelling

The predicted dominant coral type map (branching, massive and plate) was created using four steps:

Step 1: **Derivation of the input parameters for ecological model development**. To create parameters to drive the coral type model, the major coral types were extracted from the field data collected on the Heron Reef slope as previously described in Section 2.2 (n = 3008). Corals were grouped for each sample point according to three major morphologies (plate, branching and massive) as recent studies have demonstrated that variability in coral life traits is better explained by morphology than taxa (Dornelas et al., 2017).

Firstly, field measured dominant coral types at field sample points were established on the reef slope. New data points were distributed 30 m apart along a perimeter of Heron Reef that followed the 5 m depth contour. A buffer zone of 15 m was established around each perimeter point to approximate the area covered by one Landsat pixel. For each buffered point the benthic field data (derived from the individual georeferenced photos that fell within the buffer) were aggregated to represent the relative abundance of each major coral type at that point (plate, branching or massive). The result was 302 aggregate field points along the 5 m depth contour. Subsequently, these dominant coral types were associated with estimated wave climate data for their respective locations. Using a spatial join operation, each buffered point was assigned a single value for each of the 18 wave parameters, and a degree of reef slope.

Step 2: **Prediction of dominant coral type**. Using the aggregated field data, all possible combinations of wave exposure variables were explored using permutational linear mixed effect models (Primer 6.0 (Clarke et al., 2014)) to determine the environmental parameters (e.g. depth, wave exposure) that best predicted each of the coral types. From these models, equations were generated that allowed the expected coral type composition to be predicted as a function of wave exposure.

To formulate these equations we used relationships provided in the literature that were based on the mechanical forces that affect corals at different wave exposures (Madin et al., 2008). Thus, three empirical relationships were developed that predicted the relative abundance of Massive, Branching and Plate corals.

Step 3: **Prediction of the *relative abundance* of coral type**. Using the empirical relationships, predicted *relative abundance* of coral type maps were created, one for each of Branching and Massive and Plate coral types. Disturbance spatial patterns were explored for the region but no disturbances were recorded for the CBG within the last five years (e.g. major bleaching, COTS outbreaks or cyclones). According to GBR ecosystem modelling, during a five year period without disturbances, average reef coral cover recovers at about 6% per year (Ortiz et al., 2014). Therefore, any reef subjected to a disturbance should after five years, have at least 35% coral cover. As such, we are confident that disturbance effects did not confound our modelled relationships between coral type and wave exposure. Therefore, predicted relative abundance coral type distribution was determined for plate, massive and branching corals based on the assumption that there had been no recent major disturbances in the area.

Step 4: **Generation of a *predicted dominant coral type* map**. The pixel values for the three predicted *relative abundance* coral type maps were standardised. For each pixel within the 2.5 m to 10 m LAT depth in *Fore Reef Exposed* and *Fore Reef Sheltered* reef slope areas not dominated by sand (determined from the geomorphic and benthic mapping), a standardised predicted *relative abundance* of plate, massive and branching coral type value was assigned. The predicted *dominant coral type* was determined for each pixel based from these relative abundance labels and subsequently, each pixel was assigned a category of Branching Dominant, Massive Dominant or Plate Dominant.

2.4. Quantitative and qualitative validation of the mapping approaches

2.4.1. Quantitative validation

Accuracy measures were calculated for the geomorphic zonation, dominant benthic cover type, and predicted dominant coral type maps, by comparing map outputs with reference data in an error matrix to produce overall, producer and user accuracies (Congalton and Green, 2008). Reference data for each of the three map types was derived from a different source and described as follows:

- **Geomorphic zonation map reference data** (n = 172), was created by assigning a mapping category to each of 172 points through visual interpretation that were randomly distributed and overlaid on a Landsat satellite image. The assignment was conducted by experts not involved in producing the geomorphic zonation map, making them unbiased.
- **Reference data for the dominant benthic cover type map** (n = 935) and the **predicted dominant coral type map** (n = 193) were derived from the previously described field data collected in the CBG (2008 and 2014).

For **validation of the water depth** product derived from the Landsat 8 OLI imagery, reference data from field measured water depths (n = 30,071) were compared with coincident locations on the map product and regression values were calculated.

2.4.2. Qualitative validation

A qualitative assessment was conducted to take into consideration the factors providing confidence for the producers and users of the habitat maps. An approach was applied which assigned additional information pre-defining confidence levels of the data sets, models, mapping approaches and outputs (Glanville et al., 2016). A confidence level (Table 2) was assigned to each of the input and output data layers which were based on assessment of the validity of the overall process, as well as how robust and reliable the input data was.

2.5. How much coral habitat is in the shallow reefs of the Capricorn Bunker Group?

To map the zonation and composition of individual reefs within the CBG, the surface areas for each of the geomorphic zones, dominant benthic cover types and predicted dominant coral types were calculated from the respective map outputs. These results were contrasted with

Table 2
Confidence level (rated according to the level of confidence experts had in the developed mapping rule set that identified the specific spatial data) (Glanville et al., 2016).

Rating	Data source	Description
Highest	Known spatial data – expert knowledge and supporting evidence (e.g. field validation)	The mapped ecosystem measure has been accurately identified.
High	Derived spatial data – expert knowledge	High confidence in the mapping rule set.
Moderate	Derived spatial data – according to expert knowledge	Moderate confidence in the mapping rule set.
Low	Derived spatial data – expert knowledge	Low confidence in the mapping rule set.
Unknown	None	No history or knowledge about how data was collected or created

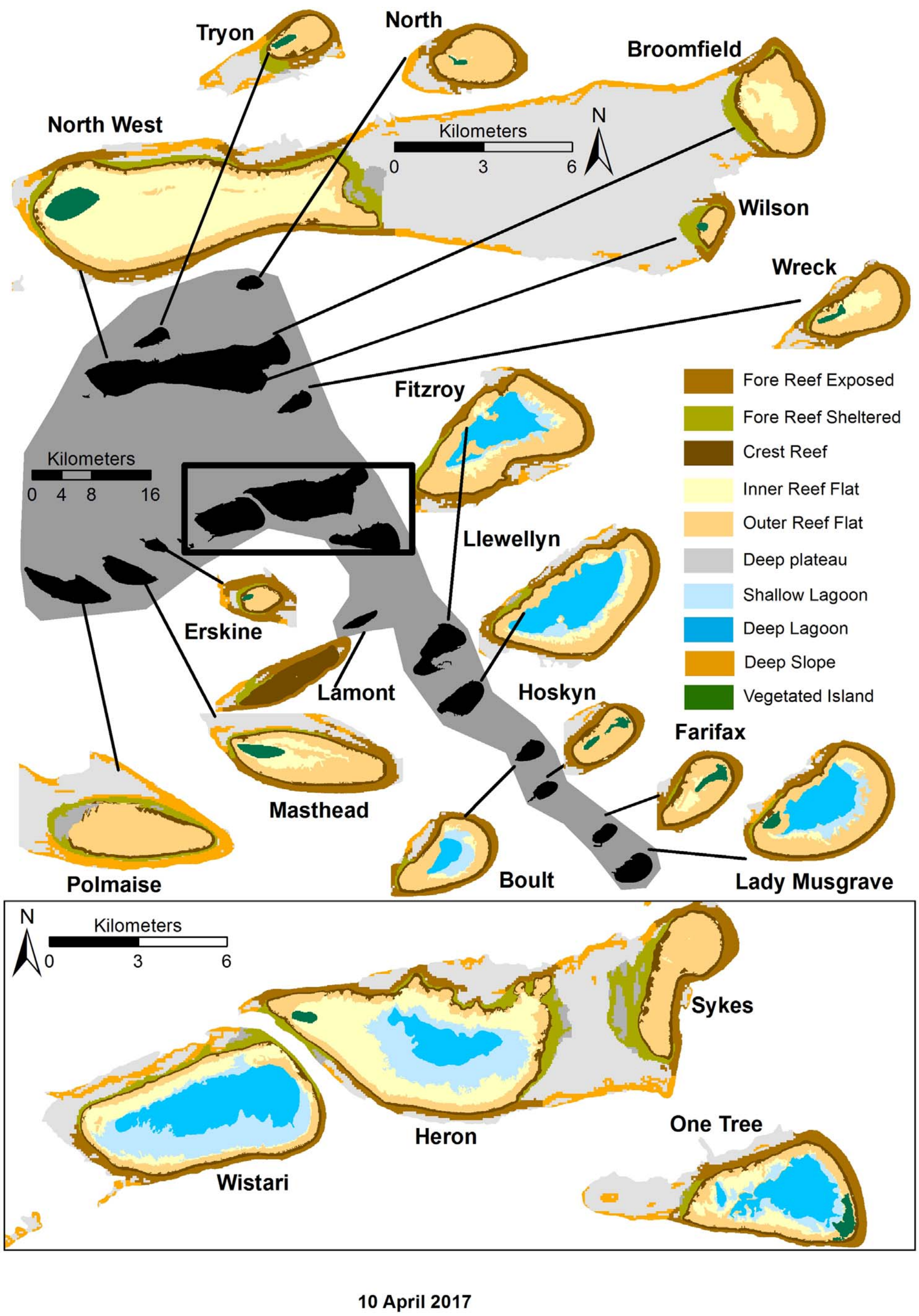

Fig. 4. Geomorphic zonation of the Capricorn Bunker Group, Southern Great Barrier Reef, Australia. The map was derived using object-based image analysis, sub-surface reflectance and water depth from Landsat 8 OLI imagery in conjunction with significant wave height.

previous area estimates from data sets that mapped geomorphic reef types (Hopley et al., 2008).

Madin and Madin (2015) suggested that knowledge of the absolute amount of consolidated reef structure provided a full picture of global coral reef health, and that these ecological estimates applied at broader spatial scales. As consolidated reef provides a structure that could support living corals or is suitable for coral to grow upon (Madin and Madin, 2015), the total area available for coral growth and the amount

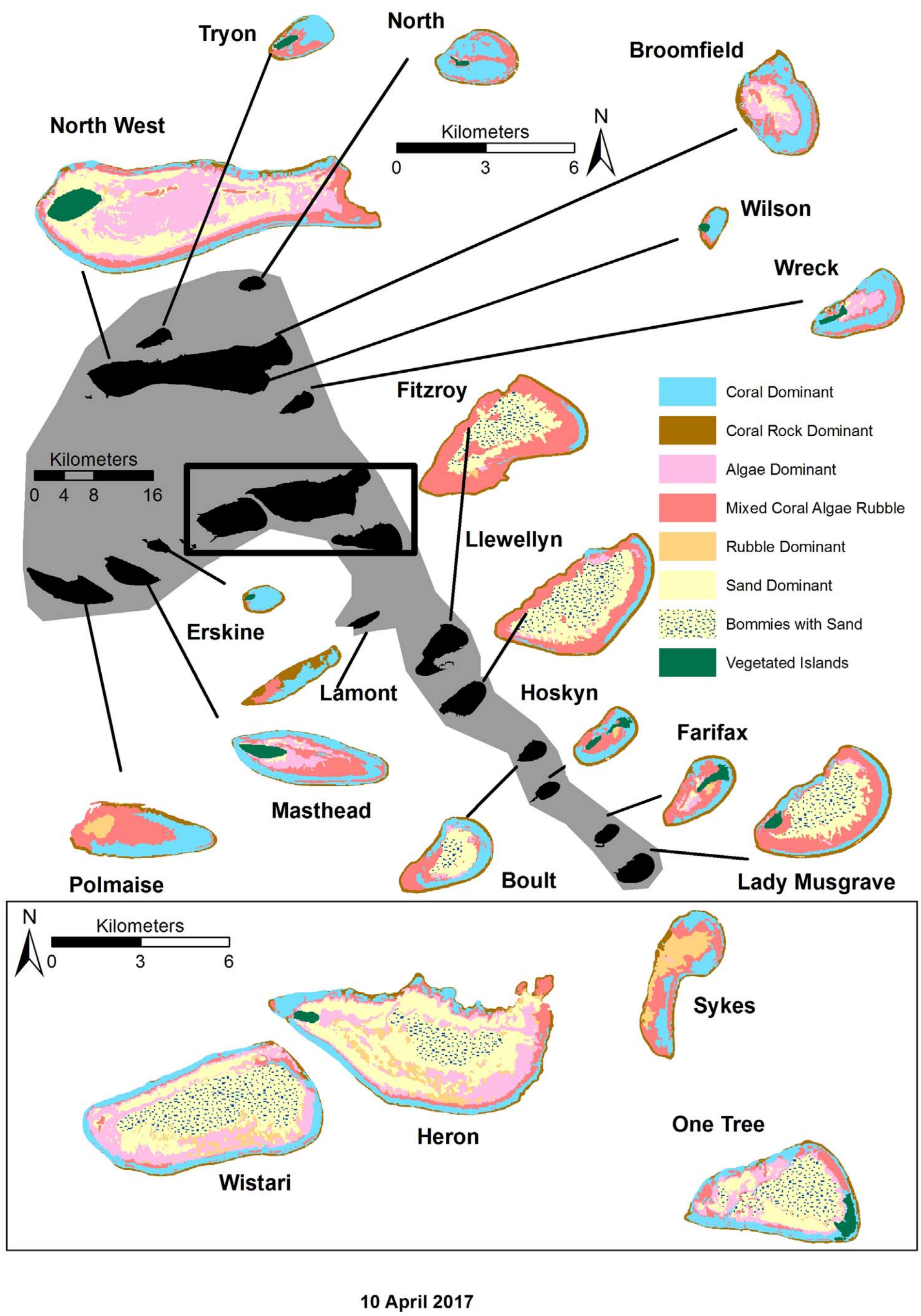

Fig. 5. The dominant benthic cover type for *Reef Top* created for the Capricorn Bunker Group, Southern Great Barrier Reef, Australia. The map was derived using object-based image analysis, seafloor reflectance, water depth from Landsat 8 OLI and the geomorphic zonation map (Fig. 4) as input data.

Table 3
Coral type relative abundance equations. The input variables were derived from a climate-based wave exposure model for each individual grid cell within the Fore Reef Exposed and Fore Reef Sheltered slope areas.

Coral type	Modelled relative abundance	r^2
Massive	$(-4.10 * \text{ubedmean}) + (0.34 * \text{Tpmean}) - (0.10 * \text{Tp90}) - (0.57 * \text{Hs95}) + (0.01 * \text{Edmean}) + (14.04 * \text{UonrootTmean}) - 1.602$	0.35
Plates	$(0.57 * \text{ubedmean}) + (3.30 * \text{Hs95}) - (9.87 * \text{Hs80}) + (7.24 * \text{Hs70}) - 0.30$	0.43
Branching	$(3.39 * \text{ubedmean}) - (0.31 * \text{Tpmean}) + (0.14 * \text{Tp90}) - (2.32 * \text{Hsmean}) + (1.40 * \text{Hs80}) - (14.31 * \text{UonrootTmean}) + 2.627$	0.63

Tpmean = mean of peak wave period, Hs = significant wave height at upper 70, 80 and 95th percentiles and mean, Edmean = mean of wave energy density per unit horizontal area (J/m^2), UonrootTmean = mean overall maximum benthic velocity, ubedmean = mean seabed peak wave orbital velocity. For a description of wave parameters refer to the Supplementary information, Table S1. An example wave parameter is shown in Supplementary Fig. S2.

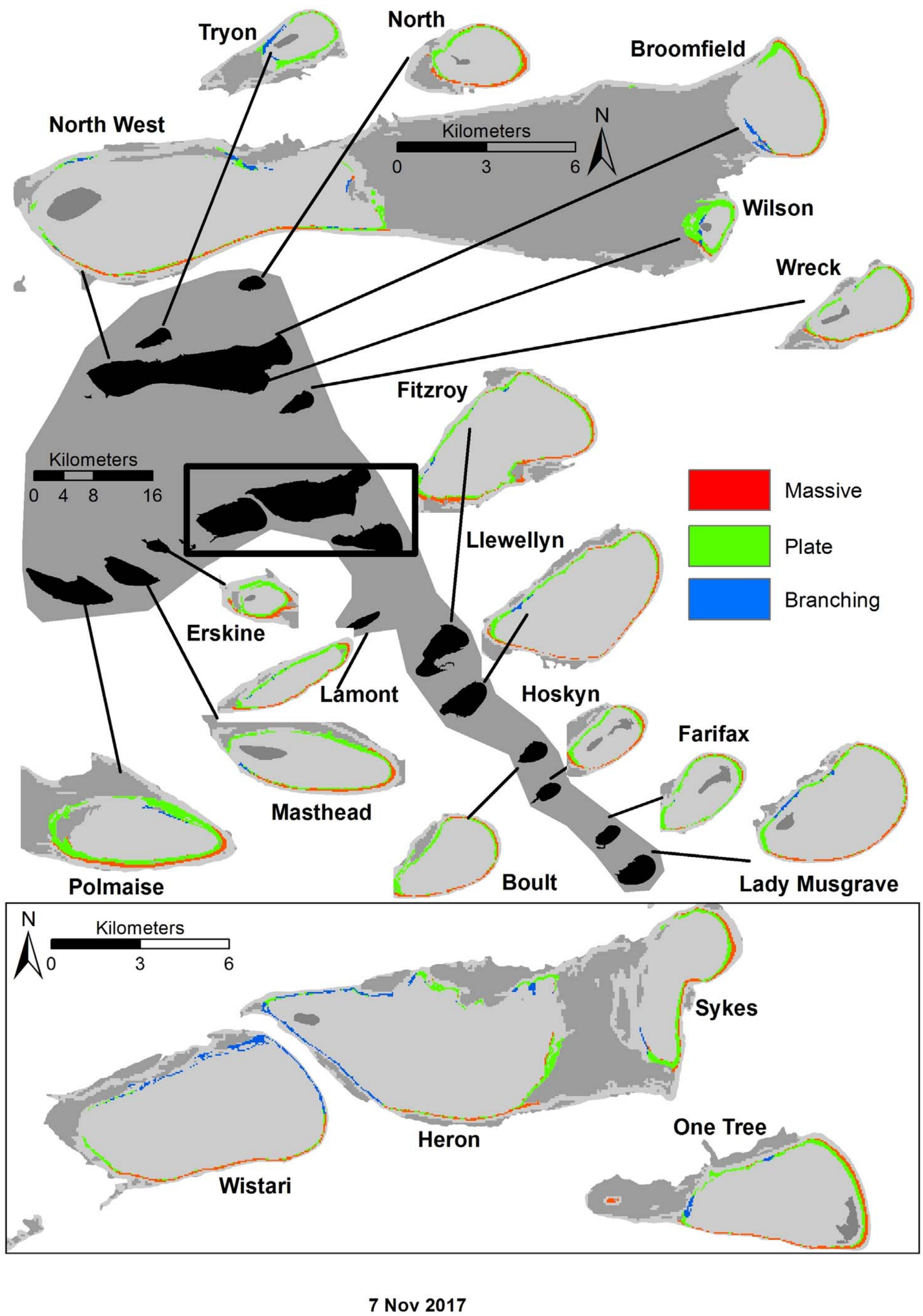

Fig. 6. The predicted dominant coral type for the 2.5 m − 10 m Reef Slope of the Capricorn Bunker Group, Southern Great Barrier Reef, Australia. The map was derived using empirical modelling of coral type relative abundance field data, in conjunction with the geomorphic zonation map (Fig. 4), reef slope information, water depth derived from Landsat 8 OLI and wave exposure parameters.

of coral present were calculated. The assumption was made that within the geomorphic zonation map, reef slope, reef crest and outer reef flat are predominantly consolidated, whereas inner reef flat, shallow lagoon and deep lagoon are predominantly unconsolidated. Subsequently, the amount of consolidated reef structure was calculated from the areas of reef slope, reef crest and outer reef flat on the geomorphic zonation map.

3. Results and discussion

3.1. Geomorphic zonation, dominant benthic cover type and predicted dominant coral type maps

A geomorphic zonation map of the CBG shallow reef area (245 km^2) was created using an OBIA method (Fig. 4). Subsequently, using the geomorphic zonation map to identify areas of *Reef Top* (187 km^2), a dominant benthic cover type map for the *Reef Top* was derived for the CBG (Fig. 5).

Coral relative abundance equations were derived (Table 3) from relationships of coral types massive, plate and branching with wave parameters. The tightest models for predicting the relative abundance

Table 4
A summary of the user, producer and overall accuracies derived from the validation error matrices generated for each of the geomorphic zonation, dominant benthic cover type and predicted dominant coral type maps.

Geomorphic zonation			Benthic cover type (Reef Top)			Predicted dominant coral type (Reef Slope)		
Overall accuracy (%)	59.5		Overall accuracy (%)	32.8		Overall accuracy (%)	48.7	
Number of samples	172		Number of samples	935		Number of samples	193	
	User (%)	Producer (%)		User (%)	Producer (%)		User (%)	Producer (%)
Deep lagoon	80.0	90.6	Algae dominant	1.9	60	Branching	54.7	61.2
Shallow lagoon	34.9	39.6	Coral/rock dominant	4.7	30.8	Massive	42.3	47.8
Inner Reef Flat	40.6	62.1	Mixed dominant	83.6	49.1	Plate	47.0	38.8
Outer Reef Flat	58.0	49.8	Rubble dominant	0.0	0.0			
Reef Crest	54.5	71.9	Sand dominant	51.3	37.5			
Back Reef Slope	59.5	61.2						
Fore Reef Slope	49.1	58.4						
Deep Plain	80.5	66.9						

of the different coral types included between four and six of the 18 wave exposure variables and explained between 35% and 63% of the variance in the dataset (Table 3).

Using the equations presented here (Table 3), the predicted relative abundance of each coral type (branching, plate and massive corals) was determined. The output was subsequently used to create a predicted dominant coral type map for *Reef Slope* (*Fore Reef Exposed* and *Sheltered*) of total extent 24 km^2 (Fig. 6) for the CBG reefs.

The areas with the lowest wave exposure were consistently dominated by branching corals. Branching corals are characterised as having lowest skeletal strength, being very susceptible to breakage by wave energy (Madin, 2005; Madin et al., 2006, 2014; Madin and Connolly, 2006). In contrast, massive and plate corals have been shown to have a higher skeletal strength, making them less susceptible to the effect of wave energy (Madin, 2005; Madin et al., 2006, 2014; Madin and Connolly, 2006). As a consequence, both plate and massive corals tend to dominate in intermediate to high wave exposure sites, as shown in Fig. 6.

A mixed community of massive and plate corals were located predominantly on the more exposed windward front of most reefs, while branching corals were dominant in highly sheltered environments. In the areas of intermediate exposure either plate corals dominated, or a mixed community was present. Plate corals have a nonlinear relationship with wave exposure where their abundance increases with wave exposure until an optimum value is reached. Beyond this optimum, increasing coral mortality due to wave damage outpaces any further growth, resulting in declining coral abundances. As such, plate abundance will subsequently decline in high wave exposure areas (Madin et al., 2008).

3.2. Validation of the mapping approaches

The geomorphic zonation map had an overall accuracy of 59.5% (n = 172) with individual categories having user accuracies in the range of 34.9% (Shallow Lagoon) - 80.5% (Deep Plain); an accuracy of 12.5% is expected by chance for eight categories (Table 4).

The dominant benthic cover type for *Reef Top* map had an overall accuracy of 32.8% (n = 935) with a user accuracy range of 1.9% (Algae)–83.6% (Mixed); an accuracy of 20.0% is expected by chance for five categories (Table 4). No validation data was available for Rubble indicated by the 0.0% accuracy. The lower accuracies observed for the *Reef Top* dominant benthic cover type map arise due to the mixture of cover types that occur in this area at the level of a single pixel (30 m × 30 m).

The predicted dominant coral type map for *Reef Slope* had an overall accuracy of 48.7% (n = 193), with user accuracies in the range of 42.3% (Massive)–54.7% (Branching) an accuracy of 33.3% is expected by chance for three categories (Table 4). Moreover, all the accuracy values (both user and producer) for the different coral types were above 33%, with some as high as 60% (Table 4).

Of the derived physical parameters, only the water depth map was assessed and resulted in an r^2 of 0.8775 (n = 30,071).

In regard to the qualitative assessment (Table 5), the geomorphic zonation map was rated high due to the combination of a high level of confidence in the input data and the approach followed, and visual assessment of the patterns within the geomorphic zones for each individual reef (Roelfsema et al., 2013).

Even though confidence in the input data sets was high, the dominant benthic cover type map was given only a moderate level of confidence for two reasons. Firstly, examination of the maps by the authors suggested that most patterns observed were as expected, such as rubble areas behind the reef crest that were absent from the Fore Reef Exposed and Sheltered zones, and coral not the dominant benthic cover type in the shallow lagoon or reef flat zones. Secondly, the imagery layer used to assign the mapping categories had a resolution of 15 m × 15 m and likely does not capture the spatial variability of the benthic categories mapped here (e.g. a 2 m × 2 m pixel (Andréfouët et al., 2003)).

A moderate level of confidence was given to the predicted dominant coral type map due to a propagation of the confidence levels of the input data for the modelling process and the accuracy assessment, even though biological or chemical factors that influence coral growth were not included in the model. We expect that confidence levels would be improved if coral type data was collected in all areas of the reef so that extremes in wave exposure were represented.

3.3. Comparison of habitat maps to existing maps

Using the datasets created in this study (Figs. 4, 5 and 6), we were able to quantify habitat characteristics at a level of detail not achieved previously for the whole CBG. This advancement in habitat information, is illustrated in Fig. 7, where our map product is compared with a geomorphic reef type map (Hopley et al., 2008). There is noticeable alignment between the area of geomorphic reef type categories mapped from this prior work and the area of geomorphic zonation categories mapped in this study (Fig. 7). For example, the geomorphic reef type of Fitzroy reef is a “lagoonal reef” (Fig. 7A) and therefore, it should have a lagoon zone. On our geomorphic zonation map, a lagoonal zone has been mapped for Fitzroy reef (Figs. 4, 7B). Similarly, the geomorphic reef type of Heron Reef is “closed lagoonal coral cay reef”. As such, it should have a reef crest, reef flat, a coral cay and a closed lagoon, all of which are present on our geomorphic zonation map (Figs. 4, 7B). Collectively, these findings show agreement of the output of the approach we have developed in this work with a geomorphic reef type map created previously (Hopley et al., 2008). This demonstrates the

Table 5
Confidence levels for the input data sets, the methods used to create the habitat maps, and for each of the output map layers (geomorphic zonation, dominant benthic cover type and predicted dominant coral type) for the Capricorn Bunker Group, Southern Great Barrier Reef, Australia (see Table 2 for confidence rating definitions).

Data type	Description	Main method	Confidence rating	Justification
Input field data	Benthic field data	Field survey	Highest	Collected and analysed following well published methods
	Water depth field data	Field survey	Highest	Collected and analysed following well published methods
	Wind field data	Field recording	Highest	Collected and analysed following well published methods
Input imagery	Landsat 8 OLI raw imagery	Image capture	Highest	Collected and analysed following well published methods
Derived environmental data	Subsurface reflectance (proxy for consolidation)	Inverse physics based image analysis	High	Published methods and High confidence input data
	Seafloor reflectance (proxy for bottom type)	Inverse physics based image analysis	High	Published methods and High confidence input data
	Water depth	Inverse physics based image analysis	High	Published methods and good quality input data and independent validated
	Slope	GIS + water depth	High	Published methods and High confidence input data
	19 wave exposure parameters	Physics modelling + water depth + wind data	High	Published methods and High confidence input data
Habitat maps	Geomorphic zones	Object based + ecological rule sets + environmental data	High	High confidence input data, established approach based on attributes
	Dominant benthic cover type	Object based + ecological rule sets + geomorphic zones	Moderate	High confidence input data, established approach but not based on attributes
	Coral type: Branching, Massive, or Plate	Empirical ecological modelling + geomorphic zones + environmental + field data	Moderate	High confidence input data, valid approach but various assumptions
	Dominant coral type	GIS + Branching, Massive, and Plate coral type	Moderate	High confidence Input data, valid approach but various assumptions

potential to use the approach developed in this paper to effectively determine geomorphic reef type.

Importantly, and for the first time, observations that combine geomorphic and/or benthic characteristics of the CBG, are possible (Figs. 4, 5, 6 and 7). Heron, North West and Wistari reefs, for instance, have the largest extent of Inner Reef Flat and Shallow Lagoon areas relative to other reefs (Figs. 4, 7B). These areas are commonly dominated by sand and algae (e.g. benthic micro algae) as is confirmed by benthic cover type data for the *Reef Top* (Figs. 5 and 7B). For the predicted dominant coral type for *Reef Slope* areas, plate corals dominate which agrees with the observations of Done, 1980 and Sweatman et al., 2001. Only a few reefs have relatively large areas of reef slope populated by branching type corals, which are more commonly found in the protected Fore Reef Sheltered areas (Done, 1982) (e.g. Heron and Wistari reefs (Figs. 6, 7D)).

The spatial and thematic information delivered by outputs of this study, provide a level of detail not seen before for large reef systems in the GBR (Fig. 8). Collectively this information would enable a more targeted approach to defining coral-dominant areas and determining what proportion of these areas are impacted by environmental drivers, or, vulnerable to these impacts (e.g. bleaching or COTS outbreaks). Similarly, as some coral types are more likely to be targeted by COTS, predicted dominant coral type maps would enable refinement of the modelling of any COTS outbreaks.

Monitoring of coral bleaching during the 1998, 2002, 2016 and 2017 mass bleaching events on the GBR utilised aerial observation in combination with in-water surveys (Hughes et al., 2017). Geomorphic zonation maps like those generated in this study could be used to identify areas of consolidated substrate. This would help focus monitoring efforts to these areas during aerial bleaching surveys and the output could provide a realistic estimate of the surface area impacted by bleaching.

Management applications as discussed would benefit from fine scale benthic habitat information, specifically on the extent of coral across an individual reef or entire reef system, like the GBR. The GBR reef outline (Lewis et al., 2003) has been used as a surrogate to represent coral for previous modelling studies in regards to COTS outbreaks on the GBR (Hock et al., 2014) and in bio-optical models (Baird et al., 2016; Reichstetter et al., 2015). If there were high detail geomorphic zonation or benthic cover type maps available, these types of models would improve as they would be parametrised with finer resolution data. These examples show that the implication for the regular production of reef benthic information for science, monitoring and management using our approach is significant.

It is acknowledged that the GBR as a whole varies in geomorphic reef type (Hopley et al., 2008) and coral distribution within reefs (Done, 1982; Done, 1983), and that these characteristics vary within reef systems worldwide (Spencer et al., 2008; Stoddart and Steers, 1977; Veron & Stafford-Smith, 1999). Taking this into consideration, these methods with some modifications, could be applied to any coral reef system for which water depth, wave exposure, sub-surface and seafloor reflectance imagery is available, as well as relevant field data that provides information on benthic cover type, dominant coral type and water depth. Globally, this information is becoming more widely available – which increases the applicability of these models.

3.4. How much coral habitat is in the shallow reefs of the Capricorn Bunker Group?

Accepting the error inherent in each map product created for this study of the shallow CBG reefs (overall accuracies: 59.5% geomorphic zonation, 32.8% benthic cover type *Reef Top*, and 48.7% predicted dominant coral type *Reef Slope*), the total reef area, area suitable for coral growth, and predicted area of coral can be calculated. These calculations could not be derived from existing habitat maps.

From the detail in the geomorphic map the total reef area of the CBG

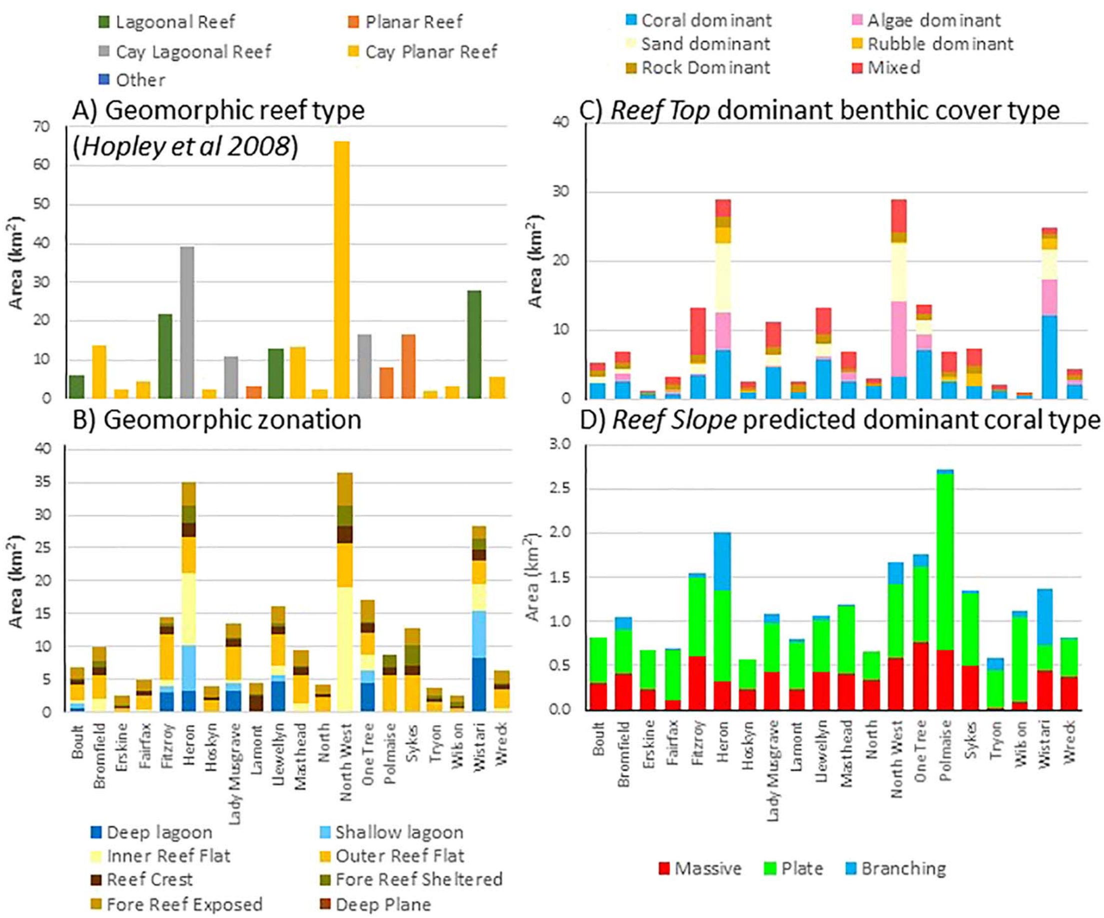

Fig. 7. Comparison of data extracted from (A) an existing geomorphic reef type map for the GBR (Hopley et al., 2008), with that from the maps created in this study: (B) geomorphic zonation, (C) dominant benthic cover type for Reef Top, and (D) predicted dominant coral type for Reef Slope.

can be calculated as 245 km^2. 152 km^2 of this area represents consolidated substrate suitable for coral growth (as determined by calculation of zonal areas for Outer Reef Flat, Reef Crest, Fore Reef Sheltered and Fore Reef Exposed). Within this 152 km^2, and using the map for dominant benthic cover *Reef Top*, 64 km^2 of suitable coral substrate on the *Reef Top* was mapped as coral dominant. Similarly, but using the predicted dominant coral type map for the *Reef Slope*, 24 km^2 of the *Reef Slope* was predicted as habitat dominated by massive, plate or branching coral forms. Together, this represents a total of 88 km^2 of coral on the CBG, with a further 64 km^2 identified as substrate suitable for coral growth.

The output spatial data sets from this study are an advancement for the monitoring and management of the CBG. If the combined ecological modelling and remote sensing techniques developed in this study were applied to the shallow reefs of a larger reef system such as the GBR, a similar comprehensive characterisation as presented for the CBG could be conducted providing a wealth of quantitative spatial information for monitoring and management.

4. Conclusions

This study has demonstrated that maps for geomorphic zonation (Figs. 4, 8h), dominant benthic cover type (Figs. 5, 8i) and predicted dominant coral type (Figs. 6, 8j) can be created for large coral reef systems (> 2000 km^2) using a novel semi-automated approach that combines eco-morphological modelling and mapping, field data and globally accessible image data sets. Further, ecological products that were generated as part of this approach include the input data sets that describe habitat variables (such as water depth (Fig. 8f), and wave exposure parameters (such as significant wave height (Fig. 8g). The approach is unique as it integrates remote sensing data sets, physical characteristics, geo-ecological rule sets and ecological modelling instead of relying upon manual delineation (Andréfouët et al., 2006) or object-based analysis (Phinn et al., 2012; Roelfsema et al., 2013) of remote sensing imagery.

Application of the methods developed in this work to the shallow offshore reefs of the full extent of the GBR would require further development to ensure that they were applicable and to determine what modifications would be required. The resulting modified method would enable informed conservation efforts and improve management policy. These map products would provide input into many facets of GBR management and monitoring including but not limited to: assessment of reef habitat suitable for coral growth; indicate composition of the reef slopes; provide aid for the design of monitoring programs, e.g. bleaching and COTS control; enable modelling of reef biophysical properties; and provide a full assessment of dominant benthic types on the reef tops.

Future work should focus on applying the approaches developed to the full extent of the GBR, or to other large reef systems globally. Additionally, the methodology should be developed further to include application to coastal turbid reefs and deeper waters. In these areas, optical remote sensing based approaches are limited, and were not addressed in this study.

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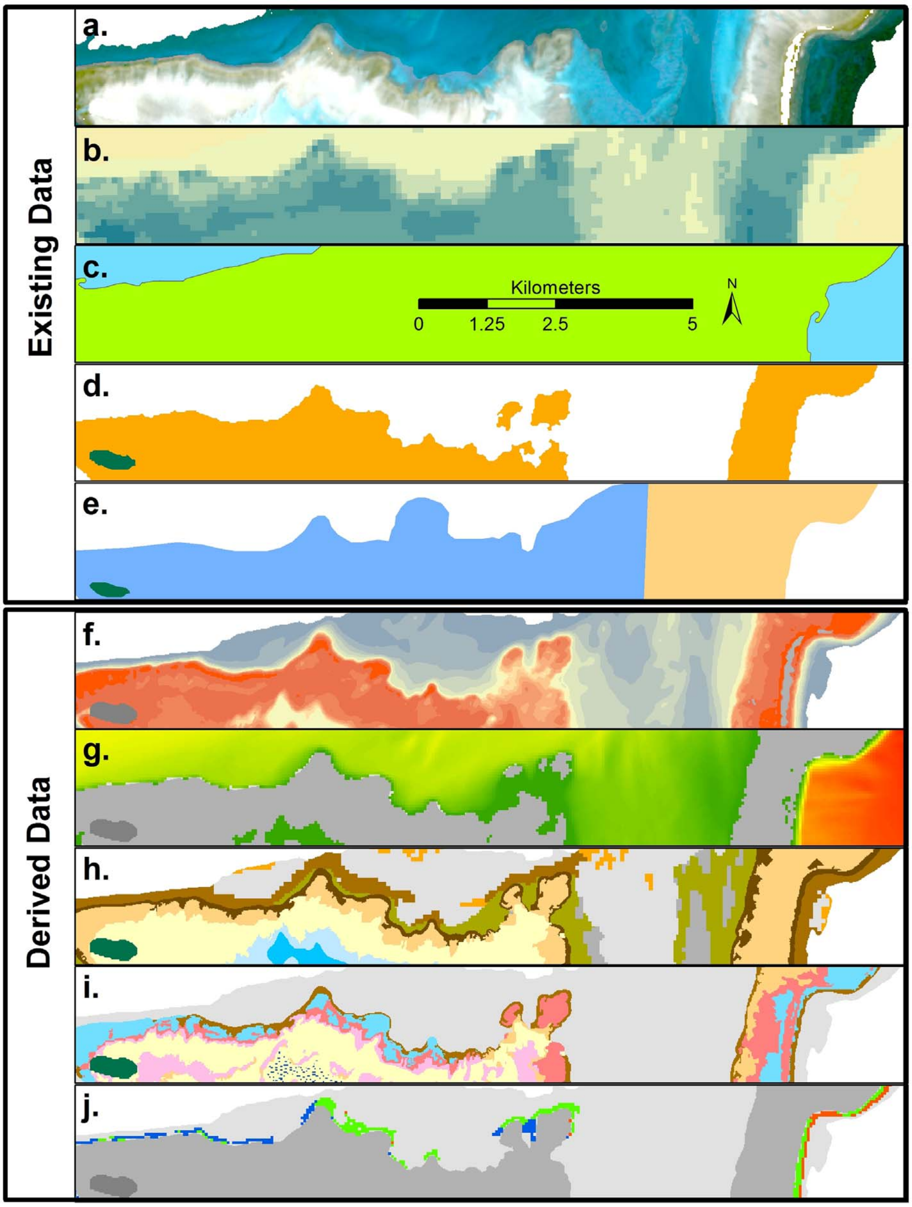

Fig. 8. Example of the thematic and spatial benthic information available for the GBR and for a subset of the CBG. Existing data describing benthic habitat for the whole of the GBR: (a) Landsat 8 OLI (USGS), (b) Water depth 100 m grid (Beaman, 2010), (c) Bioregional map (Kerrigan et al., 2010), (d) Dry reef (Lewis et al., 2003), and (e) Geomorphic reef type (Hopley et al., 2008). Colours represent the maximum amount of detail provided by each information layer. Derived data from this project describing the benthic habitat of the CBG: (f) water depth 1 m grid, (g) significant wave height, (h) geomorphic zonation map, (i) dominant cover type map for the *Reef Top*, and (j) predicted dominant coral type map for the *Reef Slope*. Colours present in each of the figures represent the different characteristics mapped. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rse.2018.02.005.

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