REPORT

Habitat maps to enhance monitoring and management of the Great Barrier Reef

Chris M. Roelfsema[1] · Eva M. Kovacs[1] · Juan Carlos Ortiz[2,3] · David P. Callaghan[4] ·
Karlo Hock[3] · Mathieu Mongin[5] · Kasper Johansen[1,9] · Peter J. Mumby[3] ·
Magnus Wettle[6] · Mike Ronan[7] · Petra Lundgren[8] · Emma V. Kennedy[1] ·
Stuart R. Phinn[1]

Abstract The Great Barrier Reef (GBR) is of immense biological, cultural and economic importance, but has also rapidly degraded over the last 30 years. Improved spatial information on reef geomorphic zonation and benthic cover type (including coral type) is critical to support scientific work to understand how the GBR is changing, and to support resource management decisions that enable conservation of the reef and its essential ecosystem services. Yet, no comprehensive maps exist that detail the geomorphic zonation or benthic cover for the GBR's $\sim$ 3000 reefs. This study presents three new types of shallow reef maps for 237 reefs in the central Cairns Management Region of the GBR Marine Park (GBRMP), explores how the detailed habitat maps created compared to current maps and posits how the new maps may support and refine current critical key science outputs and management challenges. *Geomorphic Zonation*, *Benthic Cover* and *Coral Type* habitat maps were created using a unique combined object-based image analysis and ecological modelling approach that incorporated satellite imagery, limited field data and key reef physical attributes (depth, slope, waves) using a previously peer-reviewed mapping approach developed for the Capricorn Bunker Group reefs, Southern GBR. The mapping approach was consistent and repeatable, suggesting applicability to mapping all 3000 reefs in the GBRMP. Compared to existing maps that only outline each reef, the increase in detail provided by these new habitat maps enabled discrete characterisation of each reef's geomorphology and benthic composition. With the new habitat maps, areas within each reef can be identified as either coral habitat or not coral habitat. This has not been possible previously. As such, a model of coral ecological and biophysical processes that depends on bottom reflectance of sand and coral areas can be fine-tuned. Similarly, for reef restoration, nursery structures are commonly placed in non-coral habitats, and/or coral larvae are dispersed in areas of known coral habitat. The new habitat maps presented permit more accurate identification of these areas such that restoration projects can be targeted more effectively. These findings confirm the need to now apply this mapping approach to the full extent of the GBR.

Topic Editor Stuart Sandin

✉ Chris M. Roelfsema
   c.roelfsema@uq.edu.au

1 Remote Sensing Research Centre, School of Earth and Environmental Sciences, University of Queensland, Brisbane, QLD 4072, Australia

2 Australian Institute of Marine Science, Townsville, Australia

3 Marine Spatial Ecology Lab, School of Biological Sciences, University of Queensland, Brisbane, QLD 4072, Australia

4 School of Civil Engineering, University of Queensland, Brisbane, QLD, Australia

5 CSIRO Oceans and Atmosphere, Hobart, TAS, Australia

6 EOMAP GmbH & Co. KG Head Office, Seefeld, Germany

7 Department of Environment and Heritage Protection, Brisbane, Australia

8 Great Barrier Reef Foundation, Brisbane, Australia

9 Hydrology, Agriculture and Land Observation Group, Water Desalination and Reuse Center, King Abdullah University of Science and Technology, Thuwal 23955-6900, Kingdom of Saudi Arabia

Introduction

Monitoring and management of large (> 10,000 km²) coral reef marine parks such as those in the Great Barrier Reef (GBR; 345,000 km²), the Meso-American Barrier Reef System (32,272 km²) and the Hawaiian Islands (360,000 km²) is challenging because of their spatial extent and geographic remoteness. The Great Barrier Reef Marine Park (GBRMP) comprises an estimated 3000 shallow (0–20 m) reefs that stretch along 2300 km of coastline (Lewis et al. 2003) with some reefs more than 200 km from land, making access difficult. Current GBRMP monitoring involves intensive collection of environmental and benthic field data over representative but widely distributed sites and includes programs implemented by the marine park authority (GBRMPA) (Beeden et al. 2015), the Australian Institute of Marine Science (AIMS) (De'ath et al. 2012), universities (González-Rivero et al. 2016; Hughes et al. 2017a) and citizen science organisations (Beeden et al. 2014; Done et al. 2017; Marshall et al. 2012). However, the amount of effort required to collect detailed benthic information over such large extents results in a trade-off between resolution and spatial coverage (Mumby et al. 2001). Detailed field data collection for each reef is ideal, but often not possible due to the high cost of field work/ staff and the extent of the area being mapped. Whilst observations provide detailed characterisation of the benthos of each of the field sites, they are often distributed over thousands of kilometres of a reef system and are therefore interspersed with large spatial information gaps in between (Beeden et al. 2014; De'ath et al. 2012; González-Rivero et al. 2016).

Good management and conservation of ecosystems relies on appropriate spatial information that describes the environment (Sattler and Williams 1999; Zann et al. 2017). Explicit spatial information is most commonly characterised by data describing the extent, distribution and function of the main natural features (attributes) making up an environment (Aquatic Ecosystems Task Group 2012).This is paramount for ecosystem-based management decisions as is seen for terrestrial-based systems (Kenchington and Hutchings 2012; Sattler and Williams 1999). For many marine systems, detailed habitat maps are often limited to relatively small areal extents (reefs and surrounding waters < 1000 km²) due to the difficulties associated with collecting data in order to characterise complex submerged environments (Madin and Madin 2015; Mumby et al. 2001). Our ability to characterise larger areas of coral reef in greater detail has been enhanced by an expanding availability of Earth observation sensors with various spatial, spectral and temporal resolutions (Hedley et al. 2016); improved methods for the derivation of reliable

water depth information from satellite imagery (Hamylton et al. 2015; Traganos et al. 2018b); and a growing capability for integrating eco-geomorphological object-based modelling approaches where attribute classification is combined with modelling of the distribution of the attributes (Purkis et al. 2019; Roelfsema et al. 2018). Despite this, these tools are yet to be adapted and applied to large reef systems, for integration into management policies, to enable determination of surface areas of reefs impacted. The airborne visual census of coral bleaching in each of 1998, 2016 and 2017 only provided information about which reefs were bleached. The use of detailed habitat maps covering the full extent of the reef system would allow for a better inventory of what was present prior to the bleaching event. And, following the bleaching, these data sets in combination with airborne and/or in-water field observations would provide a more accurate approximation of how much of the reef was impacted.

Like terrestrial ecosystems, spatial data for coral reefs can be acquired at different scales. Geomorphic zonation could be represented by, for example, reef slope, reef crest or reef flat, to provide information on coral reef structure and function, whilst benthic composition provides finer scale (10's m–100's m) information regarding seafloor cover type or coral type (Roelfsema et al. 2018). Detailed habitat maps of geomorphic zonation and benthic cover type across the GBR would provide information to enable science and management to answer more refined questions and support informed decision-making for conservation and resource issues across broader areas (Mumby et al. 2014).

The GBR has recently (2015–2018) been exposed to devastating anthropogenic and environmental disturbances such as cyclones (Puotinen et al. 2016), extreme warming events (Hughes et al. 2017b) and widespread population outbreaks of coral-eating crown-of-thorns starfish (CoTS) (Babcock et al. 2016). The incidence, extent and severity of disturbances are predicted to increase as the climate changes (Hughes et al. 2017a). During the coral bleaching event from 2016 to 2017, the central GBR experienced losses of up to 50% coral cover as determined by aerial and field surveys (Hughes et al. 2017a). Extent of the damage was estimated by extrapolating field observations to the current known geographic extent of the affected reefs, and/ or biophysical parameters to determine the proportion of reef area affected (Hughes et al. 2017b). A similar method is used for the development of GBRMPA reef management policies. All these models rely heavily on existing knowledge of reef extent and benthic cover type. However, the lack of spatial information particularly on benthic cover has limited the ability to derive estimates of the total area or amount of coral affected. For example, the eReefs platform uses hydrodynamics and bio-geochemical

properties to model water quality in three dimensions throughout the GBR (Baird et al. 2016). Increasingly, models of coral larval dispersal are used to identify key source reefs that play an exceptionally strong role in promoting coral recovery after mass bleaching and other disturbances (Hock et al. 2017). But these management and research decisions are limited by the level of detail and extent of the habitat maps available. As such, the outcomes of these decisions vary depending on the level of thematic detail of the input maps, the extent over which this detailed information is provided, the associated mapping accuracy, the area of interest and the question being asked.

The aim of this study was to produce habitat maps for a significant portion of GBR shallow reefs at a level of detail not previously available and to demonstrate how these spatially explicit maps can be used to support and refine key science outputs and management questions and decisions by examining three pertinent applications.

Recently, an ecological modelling and object-based approach has been used to successfully create detailed habitat maps of 20 reefs in the Capricorn Bunker Group, Southern GBR. This methodology generated detailed benthic information at a resolution needed for sophisticated decision-making (Roelfsema et al. 2018). In this study, we have built our mapping approach on our previous habitat mapping of the Capricorn Bunker Group that included 20 reefs within an area of $\sim$ 400 km^2, to characterise 237 shallow offshore reefs (total reef area of approx. 2000 km^2) from Innisfail to Lizard Island, known as the Cairns Management Region (encompassing a total area of approx. 37,000 km^2). Detailed habitat maps were created for geomorphic zonation and benthic composition (bottom type and coral type) through adaptation of the Capricorn Bunker Group approach (Roelfsema et al. 2018) and compared to reef area estimates obtained from existing maps of reef extent and geomorphic reef type. To assess how the detailed habitat information provided in the new maps could improve coral reef science, monitoring and management, they were incorporated into two GBR-specific conceptual assessments of key monitoring and management directives: (1) understanding coral ecological and biophysical processes, and (2) reef restoration.

Materials and methods

Study location

Two-hundred and thirty seven shallow offshore reefs of the Cairns Management Region (excluding nearshore fringing reefs) were targeted as part of this study (Fig. 1a). These shallow reefs rise from a 30-m deep plateau which descends to hundreds of meters off the continental shelf on the

eastern side of the barrier reefs. The reefs experience a 1–2 m tidal range, whilst the prevailing wind direction is known to be east–south–east resulting in higher waves on the offshore reefs. This study will generate more detailed parameters for each individual reef. The average reef size was 6.33 km^2, each characterised by a south/south-eastern-facing exposed reef front protecting a reef flat and back reef behind (Fig. 1b). Each reef was visible to a depth of 20 m lowest astronomical tide (LAT) using optical remote sensing imagery.

### Mapping geomorphic zonation, benthic cover and coral type

To map the geomorphic zonation and benthic composition in the Cairns Management Region, we modified an approach used to map 20 reefs in the Capricorn Bunker group (Fig. 1a) (Roelfsema et al. 2018). Although the Cairns Management Region is much larger than that of the Capricorn Bunker Group ($\sim$ 25,000 km^2 and $\sim$ 400 km^2, respectively), the reef structures in either location consist predominantly of platform-type reefs, including some coral cays and lagoons. Modifications to the methodology that were required for adaptation to the larger 237 reef area mapped in this study are documented below.

Input data

Satellite products Sub-surface and seafloor reflectance as well as tide-corrected water depth to mean surface level (MSL) were derived from a mosaic of 33 Landsat 8 Operational Land Imager (OLI) scenes, at a 15 m × 15 m resolution, calculated using the modular inversion and processing (MIP) system that has been tested and validated worldwide (Cerdeira-Estrada et al. 2012; EOMAP 2016; Heege et al. 2004; Kobryn et al. 2013; Ohlendorf et al. 2011; Siermann et al. 2014).

Waves Wave climate descriptors (18 different wave parameters) were determined using numerical modelling of wave generation and propagation throughout the Cairns Management Region, using a simulating waves nearshore (SWAN) model (Callaghan et al. 2015), and near-reef transformations using local wind data and Landsat 8 OLI-derived water depth. See Callaghan et al. (2015) for detailed methods and a description of the 18 output wave climate descriptors.

Field data Field data (Fig. 1b) were collected and used to derive benthic cover type, coral type and depth. Benthic information including coral type was extracted from geo-referenced photoquadrats, representing 1 m × 1 m of the seafloor, collected along transects located on the reef top
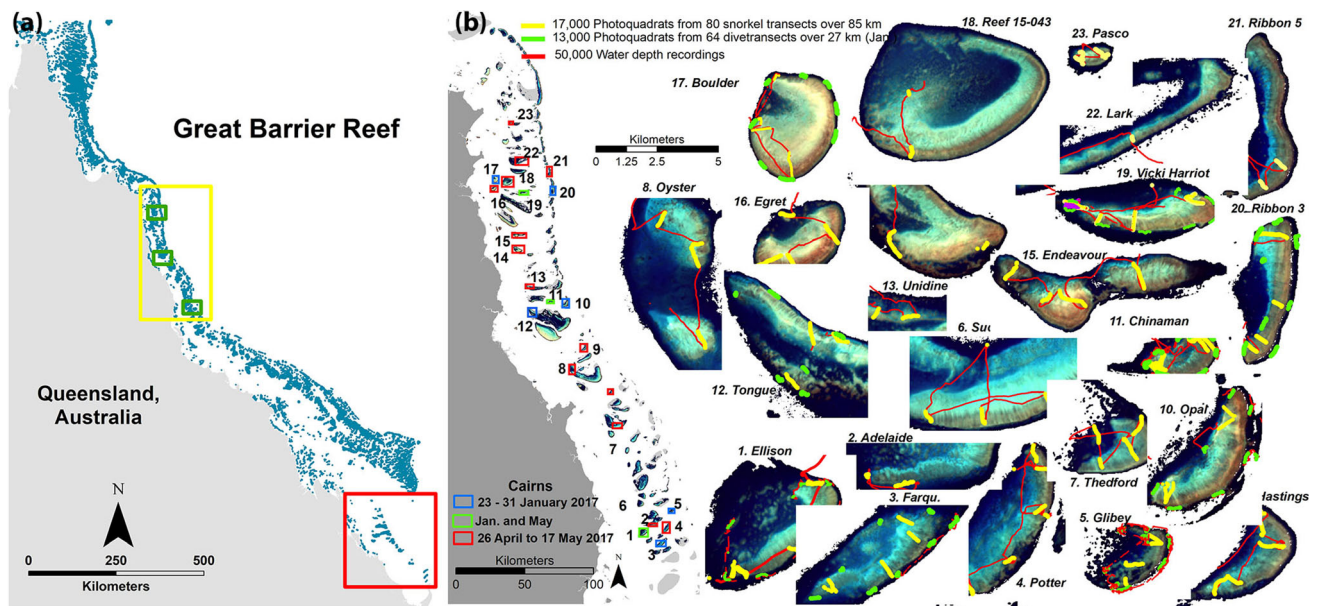
Fig. 1 Study site. **a** Great Barrier Reef, Australia, indicating the Cairns Management Region (this study; yellow box), the training areas used to calibrate the mapping approach (green boxes), and the Capricorn Bunker Group, Southern GBR region (Roelfsema et al. 2018) are indicated, and **b** locations of the field data collected within the Cairns Management Region, with snorkel (yellow), dive (green) and bathymetry (red) transects overlaid on the 23 reefs sampled

(< 3 m mean sea level (MSL)) and the reef slope (approx. 5 m MSL) for 23 reefs of the Cairns Management Region between January and May 2017 (Fig. 1a; refer to Roelfsema and Phinn (2010) for field methodology and Roelfsema et al. (2017) for access to the data). Briefly, a snorkeller or diver traversed the designated transect towing a GPS on a float, taking photoquadrat images of the benthos every 2–4 m. Time synchronisation of the camera and GPS enabled geolocation of the captured images. For reef top assessment, 17,000 photoquadrats were collected along 80 snorkel transects (each 500–1000 m in length), with a total length of 85 km. For the reef slope assessment, 13,000 photoquadrats along 64 dive transects (each 400–600 m in length) with a total length of 27 km were collected.

Benthic community composition estimates were derived from photoquadrats automatically using CoralNet (Beijbom et al. 2015), where in the previous study this was done manually. Training and validation of the automated annotator were performed using a GBR-specific category scheme (González-Rivero et al. 2016). For this study, 50 random points were overlaid per photoquadrat with a random selection of approximately 5% of all photoquadrats collected that were used to train the annotator and approximately 2.5% that were used to validate the machine learning approach. For simplification of the mapping process, the categories were generalised to coral growth form (massive, branching and plate), algae, seagrass, rock, rubble, sand and other.

Field-derived water depth Measurements (n = 50,000) were collected on the same reefs as the benthic surveys using a Garmin GPS echo sounder 550C (accuracy ± 5 m; Fig. 1b) and corrected with MSL [using the tidal model driver (TMD) MATLAB toolbox model 7.2; (Egbert and Erofeeva 2002)], to validate the water depth maps derived from the Landsat 8 OLI imagery.

Geomorphic zonation and benthic cover mapping approach

Geomorphic Zonation and *Benthic Cover* maps were generated from object-based analysis (OBA) using the Trimble eCognition 9.3 software. OBA 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 membership rule set (Blaschke 2010). These membership rules assign classes to segments based on physical attributes, the colour and texture of image pixels, and ecological neighbourhood relationships. Neighbourhood relationships relate to properties of adjacency and enclosure between mapping classes based on ecology (Table 1).

In this study, a hierarchical classification rule set was first applied for the geomorphic zonation followed by benthic composition based on a previous developed rule set for mapping the Capricorn Bunker Group (Roelfsema et al 2018) and using the following spatial data layers as input: sub-surface reflectance of the Landsat 8 OLI image mosaic

Table 1 A summary of geomorphic categories and the core attributes and thresholds used to assign labels to the segmented satellite imagery using the object-based analysis approach adjusted from Roelfsema et al. (2018)

Level	Mapping category	Neighbourhood relationship (s)	Depth (MSL; m)	Slope (°)	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 to "not reef top"	< 0.75 m	0–10	n.a	Low B + G + R
	Outer flat	Not: inner flat, reef crest. Adjacent to reef crest	< 0.75 m	0–5	n.a	Med B + G + R
	Inner flat	Adjacent to outer flat	< 0.75 m	0–5	n.a	High B + G + R
	Shallow lagoon	High brightness level	0.5–0.75 m	0–5	n.a	High B + G + R
	Patch reefs	Adjacent to back reef sheltered; area > 10 pxl	3–10 m	n.a	n.a	n.a
	Open complex lagoon	Back reef sheltered with relative distance to patch reef < 1050 m	3–10 m	n.a	n.a	n.a
	Plateau 3–10 m	Plane	3–10 m	< 10	n.a	n.a
Not reef top	Fore reef exposed	Adjacent to reef crest or inner/outer flat	0.75–10 m	5–90	> 2 m	n.a
	Back reef sheltered	Adjacent to reef crest	0.75–10 m	5–90	< 2 m	n.a
	Deep slopes	Dependent upon slope attribute	10–20 m	> 10	n.a	n.a
	Deep plateau	Dependent upon depth attribute	10–20 m	0–5	n.a	n.a
	Deep lagoon	Surrounded by "reef top"	35–15 m	0–90	n.a	n.a

Sub-surface reflectance bands: *B* blue, *G* green and *R* red

and physical attributes such as satellite image-derived water depth, slope (calculated from water depth) and significant wave height.

The Capricorn Bunker Group rule set was further developed in this study by applying and adjusting it for three subsets of the 237 reefs within the Cairns Management Region. Each subset included four to five reefs that were visited in the field campaign (Fig. 1a; green boxes) and differentiated according to reef type, geomorphic zone type and benthic cover type. In order for the software to process this large reef area, the rule set was sequentially applied to each of the 237 reefs of the Cairns Management Region via an iterative batch process. On completion, the individual reef maps were mosaicked into a single seamless map.

Membership rules for the geomorphic zonation were based on thresholds for physical attributes, sub-surface reflectance values and neighbourhood relationships. The sub-surface reflectance was considered a proxy for consolidated (dark, e.g. reef matrix, coral, algae) or

unconsolidated material (bright, e.g. sand), as previously described in Roelfsema et al. (2018). See Table 1f or a summarised description of the geomorphic classification relationship rules.

Benthic cover type was determined only for geomorphic zones shallower than 3 m MSL. In combination with field data, rule sets were refined for texture and brightness to label segments with a dominant benthic cover class (coral/algae, sand, rock, rubble, other). The 15 m × 15 m resolution of the input imagery did not enable confidence in assignment of a benthic cover type for features in deeper waters.

Predictive coral-type modelling

The *Coral Type* habitat map was modelled for reef slope areas only as compared to the reef top, the reef slope has a greater range of wave energies. Coral type was modelled independently using four steps. It included the use of boosted regression trees to predict the relative abundance

of each coral-type habitat (branching, plate and massive) in each image pixel using empirical ecological relationships (Clarke et al. 2014; Madin et al. 2008). This was based on the wave climate for the consolidated areas of the leeward and windward slopes to a depth of 10 m as deeper depth had less predictive power. Additionally, to develop the relationships, all field data collected on the slopes in the Cairns Management Region were used in addition to that collected on the slope at Heron Island (Capricorn Bunker Group, Southern GBR). The data were randomly split such that 75% of the field data were used for the development of the empirical ecological relationships, whilst the remaining 25% of the field data were used to validate the final output.

Step 1: Derivation of the input parameters for ecological model development The major coral types were extracted from the field data and were grouped for each sample point according to three major coral morphologies (plate, branching and massive). New data points were distributed 30 m apart along the 5-m-depth contour of the reef slope, and 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 photographs that fell within the buffer) were aggregated to represent the relative abundance of each major coral type at that point (plate, branching or massive). Subsequently, using a spatial join operation, each buffered point was assigned a single value for each of the 18 wave parameters and a degree of slope associated with their respective locations.

Step 2: Prediction of coral type Using the aggregated field data, all possible combinations of the 18 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 was determined for each of the branching, massive and plate coral types.

Step 4: Generation of a coral type map The predicted *relative abundance* values for each coral type were standardised. For each reef slope pixel within the 2.5–10 m MSL 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 dominant *coral type* was determined for each reef slope pixel based on these standardised predicted relative abundance values, and subsequently, each reef slope pixel was assigned a category of branching dominant, massive dominant or plate dominant.

Qualitative and quantitative validation

A point-based quantitative assessment was performed as described previously (Roelfsema et al. 2018) where a confusion matrix was used to determine map accuracy, using the field data acquired for this study area (validation data: *Geomorphic Zonation*, n = 174; *Benthic Cover*, n = 14,366; *Coral Type*, n = 193; Supplementary Table S1). Additionally, a qualitative assessment assigned confidence levels for the input data and processing steps. These confidence levels were determined previously for the Capricorn Bunker Group and were assumed the same for this study (Roelfsema et al. 2018) (Supplementary Tables S2 and S3).

Comparison of habitat information with existing maps

To assess the increased spatial and thematic detail that the habitat maps generated in this study provided, they were contrasted with existing maps of reef extent (Lewis et al. 2003) and geomorphic reef type (Hopley et al. 2008). These two existing maps currently provide the highest level of habitat detail available for each of the 3000 individual GBR reefs. The reef extent map shows a simple outline for each reef, whilst the geomorphic reef-type map shows the location of each reef and its assigned geomorphic reef type, e.g. crescent, lagoonal or platform reef. Both map products are currently used for management (e.g. the 2003 marine park zonation plan (GBRMPA 2004)), and for the assessment of environmental impacts through modelling (e.g. eReefs (Baird et al. 2016)).

The following estimations of reef area were calculated for each of the specified map layers:

1. Reef extent map (Lewis et al. 2003): The described reef area above an unknown depth;
2. Geomorphic reef-type map (Hopley et al. 2008): The described reef area above an unknown depth;
3. *Geomorphic Zonation* map (this study):

   a. The area of each geomorphic zone above 20 m, as this was the maximum depth this study could map
   b. The area of each geomorphic zone above 10 m, as this was the depth that was the closest representation of the currently available reef outline (Lewis et al. 2003)

c. The area of geomorphic zones above 10 m that are predominantly hard substrate (windward reef slope, reef crest, outer reef flat, small reefs, patch reefs), as these are considered areas where coral could settle or where coral is present, at a depth that is the closest representation to the current reef outline (Lewis et al. 2003)

4. *Benthic Cover* map (this study): The area to a depth of 3 m where the dominant benthic cover type was mapped as coral, algae or rock (hard substrate);

5. *Coral Type* map (this study): An estimate of the amount of reef habitat that is favourable for the dominance of one of three different coral types (massive, platy or branching).

We assumed that consolidated reef surface (hard substrate) provides a structure that is suitable to support coral development and growth (Madin and Madin 2015).

Potential applications: how can detailed habitat information improve coral reef science, monitoring and management?

Two applications were used to explore the potential of the increased habitat information in the maps generated in this study to influence research and management outcomes. The proposed applications were: (1) understanding coral ecological and biophysical properties on the GBR (eReefs Baird et al. 2016); and (2) evaluation of potential sites for reef

restoration. Each of these activities relies on reef habitat spatial data as a basis: a habitat map is used to assign bottom reflectance values to specific bottom types to inform a physics-based model of coral ecological and biophysical processes; for reef restoration efforts, a habitat map permits identification of sheltered sandy areas or areas of potential coral habitat for nursery frame situation and larvae dispersal, respectively. We discuss how (a) improved thematic detail, (b) improved detail of mapped habitat complexity, and (c) a broader mapped spatial extent could influence the understanding of the biophysical process in question and therefore improve the accuracy and reliability of each application.

Results and discussion

Mapping geomorphic zonation, benthic cover and coral-type habitat

Habitat information, including *Geomorphic Zonation*, *Benthic Cover* and *Coral Type*, was mapped for 237 reefs in the study area (Fig. 2).

In addition to the habitat maps, additional information layers regarding reef physical attributes are now available for each individual reef for the full extent of the study area. These include a normalised sub-surface reflectance Landsat 8 OLI mosaic, water depth, slope and wave hindcast parameters. (Physical attribute map examples are shown in Supplementary Figure S1.)
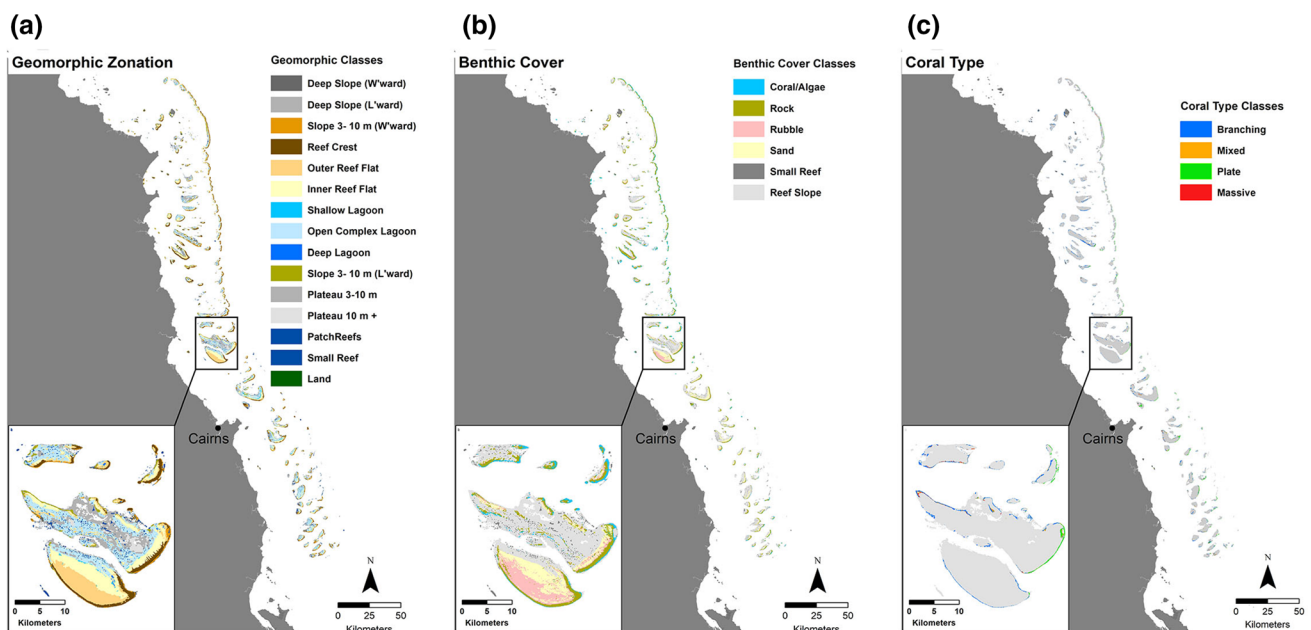
Fig. 2 Maps representing **a** *Geomorphic Zonation*, **b** *Benthic Cover* and **c** *Coral Type* for the 237 reefs in the Cairns Management Region, Great Barrier Reef, Australia. These maps were created by adjustment of a previously developed approach (Roelfsema et al. 2018) and used satellite imagery, field data and physical attributes such as depth, slope and wave attributes with object-based analysis and ecological modelling routines

A quantitative validation of the different maps resulted in an overall accuracy for the *Geomorphic Zonation* map of 56.1%, 49.7% for the *Benthic Cover* map and 64.2% for the *Coral Type* habitat map (Supplementary Table S1). These accuracy levels are acceptable considering the extent of the study area (approx. 37,000 km^2), the number of reefs that were consistently mapped (237) and the level of thematic detail provided by the *Geomorphic Zonation* map, *Benthic Cover* map and *Coral Type* habitat maps having 12, five and four categories, respectively (Roelfsema and Phinn 2013). As such, the level of thematic detail has increased, providing information within the current reef outline (Lewis et al. 2003) about geomorphic zonation, benthic cover type and coral type. In comparison, Purkis et al. (2019) mapped 65,000 km^2 of reef at 70–90% accuracy using field data collected for each reef area to be mapped in conjunction with satellite imagery of higher resolution than that used in this study. Additionally, the qualitative assessment of the approach and each of the data types used was considered the same as reported in the previous study. (For more details, refer to Roelfsema et al. 2018).

The unique mapping approach presented uses limited field data, is repeatable and has been developed and implemented to consistently map a large reef system, 237 reefs, a total reef area of approximately 2000 km^2, and representing a large proportion of the 3000 shallow offshore reefs ($\sim$ 25,000 km^2) of the GBR. Freely available Landsat 8 OLI satellite imagery formed the basis for the derivation of the physical attributes and the subsequent mapping and modelling. Therefore, this mapping approach paves the way for the creation of habitat maps for the full extent of the GBR or other large reef systems, which are covered by Landsat OLI 8 imagery. Application of this approach to a larger reef system would require an additional, relatively small set of calibration and validation field data for a subset of carefully selected representative reefs distributed across the chosen reef system. The sampling design for reference data collection would vary according to the complexity and extent of the reef system to be mapped and would be a trade-off between what is achievable whilst characterising the representative reef regions within the system (Congalton and Green 1999; Roelfsema and Phinn 2013; Stehman 2001; Stehman and Czaplewski 1998).

Output maps and mapping methodologies are expected to improve with higher-resolution sensor types, such as the freely available Sentinel-2 satellite data. Compared to Landsat 8 OLI (30 m $\times$ 30 m), Sentinel-2 has global coverage, a similar spectral resolution and signal-to-noise ratio, but with a higher spatial (10 m $\times$ 10 m pixels) and temporal resolution (five-day revisit time). Sentinel-2′s spatial resolution would further increase the detail of the habitat maps and/or physical attributes, spatially and thematically. Additionally, the more frequent temporal resolution may assist with attaining imagery with lower tides, smaller waves and low cloud cover (Hedley et al. 2018).

The approach differentiates itself from other published mapping approaches for large reef systems as it is repeatable and consistent over a large extent. Previous mapping of large reef systems included manual delineation of individual reefs by experts using the Landsat satellite image archive to map geomorphic zonation globally (Andréfouët et al. 2006); intensive field campaigns combined with object-based analysis of high spatial resolution remote sensing imagery, to map geomorphic zonation and dominant benthic cover level for selected reef regions over a 10-year period (Purkis et al. 2019); manual digitisation of high-resolution imagery combined with a pixel-based mapping approach to map geomorphic zonation and dominant benthic cover-type level for selected US territory reef regions over a 10-year period (Monaco et al. 2012) or cloud-based processing which potentially provides the option to overcome global mapping efforts relying on manual digitisation and/or large field-based data sets (Traganos et al. 2018a).

Comparison of habitat information with existing maps

This study provided detailed thematic information for each individual reef of the Cairns Management Region through the mapping of reef habitat at three hierarchical levels: (1) *Geomorphic Zonation* (12 mapping categories), (2) *Benthic Cover* (five mapping categories) and (3) *Coral Type* (four mapping categories). Additionally as part of the mapping process, data layers for physical attributes were produced at the same extent and level of spatial detail for the first time. (Refer to Materials and Methods; water depth, slope and 18 wave parameters; Supplementary Figure S1.) In contrast, the existing reef extent map described gross reef outline to an unknown depth (Fig. 3a) and only defined geomorphic reef type (e.g. reef patch and cay planar reef), whilst the existing geomorphic reef-type map assigned a label to each reef outline that described the gross reef type (Fig. 3b). Both of the existing habitat maps display lower thematic detail as a single-area attribute was assigned to reefs in the reef extent layer (Lewis et al. 2003), and only ten categories were assigned in the geomorphic reef-type layer (Hopley et al. 2008). Neither of these existing map layers provided information on the benthic cover type and/or coral type within the outline of the reef.

However, the *Geomorphic Zonation* map created in this study (Fig. 3c) provides clear delineation of reef zones such that the reef area to a known depth (Fig. 3d), i.e. 10 m which was previously unknown, can be identified. This can

Fig. 3 An example around Tongue reef that shows how the new higher spatial and thematic resolution habitat maps created in this study refine the existing description of reef habitat. **a** Landsat 8 OLI satellite imagery overlaid with an outline of the existing reef extent layer to unknown depth (Lewis et al. 2003), **b** corresponding region of reef area (unknown depth) as described by the existing geomorphic reef-type map ((Hopley et al. 2008); orange = planar reef; pink = reef patches; green = Crescentic reef), **c** corresponding region of the *Geomorphic Zonation* map to a depth of 20 m (this study), **d** corresponding region of reef area to a 10 m depth identified from the *Geomorphic Zonation* map, **e** corresponding region of potential coral habitat (reef crest, windward reef slope, outer reef flat, small reef, patch reef) identified from the *Geomorphic Zonation* map and **f** corresponding areas above 10 m depth mapped as a coral category identified from the *Benthic Cover* map. Each of **a** through **f** is overlaid with an outline of the existing reef extent layer (Lewis et al. 2003)
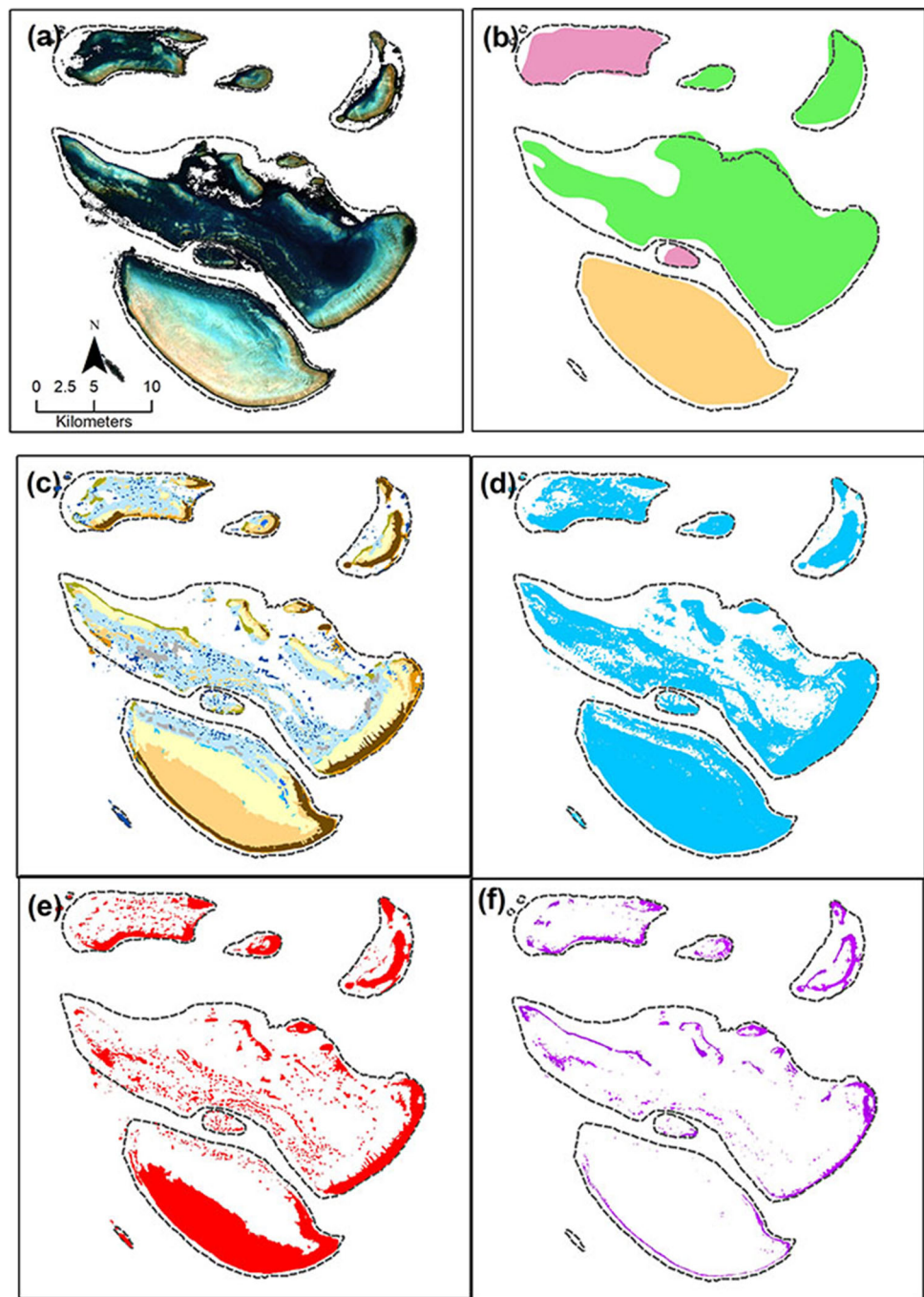

be further refined to represent zones, which consist predominantly of hard substrate, i.e. areas of potential coral habitat (Fig. 3e). Subsequently, in conjunction with the *Benthic Cover* and *Coral Type* maps, the area of potential coral habitat (areas where coral could settle or where coral is present; Fig. 3e) can be identified (Fig. 3f).

From this, we were able to estimate the area of specific regions of the shallow Cairns Management Region reefs (Fig. 4). From the existing data layers, the total reef extent to unknown depth was calculated to be 3164 km² (Lewis et al. 2003), whilst total reef area by geomorphic reef type was calculated to be 2489 km² (Hopley et al. 2008). In contrast, the total reef area above 20 m mapped for the Cairns Management Region reefs in this study was calculated to be 1984 km², and the total reef area above 10 m was 1685 km².

Due to the finer spatial and thematic resolution habitat information in the maps created in this study, a more refined determination of potential coral habitat can be made (Fig. 4a) where previously this could only be based on a
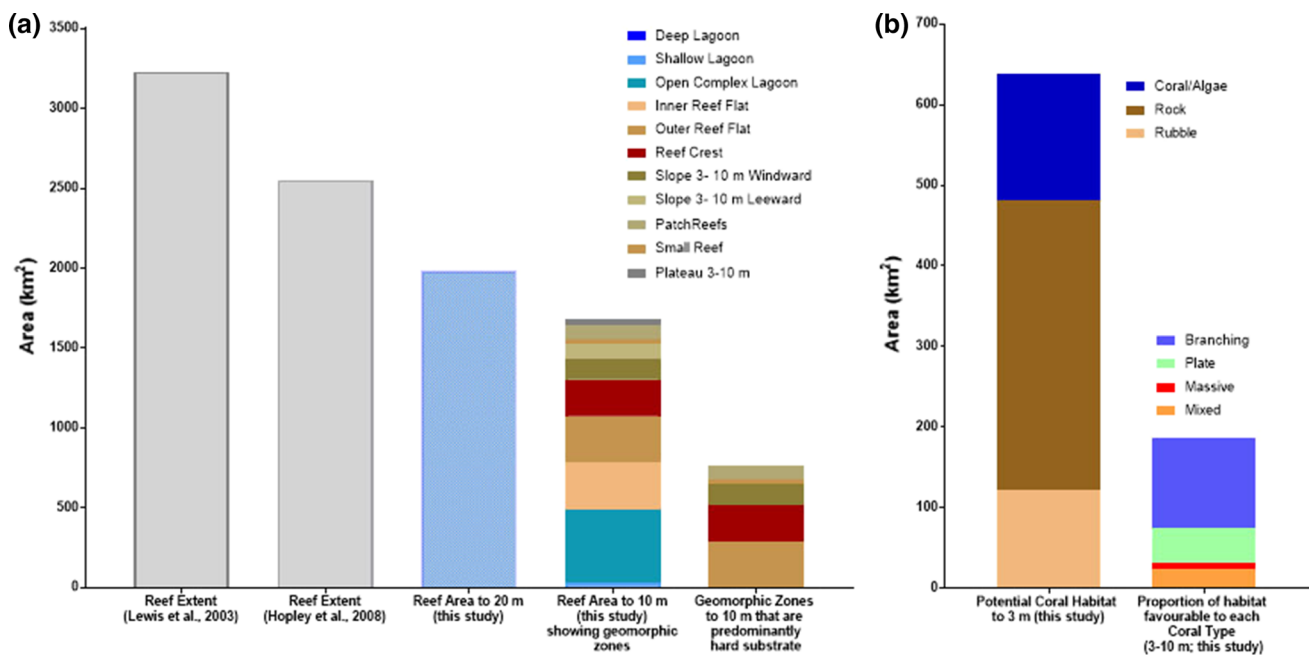
Fig. 4 Estimated areal extent of individual mapping categories sourced from currently utilised map layers, and map layers created in this study. For the reefs of the Cairns Management Region, estimations were made at the **a** geomorphic level and **b** benthic level

generic reef outline as no further detail was present. In this study, we defined potential coral habitat as geomorphic zones that were situated above a depth of 10 m and that consist predominantly of hard substrate (reef crest, outer reef flat, windward slope to 10 m, patch reefs, small reefs). Geomorphic zones meeting these criteria and representing potential coral habitat encompassed an area of 761 km^2 (45%). Subsequently, using the *Benthic Cover* map, the calculated area mapped as potential coral habitat (consolidated: coral/algae, rock, rubble to a depth of 3 m) on the reef top was 637 km^2 (Fig. 4b). Further, using the *Coral Type* map, the most abundant coral type with a calculated reef slope area of 112 km^2 (to a depth of 10 m) was predicted to be potential branching coral habitat, with 8 km^2 and 42 km^2 predominantly massive and tabular habitat, respectively, whilst another 24 km^2 was a mixture of coral types. As such, use of the existing maps to calculate potential coral habitat would have led to an overestimation of coral cover (Figs. 3 and 4). We therefore suggest that the *Geomorphic Zonation*, *Benthic Cover* and *Coral Type* maps should be used to determine reef areas more accurately, with potential implications for conservation, reef restoration and management policies.

Potential applications: higher-resolution maps for coral reef science, monitoring and management

To showcase the potential advantages provided by the increased spatial and thematic detail yielded by the maps in this study, their applications to real-world research and management projects were examined with a focus on water quality and reef restoration.

Potential application 1: understanding coral ecological and biophysical processes on the GBR

Water quality management in the GBR is important for the reef and the health of other coastal ecosystems (Schaffelke et al. 2017). Nutrient and sediment input from catchments increase nutrient loading and reduce light levels leading to poor growing conditions for corals. The eReefs tool was developed to deliver numerical models capable of simulating and predicting the physical hydrodynamic state, sediment transport, water quality and basal ecology of the Great Barrier Reef lagoons and reef matrix (Baird et al. 2016, 2018). The eReefs modelling information system integrates benthic habitat, river catchment, hydrodynamics, sedimentation and wave propagation, resulting in optical and biogeochemical models. Both models (1 and 4 km resolution) provide skilful predictions of drivers of coral processes such as coral calcification, spectrally resolved bottom light, temperature and water column concentrations of dissolved inorganic nutrients and particulate organic matter across the entire length of the GBR (Fig. 5) (Skerratt et al. 2019). Accurate information about benthic distribution of coral habitat is required to configure the models and populate each model grid cell.

As no detailed habitat map existed to provide more detailed information on coral habitat extent within each reef (Mongin et al. 2016), the initial coral distribution was

Fig. 5 Contribution of a detailed *Geomorphic Zonation* map to eReefs modelling of coral ecological and biophysical processes. **a** The current eReefs modelling using potential coral habitat determined from the existing reef extent layer and represented at a 4 km grid resolution, **b** current eReefs modelling using potential coral habitat determined from the existing reef extent layer and represented at a 1 km grid resolution and **c** eReefs modelling using areas of potential coral habitat determined from the *Geomorphic Zonation* map created in this study, which results in a model output at a higher spatial resolution, providing more discreet values for the output parameters. The black outline in each panel represents the reef extent as mapped in this study
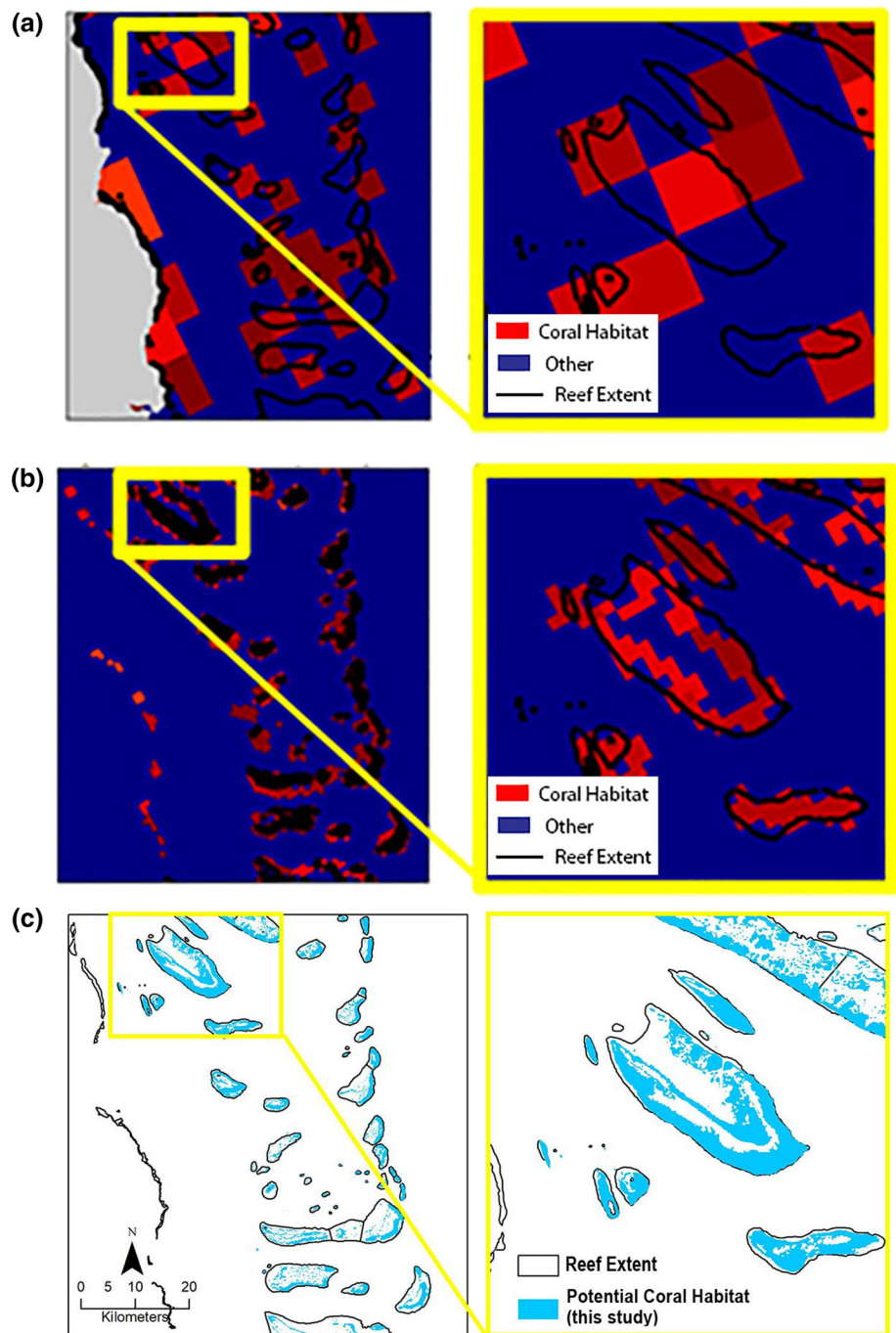
based on the reef extent layer (Lewis et al. 2003) with the assumption that this whole area represented coral habitat (Fig. 3b), which calculated for the Cairns Management area that equates to 3164 km². When modelled at a 4 km horizontal resolution, large reefs are represented by few grid cells in a pixelated arrangement with no intra-reef complexity (Fig. 5a). And when modelled using a 1 km horizontal resolution (Fig. 5b), the increased resolution (from 4 to 1 km) led to an overestimation of coral habitat

(Mongin et al. 2016). These overestimation errors are propagated to the calculated eReefs output parameters.

The use of finer-resolution habitat maps would provide a more accurate representation of the extent of coral habitat within the reef extent, which would be more realistic in terms of benthic area, i.e. a large total area with a reduced and more accurate estimation of the extent of coral habitat and, subsequently, more accurate representation of the modelled parameters. Replacement of the current reef extent layer (Lewis et al. 2003) (defining coral habitat as

3164 km^2) in the model with this study's coral habitat extent derived from the *Geomorphic Zonation* map (761 km^2; represented by zones of hard substrate—outer reef flat, reef crest, windward slope, patch reefs and small reefs to a depth of 10 m) resolved the coral calcification flux determination discrepancy at the reef scale (Fig. 5c). Similarly, spectrally resolved bottom light characterisation was improved by the spatial detail of the two bottom types used, light and dark, which represent sand and coral habitat, respectively, and are better defined by the higher thematic and spatial detail of the habitat maps created in this study.

The improvement in the eReefs water quality models with finer benthic parameterisation (e.g. coral habitat, sand) allowed for the elimination of the sub-grid-scale parameterisation and better represented the diversity of coral processes inside a reef and optical properties around the reef environment. This can be used to quantify the impact of anthropogenic threats and provide testing platforms for managing solutions at the reef scale which would now include spatial geomorphic or benthic variations of the habitat within a reef, no longer limited to the reef as a whole.

## Potential application 2: selection of sites suitable for reef restoration

As coral reefs around the world degrade, reef managers are turning to reef restoration techniques in an attempt to bolster recovery of damaged reefs (Bayraktarov et al. 2019). The key challenge facing coral restoration is to make it cost-effective and feasible at an ecologically relevant scale. Outcomes from the Australian Reef Restoration and Adaptation Program concept feasibility study (Hardisty et al. 2019) indicate that automation will be key for any large-scale intervention activities. Interventions under consideration range from deploying coral larvae in clouds or settled on devices, to distributing treatments to existing corals to increase their health and recovery potential. It is highly likely that much of this will be done by above or underwater autonomous vehicles, which rely on pre-programmed routes.

Selection of appropriate sites for restoration activities can make the difference between success and failure (Sherman et al. 2001). Maps of reef zonation indicate sharp boundaries in physical environmental characteristics (e.g. light, flow, depth) that are important for site selection. Additionally, benthic habitat maps are important in site selection as successful restoration activities rely on identification of hard substrate for planting out (Bayraktarov et al. 2019; Boström-Einarsson et al. 2018) (e.g. rock on benthic maps) in areas where coral communities have been or are able to thrive (e.g. coral on benthic map), and with

suitable conditions including high light and water flow (e.g. upper reef slope in geomorphic maps). Meanwhile, physical restoration (e.g. rubble stabilisation) would require knowledge of rubble extent (benthic maps), as well as information on reef slope and water flow. Even in the more classic commonly adopted example of reef restoration coral gardening, optimal placement of in-water coral nurseries is required where constructions are placed in protected parts of reef systems. These nursery frames are ideally placed in protected sandy areas in the lee of reefs where they are left to grow (Nedimyer et al. 2011). The subsequent out-planting of coral nubbins nurtured on these frames requires hard substrate. Successful coral growth is dependent on factors such as water quality, light and the presence of a hard surface for coral larvae to settle on or for adult colonies to be attached to. Hence, knowledge of areas of hard substrate for coral attachment or sheltered sandy areas for deployment of gardening frames may help direct restoration efforts (Fig. 6).

In this case study, the *Benthic Cover* map can direct reef restoration efforts towards locating reef areas that are likely to be successful (e.g. consolidated hard substrate) and away from areas unlikely to be suitable for successful coral growth (e.g. unconsolidated substrate). The habitat maps created in this study revealed that within the sample reef area shown in Fig. 6 (green outlines), 1.48 km^2 and 15.51 km^2 (Fig. 6d) represented consolidated material appropriate for seeding corals for reef restoration, compared to 134 km^2 and 55 km^2, respectively, calculated from the current reef layer (Fig. 6a). Similarly, shallow unconsolidated areas suitable for the placement of frames can be identified. Additionally, physical attribute layers created in this study (wave parameters, depth and slope), in conjunction with the output *Geomorphic Zonation*, *Benthic Cover* and *Coral Type* maps, would be beneficial for modelling the suitability of the proposed restoration sites. For example, restoration frames require a sheltered, horizontal surface, which could be identified from the wave and slope attributes, in addition to an appropriate surface (hard substrate), which can be identified from the geomorphic zonation map. Further, the *Benthic Cover* and *Coral Type* maps would enable identification of areas dominated by a particular coral form at any chosen site. Therefore, these data sets would increase the potential for government or non-government organisations to identify appropriate areas for coral restoration.

Using these two potential user applications, we suggest that the subsequent application of the methods and maps developed in this work to the full extent of the shallow offshore reefs of the GBR would provide managers and stakeholders with the means to devise more effective policies in regards to coral ecological and biophysical processes and restoration of these precious habitats. Map
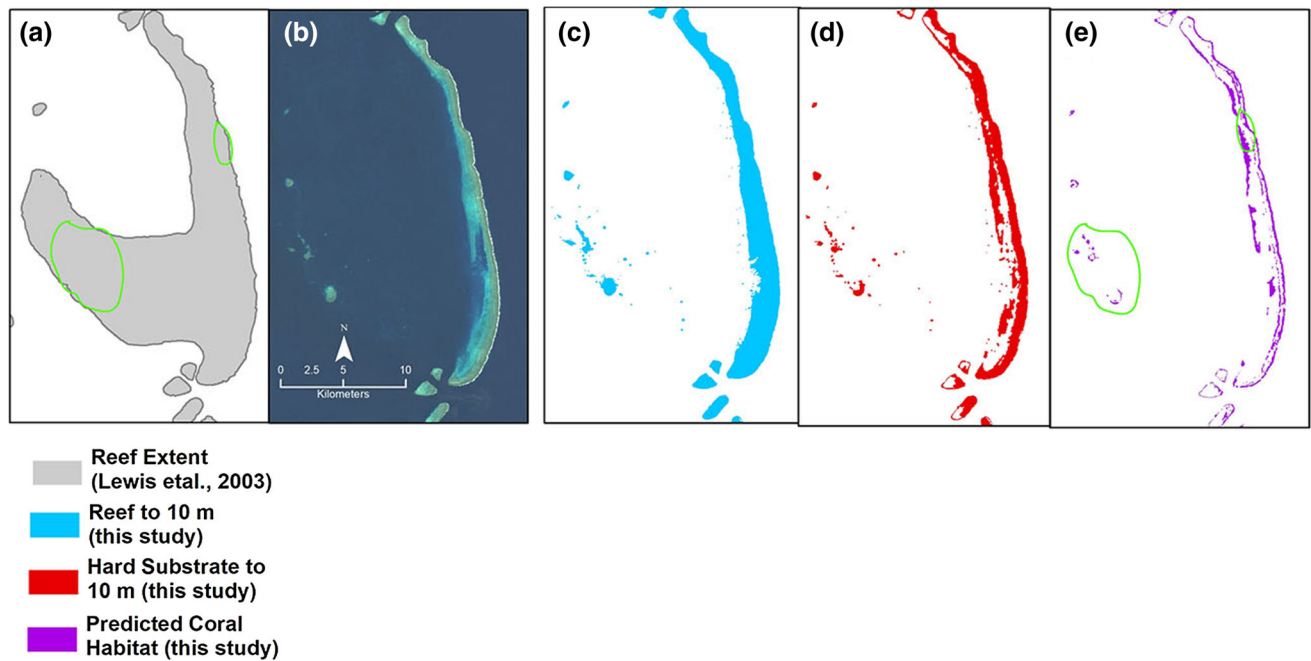
Fig. 6 Contribution of a detailed *Benthic Cover* map to reef restoration efforts, which require knowledge of where sheltered areas with soft substrate for the placement of frames with coral nubbins are located, or where hard substrate is for coral larvae to settle. **a** The existing reef outline (Lewis et al. 2003) provides a broad prediction of reef extent, **b** Landsat 8 OLI satellite imagery can be used to view the gross outline of the reef, **c** reef area above a depth of 10 m, **d** area of hard substrate derived from the *Geomorphic Zonation* map created in this study to a depth of 10 m and **e** the area of coral cover determined from the *Benthic Cover* and *Coral Type* habitat maps created in this study. Green outlines indicate the areas used for comparison in the text

products that provide greater spatial and thematic detail and are timely than those previously available could assist in the assessment of reef habitat suitable for coral growth (e.g. coral restoration), provide an indication of the composition of the reef slopes and enable accurate quantitation of dominant benthic types on the reef tops. Collectively, by providing input habitat maps at relevant spatial scales, this information would benefit the evaluation of areas of potential risk during bleaching events, assist with the future development of management programs (e.g. CoTS control) and improve modelling of reef biophysical properties and restoration efforts on the GBR or other large reef systems. The potential applications discussed provide an example of ongoing research in this field, and a description of additional applications is expected in future. Such examples include the estimation of sediment budgets (Hamylton et al. 2016); modelling of fish biomass and species richness (Knudby et al. 2011); an assessment of reef resilience (Knudby et al. 2013), and parameterising the design of marine-protected areas (Tulloch et al. 2017). Hence, creation of a GBR-wide habitat map would not only provide increased spatial and thematic detail, but the potential benefit to modelling and management applications of this large reef system is extensive.

Conclusions

This study produced habitat maps for individual reefs of the Cairns Management area, a combined reef area of 1984 km^2, that represents approximately 8% of GBR shallow reefs [$\sim$ 25,000 km^2 (Lewis et al. 2003)] at a level of complexity not previously available. The 237 reefs of the Cairns Management Region were mapped in this study to the level of *Geomorphic Zonation*, *Benthic Cover* and *Coral Type* (Fig. 2). Until now, only the outline and reef type of each of these reefs was available.

The unique mapping approach presented uses limited field data, is repeatable and consistent and is therefore scalable to the full extent of the 3000 shallow GBR reefs. This is based on two studies—the initial development of the mapping approach for the 20 reefs of the Capricorn Bunker Group (Roelfsema et al. 2018) and the subsequent adaptation of the protocol in this study to the 237 reefs of the Cairns Management Region of the GBR. Creation of habitat maps for the full extent of the GBR, or other large reef systems, would require a seamless satellite image mosaic with similar radiometric, spectral and spatial characteristics as used for this study; the ability to derive physical attributes; the availability of field data collected at representative reefs so that the modelling and mapping

parameters and the eco-geomorphological rule set could be adjusted and fine-tuned for application to a greater area.

The study demonstrated how spatially explicit and highly detailed maps for a reef system of a size applicable to management applications could be used to support and refine key science outputs and management questions and decisions, via assessment of two potential applications: (1) understanding coral ecological and biophysical properties and (2) reef restoration. Applications for which the detailed habitat maps create in this study may be beneficial are not limited to what is presented in this paper. Additionally, these map layers are being trialled in the Cairns Management Region with a view to optimisation of marine park re-zonation and day-to-day management of this area.

Currently, the developed methods form the basis of two major large extent coral reef mapping efforts: (1) delivery by 2021 of the first geomorphic zonation, benthic cover type and coral-type maps for the full extent of the Great Barrier Reef and (2) mapping of larger reef systems through the Allen Coral Atlas global coral reef mapping initiative (www.allencoralatlas.com) (Lyons et al. 2020). Further development of the methodology will include application to coastal turbid reefs and deeper waters, which were not addressed in this study, and will provide for mapping additional complex habitats including shallow seagrass meadows.

References

Andréfouët S, Muller-Karger FE, Robinson JA, Kranenburg CJ, Torres-Pulliza D, Spraggins S, Murch B (2006) Global assessment of modern coral reef extent and diversity for regional science and management applications: a view from space. In: S.T. Nakamori, H. Hidaka, H. Kayanne, B.E. Casareto, K. Nadaoka, H. Yamano, M. Tsuchiya, & K. Yamazato (eds) 10th international coral reef symposium. International Coral Reef Society, Okinawa, pp 1732–1745

Aquatic Ecosystems Task Group (2012) Aquatic ecosystems toolkit. Module 2. Interim Australian national aquatic ecosystem classification framework. In: Australian government department of sustainability, environment, water, population and communities, Canberra

Babcock RC, Dambacher JM, Morello EB, Plagányi ÉE, Hayes KR, Sweatman HPA, Pratchett MS (2016) Assessing different causes of crown-of-thorns starfish outbreaks and appropriate responses

for management on the Great Barrier Reef. PLoS ONE 11:e0169048

Baird ME, Cherukuru N, Jones E, Margvelashvili N, Mongin M, Oubelkheir K, Ralph PJ, Rizwi F, Robson BJ, Schroeder T, Skerratt J, Steven ADL, Wild-Allen KA (2016) Remote-sensing reflectance and true colour produced by a coupled hydrodynamic, optical, sediment, biogeochemical model of the Great Barrier Reef, Australia: Comparison with satellite data. Environ Model Softw 78:79–96

Baird ME, Mongin M, Rizwi F, Bay LK, Cantin NE, Soja-Woźniak M, Skerratt J (2018) A mechanistic model of coral bleaching due to temperature-mediated light-driven reactive oxygen build-up in zooxanthellae. Ecol Model 386:20–37

Bayraktarov E, Stewart-Sinclair PJ, Brisbane S, Boström-Einarsson L, Saunders MI, Lovelock CE, Possingham HP, Mumby PJ, Wilson KA (2019) Motivations, success, and cost of coral reef restoration. Restor Ecol 27:981–991

Beeden R, Maynard J, Puotinen M, Marshall P, Dryden J, Goldberg J, Williams G (2015) Impacts and recovery from severe tropical cyclone Yasi on the Great Barrier Reef. PLoS ONE 10:e0121272

Beeden RJ, Turner MA, Dryden J, Merida F, Goudkamp K, Malone C, Marshall PA, Birtles A, Maynard JA (2014) Rapid survey protocol that provides dynamic information on reef condition to managers of the Great Barrier Reef. Environ Monit Assess 186:8527–8540

Beijbom O, Edmunds PJ, Roelfsema C, Smith J, Kline DI, Neal BP, Dunlap MJ, Moriarty V, Fan T-Y, Tan C-J, Chan S, Treibitz T, Gamst A, Mitchell BG, Kriegman D (2015) Towards automated annotation of benthic survey images: variability of human experts and operational modes of automation. PLoS ONE 10:e0130312

Blaschke T (2010) Object based image analysis for remote sensing. J Photogram Remote Sens 65:2–16

Boström-Einarsson L, Ceccarelli D, Babcock RC, Bayraktarov E, Cook N, Harrison P, Hein M, Shaver E, Smith A, Stewart-Sinclair PJ, Vardi T, I.M., M. (2018). Oral restoration in a changing world—a global synthesis of methods and techniques. In: Program NES (eds) Reef and Rainforest Research Centre Ltd, Cairns, pp 63–65

Callaghan DP, Leon JX, Saunders MI (2015) Wave modelling as a proxy for seagrass ecological modelling: comparing fetch and process-based predictions for a bay and reef lagoon. Estuar Coast Shelf Sci 153:108–120

Cerdeira-Estrada S, Heege T, Kolb M, Ohlendorf S, Uribe A, Muller A, Garza R, Ressl R, Aguirre R, Marino I, Silva R, Martell R, IEEE (2012) Benthic habitat and bathymetry mapping of shallow waters in Puerto Morelos reefs using remote sensing with a physics based data processing. In: 2012 IEEE international geoscience and remote sensing symposium. pp 4383–4386

Clarke KR, Gorley RN, Somerfield PJ, Warwick RM (2014) Change in marine communities: an approach to statistical analysis and interpretation, 3rde edn. PRIMER-E, Plymouth

Congalton RG, Green K (1999) Assessing the accuracy of remotely sensed data: principles and practices. Lewis Publishers, Boca Rotan

De'ath G, Fabricius KE, Sweatman H, Puotinen M (2012) The 27–year decline of coral cover on the Great Barrier Reef and its causes. Proc Natl Acad Sci 109:17995–17999

Done T, Roelfsema CM, Harvey A, Schuller L, Hill J, Schlappy M, Lea A, Bauer-Civiello A, Loder J (2017) Reliability and utility of citizen science reef monitoring data collected by Reef Check Australia, 2002–2015. Mar Pollut Bull 117:148–155

Egbert GD, Erofeeva SY (2002) Efficient inverse modeling of barotropic ocean tides. J Atmos Ocean Technol 19:183–204

EOMAP (2016). First high resolution map of the entire reef from the world's biggest satellite-derived bathymetry survey. In: EGC KG

(Ed.) (p.). Schlosshof 4a | D-82229. EOMAP GmbH & Co. KG, Seefeld

GBRMPA (2004) Great barrier reef marine park zoning plan 2003. In: GBRMPA (ed) Great Barrier Reef Marine Park Authority, Townsville

González-Rivero M, Beijbom O, Rodriguez-Ramirez A, Holtrop T, González-Marrero Y, Ganase A, Roelfsema C, Phinn S, Hoegh-Guldberg O (2016) Scaling up ecological measurements of coral reefs using semi-automated field image collection and analysis. Remote Sens 8:30

Hamylton S, Hedley J, Beaman R (2015) Derivation of high-resolution bathymetry from multispectral satellite imagery: a comparison of empirical and optimisation methods through geographical error analysis. Remote Sens 7:15829

Hamylton SM, Carvalho R, Duce S, Roelfsema C, Vila-Concejo A (2016) Linking pattern to process in reef sediment dynamics at Lady Musgrave Island, southern Great Barrier Reef. Sedimentology, n/a-n/a

Hardisty P, Roth CH, Silvey PJ (2019) Reef restoration and adaptation program—investment case. In: A report provided to the Australian Government from the Reef Restoration and Adaptation Program

Hedley J, Roelfsema C, Chollett I, Harborne A, Heron S, Weeks S, Skirving W, Strong A, Eakin C, Christensen T, Ticzon V, Bejarano S, Mumby P (2016) Remote sensing of coral reefs for monitoring and management: a review. Remote Sens 8:118

Hedley JD, Roelfsema C, Brando V, Giardino C, Kutser T, Phinn S, Mumby PJ, Barrilero O, Laporte J, Koetz B (2018) Coral reef applications of Sentinel-2: coverage, characteristics, bathymetry and benthic mapping with comparison to Landsat 8. Remote Sens Environ 216:598–614

Heege T, Bogner A, Pinnel N (2004) Mapping of submerged aquatic vegetation with a physically based process chain. In: C.R. Bostater, R. Santoleri (eds) Remote sensing of the ocean and sea ice 2003, pp 43–50

Hock K, Wolff NH, Ortiz JC, Condie SA, Anthony KRN, Blackwell PG, Mumby PJ (2017) Connectivity and systemic resilience of the Great Barrier Reef. PLoS Biol 15:e2003355–e2003355

Hopley D, Smithers S, Parnell K (2008) The geomorphology of the Great Barrier Reef: development, diversity, and change. Cambridge University Press, Cambridge

Hughes TP, Barnes ML, Bellwood DR, Cinner JE, Cumming GS, Jackson JBC, Kleypas J, van de Leemput IA, Lough JM, Morrison TH, Palumbi SR, van Nes EH, Scheffer M (2017a) Coral reefs in the anthropocene. Nature 546:82–90

Hughes TP, Kerry JT, Álvarez-Noriega M, Álvarez-Romero JG, Anderson KD, Baird AH, Babcock RC, Beger M, Bellwood DR, Berkelmans R, Bridge TC, Butler IR, Byrne M, Cantin NE, Comeau S, Connolly SR, Cumming GS, Dalton SJ, Diaz-Pulido G, Eakin CM, Figueira WF, Gilmour JP, Harrison HB, Heron SF, Hoey AS, Hobbs J-PA, Hoogenboom MO, Kennedy EV, Kuo C-Y, Lough JM, Lowe RJ, Liu G, McCulloch MT, Malcolm HA, McWilliam MJ, Pandolfi JM, Pears RJ, Pratchett MS, Schoepf V, Simpson T, Skirving WJ, Sommer B, Torda G, Wachenfeld DR, Willis BL, Wilson SK (2017b) Global warming and recurrent mass bleaching of corals. Nature 543:373–377

Kenchington R, Hutchings P (2012) Science, biodiversity and Australian management of marine ecosystems. Ocean Coast Manag 69:194–199

Knudby A, Jupiter S, Roelfsema C, Lyons M, Phinn S (2013) Mapping coral reef resilience indicators using field and remotely sensed data. Remote Sens 5:1311–1334

Knudby A, Roelfsema C, Lyons M, Phinn S, Jupiter S (2011) Mapping fish community variables by integrating field and satellite data, object-based image analysis and modeling in a traditional Fijian fisheries management area. Remote Sens 3:460–483

Kobryn HT, Wouters K, Beckley LE, Heege T (2013) Ningaloo reef: shallow marine habitats mapped using a hyperspectral sensor. PLoS ONE 8:e70105

Lewis A, Lowe D, Otto J (2003) Remapping the Great Barrier Reef In: Position magazine. South Pacific Science Press International, pp 46–49

Lyons BM, Roelfsema CM, Kennedy EV, Kovacs EM,Borrego-Acevedo R, Markey K, Roe M, Yuwono DM, Harris DL, Phinn SR, Asner G, Li J, Knapp DE, Fabina NS, Larsen K, Traganos D, Murray NJ (2020) Mapping the world's coral reefs using a global multiscale earth observation framework. Remote Sens Ecol Conserv. https://doi.org/10.1002/rse2.157

Madin JS, Madin EMP (2015) The full extent of the global coral reef crisis. Conserv Biol 29:1724–1726

Madin JS, O'Donnell MJ, Connolly SR (2008) Climate-mediated mechanical changes to post-disturbance coral assemblages. Biol Let 4:490–493

Marshall NJ, Kleine DA, Dean AJ (2012) CoralWatch: education, monitoring, and sustainability through citizen science. Front Ecol Environ 10:332–334

Monaco ME, Andersen SM, Battista TA, Kendall MS, Rohmann SO, Wedding LM, Clarke AM (2012) National summary of NOAA's shallow-water benthic habitat mapping of U.S. coral reef ecosystems. In: NOAA (ed) NOAA technical memorandum center for coastal monitoring and assessment biogeography branch. NOAA, Silver Spring, MD

Mongin M, Baird ME, Tilbrook B, Matear RJ, Lenton A, Herzfeld M, Wild-Allen K, Skerratt J, Margvelashvili N, Robson BJ, Duarte CM, Gustafsson MSM, Ralph PJ, Steven ADL (2016) The exposure of the Great Barrier Reef to ocean acidification. Nat Commun 7:10732

Mumby PJ, Chisholm JRM, Clark CD, Hedley JD, Jaubert J (2001) Spectrographic imaging—a bird's-eye view of the health of coral reefs. Nature 413:36–36

Mumby PJ, Wolff NH, Bozec Y-M, Chollett I, Halloran P (2014) Operationalizing the resilience of Coral Reefs in an era of climate change. Conserv Lett 7:176–187

Nedimyer K, Gaines K, Roach S (2011) Coral Tree Nursery©: an innovative approach to growing corals in an ocean-based field nursery.In: AACL Bioflux aquaculture, aquarium, conservation and legislation, 4

Ohlendorf S, Muller A, Heege T, Cerdeira-Estrada S, Kobryn HT (2011) Bathymetry mapping and sea floor classification using multispectral satellite data and standardized physics-based data processing. In: CR Bostater, SP Mertikas, X Neyt, M Velez Reyes (eds) Remote sensing of the ocean, sea ice, coastal waters, and large water regions 2011

Puotinen M, Maynard JA, Beeden R, Radford B, Williams GJ (2016) A robust operational model for predicting where tropical cyclone waves damage coral reefs. Sci Rep 6:26009

Purkis SJ, Gleason ACR, Purkis CR, Dempsey AC, Renaud PG, Faisal M, Saul S, Kerr JM (2019). High-resolution habitat and bathymetry maps for 65,000 sq. km of Earth's remotest coral reefs. Coral Reefs

Roelfsema C, Kovacs E, Ortiz JC, Wolff NH, Callaghan D, Wettle M, Ronan M, Hamylton SM, Mumby PJ, Phinn S (2018) Coral reef habitat mapping: a combination of object-based image analysis and ecological modelling. Remote Sens Environ 208:27–41

Roelfsema C, Phinn S (2010) Integrating field data with high spatial resolution multispectral satellite imagery for calibration and validation of coral reef benthic community maps. J Appl Remote Sens 4:043527–043527–043528

Roelfsema CM, Kovacs EM, Phinn SR (2017) Georeferenced photographs of benthic photoquadrats acquired along 160

transects distributed over 23 reefs in the Cairns to Cooktown region of the Great Barrier Reef, January and April/May, 2017. In: PANGAEA

Roelfsema CM, Phinn RS (2013) Validation. In: Goodman J, Purkis S, Phinn SR (eds) Coral Reef Remote Sensing: A Guide for Multi-level Sensing Mapping and Assessment. Elsevier, Amsterdam

Sattler PS, Williams R (1999) The conservation status of Queensland's bioregional ecosystems. In: Sattler P, Williams R (eds) Environmental protection agency. Queensland Government, Brisbane

Schaffelke B, Collier C, Kroon F, Lough J, McKenzie L, Ronan M, Uthicke S, Brodie J (2017) Scientific consensus statement 2017. Scientific consensus statement 2017: a synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 1: The condition of coastal and marine ecosystems of the Great Barrier Reef and their responses to water quality and disturbances. State of Queensland, 2017. https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0030/45993/2017-scientific-consensus-statement-summary-chap01.pdf

Sherman RL, Gilliam DS, Spieler RE (2001) Site-dependent differences in artificial reef function: implications for coral reef restoration. Bull Mar Sci 69:1053–1056

Siermann J, Harvey C, Morgan G, Heege T (2014) Satellite derived bathymetry and digital elevation models (DEM). In: International petroleum technology conference. Doha, Qatar

Skerratt JH, Mongin M, Baird ME, Wild-Allen KA, Robson BJ, Schaffelke B, Davies CH, Richardson AJ, Margvelashvili N, Soja-Wozniak M, Steven ADL (2019) Simulated nutrient and plankton dynamics in the Great Barrier Reef (2011–2016). J Mar Syst 192:51–74

Stehman SV (2001) Statistical rigor and practical utility in thematic map accuracy assessment. Photogram Eng Remote Sens 67:727–734

Stehman SV, Czaplewski RL (1998) Design and analysis for thematic map accuracy assessment: fundamental principles. Remote Sens Environ 64:331–344

Traganos D, Aggarwal B, Poursanidis D, Topouzelis K, Chrysoulakis N, Reinartz P (2018a) Towards global-scale seagrass mapping and monitoring using Sentinel-2 on google earth engine: the case study of the Aegean and Ionian seas. Remote Sens 10:1227

Traganos D, Poursanidis D, Aggarwal B, Chrysoulakis N, Reinartz P (2018b) Estimating satellite-derived bathymetry (SDB) with the google earth engine and Sentinel-2. Remote Sens 10:859

Tulloch VJ, Klein CJ, Jupiter SD, Tulloch AIT, Roelfsema C, Possingham HP (2017) Trade-offs between data resolution, accuracy, and cost when choosing information to plan reserves for coral reef ecosystems. J Environ Manage 188:108–119

Zann M, Kenna E, Ronan M (2017) Queensland intertidal and subtidal ecosystem classification scheme version 1.0: module 1—introduction and implementation of intertidal and subtidal ecosystem classification. In: Q.W.P. Department of Environment and Heritage Protection, Queensland Government, Brisbane (eds) Queensland intertidal and subtidal ecosystem classification scheme. Department of Environment and Heritage Protection, Queensland Wetlands Program, Queensland Government, Brisbane