Tropical Water Quality Hub

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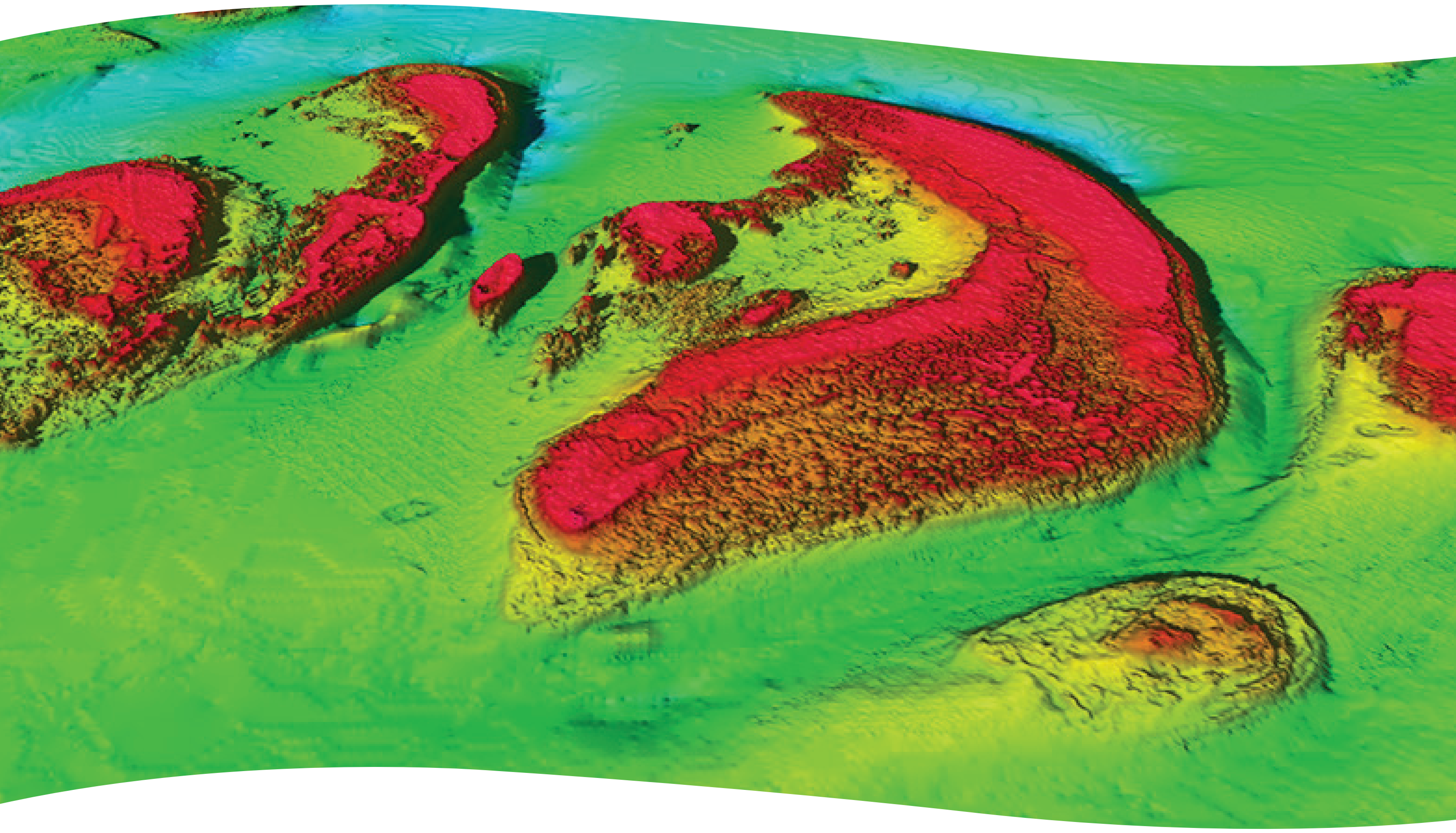
Technical Report

Assessment of deep-water habitat for crown-of-thorns starfish (COTS) in the Great Barrier Reef

Robin J. Beaman



JAMES COOK UNIVERSITY
AUSTRALIA

Assessment of deep-water habitat for crown-of-thorns starfish (COTS) in the Great Barrier Reef

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Cover photographs:
3D view of Moore and Sudbury Reefs on the northern Great Barrier Reef
Crown-of-thorns starfish covering a coral pinnacle at Rib Reef (photo courtesy of Dr David Westcott, CSIRO)

This report is available for download from the NESP Tropical Water Quality Hub website:
http://www.nesptropical.edu.au

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ACRONYMS

AHO .... Australian Hydrographic Office
ALB............... airborne lidar bathymetry
ASCII .... American Standard Code for Information Interchange
AUSLIG .... Australian Surveying and Land Information Group
AUV .... autonomous underwater vehicle
BTM .... Benthic Terrain Modeler
BPI................ Bathymetric Position Index
CCA .... crustose coralline algae
COTS............ crown-of-thorns starfish
CSAR............ Caris Spatial Archive
CSIRO........... Commonwealth Scientific and Industrial Research Organisation
DEM .... digital elevation model
DSM .... digital surface model
DST............... Decision Support Tool
eDNA .... environmental DNA
ENC .... Electronic Navigational Chart
EOMAP......... Earth Observation and Environmental Services
GA .... Geoscience Australia
GBR .... Great Barrier Reef
GBRMPA ...... Great Barrier Reef Marine Park Authority
GIS................ geographic information system
GMT .... Generic Mapping Tools
ESRI.............. Environmental Systems Research Institute
IHO................ International Hydrographic Organisation
IPM................ Integrated Pest Management
ITEM .... Intertidal Extents Model
LAT .... lowest astronomical tide
LGM .... Last Glacial Maximum
MBES............ multibeam echo sounder
MCE .... mesophotic coral ecosystem
MSL .... mean sea level
MSQ.............. Maritime Safety Queensland
MTSRF.......... Marine and Tropical Sciences Research Facility
NSS............... near-sea-surface
QPS .... Quality Positioning Services
SBES .... singlebeam echosounder
SDB .... satellite derived bathymetry
SRTM............ Shuttle Radar Topographic Mission

ABBREVIATIONS

ka .... thousand years
pop .... population

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EXECUTIVE SUMMARY

(1) This project integrated all the available source bathymetry data currently used within the latest gbr100 grid and generated a much higher-resolution gbr30 bathymetry grid (~30 m pixel spacing) over the GBR shelf area. The gbr30 grid is publically available for download on the Geoscience Australia website at: http://pid.geoscience.gov.au/dataset/115066

The gbr30 grid is recommended for use as a spatial dataset to feed into the Local and Regional Decision Support Tool (DST) being developed by CSIRO for Integrated Pest Management. Other uses of the grid may extend beyond COTS control efforts to include hydrodynamic modelling, natural hazard assessment, to plan and build offshore infrastructure, and to benefit tourism and fishing.

(2) The gbr30 grid was used to generate spatial datasets and descriptive statistics of the 22 ‘super spreader’ and tourism reefs, to better understand the extent of deep-water habitat at these sites. Output files included Fledermaus 3D visualisation files, Google Earth kmz, ESRI raster grids, hillshade geotifs, ESRI shapefiles, Excel spreadsheets and histograms, xyz files.

These spatial datasets are recommended for operational use in helping with COTS control at these 22 ‘super spreader’ and tourism sites by understanding the topographic variability and overall depth distribution of each reef. Benthic Terrain Modeler was used to extract the crest and slope areas deeper than 15 m, which are likely to be potential deep-water coral habitats.

(3) An assessment was conducted on whether submerged banks or deeper reefs may provide deep-water coral habitat for COTS, and the implications for the design of the control program. Extensive mesophotic (twilight zone) coral ecosystems have been described on these banks and deeper reefs with zooxanthellate corals found to ~60 m. However, the scientific literature does not record any evidence of COTS outbreaks being found in depths significantly below the zone of highest coral cover on emergent reefs, which generally peak at ~10-15 m.

The assessment concluded there is a low risk of adult COTS outbreaks in deep-water habitats below the zone of highest coral cover. The assessment also discounted the deep-water recruitment hypothesis for larvae settling in deep-water on the basis of observations of COTS movements over their lifecycle. The assessment concluded there is low risk of larval COTS to be found in deep-water habitats on emergent reefs below the zone of highest coral cover.

The recommendation is that COTS control efforts should continue in the relatively shallow waters of emergent reefs, and to not expend resources searching for COTS outbreaks in deeper waters significantly below the zone of highest coral cover.

1.0 INTRODUCTION

Integrated Pest Management (IPM) for crown-of-thorns (COTS) starfish is a new approach of transdisciplinary work and synthesis of knowledge to help solve COTS outbreaks on the Great Barrier Reef (GBR). The COTS Working Group convened in 2017 under the leadership of Dr David Westcott, CSIRO, and comprised of experts in coral and COTS ecology, oceanography, robotics, gene technology, biocontrol and diver control operations. The objective was to deliver the research tools and information that could feed into COTS control efforts through a Local and Regional Decision Support Tool (DST) being developed by CSIRO (Figure 1).

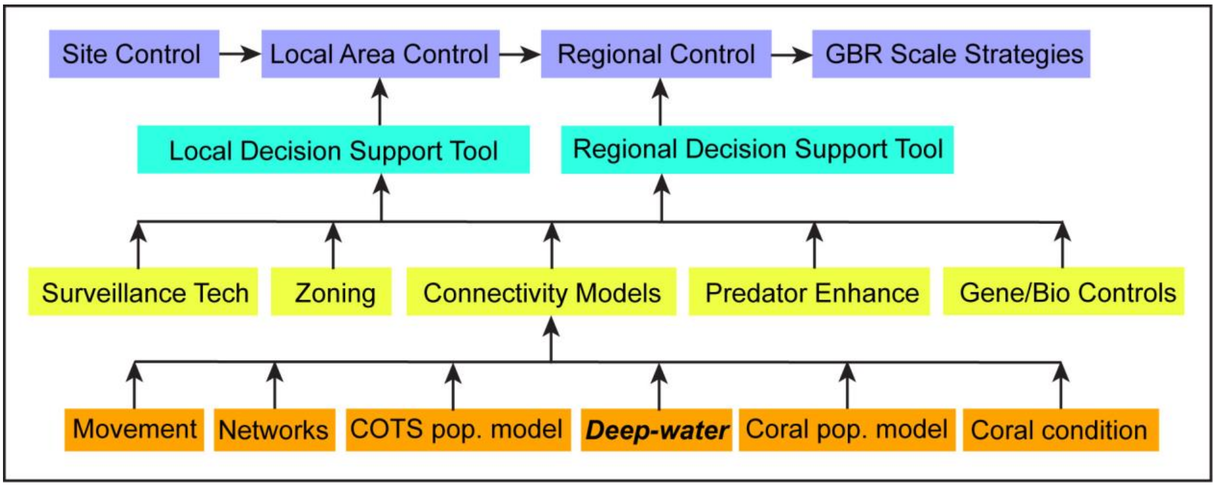

Figure 1: Diagram of research tools and information considered by the COTS Working Group

The Local and Regional DSTs require a wide range of research tools and information that can help answer important questions around COTS outbreaks on the GBR, such as where and when to send our control effort, and how to initially detect outbreaks and then how best to respond? Tools and information for the DST include diver and robot surveillance capabilities and limitations, the effects of GBR Marine Park Zoning on outbreaks, the potential for predator enhancements (e.g. Giant triton shells or eDNA of predators), gene and biological controls.

Additional research tools are the connectivity models that help to explain the oceanographic conditions and geographic location of coral reefs that are at greater risk of disturbances, such as bleaching and COTS outbreaks. Hock et al. (2017) developed a model of regional connectivity patterns between the reef polygons identified in the GBR_Features dataset (GBRMPA, 2013), together with high-resolution dispersal simulations of coral larvae to show which reefs are most likely to support recovery from disturbances due to their high connectivity.

Oceanographic and climate models were also used to show which reefs were more likely to have a lower risk of exposure to coral bleaching due to proximity to cooler deep-ocean currents, and which reefs were more likely to have a lower supply of COTS larvae (Hock, et al., 2017). Combined with field survey data of COTS outbreaks, the regional-scale maps show which reefs have a systemic resilience to impacts and were labelled as robust source reefs (Hock, et al., 2017). In general, these robust reefs were found at sites along the outer-shelf, from the far northern GBR and south to a large cluster of robust reefs in the Swain Reefs.

Connectivity models require a range of spatial datasets as the source data for reef locations, including optical and sea surface temperature satellite imagery, or reef boundary polygons derived from nautical charts, aerial and satellite imagery. In the case of the GBR_Features dataset (GBRMPA, 2013) used in the GBRMPA Zoning maps, the main features (e.g. reefs, islands, coastline etc.) had been digitised through a contract with Australian Surveying and Land Information Group (AUSLIG) but required much edge matching as the data were supplied from 11 separate map sheets using the original Landsat-MSS images (Hopley, Smithers, & Parnell, 2007).

Oceanographic modelling also requires spatial datasets such as digital elevation models (DEMs) to provide the topographic surface and boundary conditions for the modelling. The Marine and Tropical Sciences Research Facility (MTSRF) Project 2.5i.1 'Hydrodynamics at the whole of GBR scale', utilised the gbr100 DEM - a bathymetry (or depth) grid - of the entire GBR and offshore Coral Sea area to provide the boundary conditions for the 3D hydrodynamic modelling of the GBR shelf. The gbr100 grid uses a pixel resolution of ~100 m and had been developed as an output of Project 3D-GBR (Beaman, 2010).

The gbr100 grid was also used to identify the location and extent of deep-water habitats through digitised maps of the submerged banks and near-sea-surface (NSS) reefs (Harris et al., 2013). This research questioned how common are deep reef habitats in comparison with NSS reefs? About 39% of the available seabed on submerged banks is capped by NSS coral reefs (16,110 km^2), and the other 61% of bank area (25,600 km^2) is submerged at a mean depth of around 27 m and represents potential deep reef habitat (Harris, et al., 2013).

The prevalence of submerged banks on the GBR shelf raises questions around the potential of submerged banks or deeper (>15 m depth) reefs to act as deep-water habitat for COTS? Amongst the shallow reefs on the northern GBR, there are a number of shallow (or NSS) reefs that have permanent COTS study sites, selected because they are known 'super spreader' (i.e. repeat outbreak) sites or have special value as Tourism sites (Table 1). COTS control teams would benefit from understanding the spatial relationship of these sites to the overall reef topography, beyond what can be viewed in the nautical charts or in the Zoning maps.

Table 1: Reef names and characteristics of 'super spreader' and tourism reefs with permanent COTS sites

	Reef Name (ID)	**Characteristics**
1	St Crispin Reef (16-019)	Tourism
2	Undine Reef (16-020)	Super spreader
3	Rudder Reef (16-023)	Super spreader
4	Chinaman Reef (16-024)	Super spreader
5	Opal Reef (16-025)	Tourism
6	Tongue Reef (16-026)	Tourism, Super spreader
7	Batt Reef (16-029)	Super spreader
8	Low Isles (16-028)	Tourism
9	Norman Reef (16-030)	Tourism
10	Saxon Reef (16-032)	Tourism
11	Hastings Reef (16-057)	Tourism, Super spreader
12	Michaelmas Reef (16-060)	Tourism, Super spreader
13	Green Island Reef (16-049)	Tourism, Super spreader
14	Arlington Reef (16-064)	Super spreader

15	Flynn Reef (16-065)	Tourism
16	Milln Reef (16-060)	Tourism
17	Thetford Reef (16-068)	Tourism, Super spreader
18	Moore Reef (16-071)	Tourism
19	Briggs Reef (16-074)	Tourism
20	Fitzroy Island Reefs (16-054)	Tourism
21	Elford Reef (16-073)	Super spreader
22	Rib Reef (18-032)	Current outbreak

Moreover, the limitations on dive time and depth means that COTS control is usually concerned with the top 15 m of reef. However, we know that: (1) COTS occur to depths as great as 50 m, (2) there are anecdotal reports that COTS move into controlled areas from deeper habitat, and (3) reports from elsewhere indicate that controlling COTS below 15 m may be important for lasting control. If deep-water habitat is significant, as this anecdotal information suggests, then identifying this deep-water habitat will be another factor to consider in designing successful control programs and may require changes to current management practice.

The aims of the deep-water habitat component of the COTS Working Group project were to:

(1) Integrate all the available source bathymetry data used in the latest gbr100 grid and to generate a much higher-resolution gbr30 grid (~30 m pixel spacing) over the GBR shelf area.
(2) Use the gbr30 grid to generate spatial datasets and descriptive statistics of the 22 'super spreader' and tourism reefs, to understand the extent of potential deep-water habitat.
(3) Conduct an assessment of the potential for submerged banks or deeper reefs to act as deep-water habitat for COTS, and the implications of this for the design of the control program.

2.0 METHODOLOGY

2.1 Development of the gbr30 bathymetry grid

The gbr30 bathymetry grid is an output of Project 3D-GBR, a collaboration between James Cook University, industry and Government, to compile all the available bathymetry source data and develop regional-scale digital elevation models (DEMs) for the Great Barrier Reef and adjacent Coral Sea. The resulting gbr30 grid, with a horizontal pixel resolution of ~30 m, is fundamental dataset for visualising the finer-scale topographic detail of shallow reefs and the surrounding deeper banks. The gbr30 grid therefore provides the source data for an assessment of the deep-water habitat on the GBR. The following methodology outlines the various source bathymetry datasets used to develop the grid and the development process.

2.1.1 MBES source data

The Australian Hydrographic Office (AHO)-supplied the majority of multibeam echo sounder (MBES) data on the GBR shelf. Geoscience Australia (GA) provided other MBES data, acquired mostly offshore by Australia’s Marine National Facility vessels and also foreign research vessels transiting through the area. Extensive editing on the source data were conducted using QPS Fledermaus and Caris HIPS&SIPS software, and by applying sound velocity and mean sea level (MSL) tide corrections where necessary.

2.1.2 SBES source data

The AHO have conducted extensive singlebeam echo sounder (SBES) surveys across the GBR shelf for safety of navigation purposes. Other SBES data were from Maritime Safety Queensland (MSQ), various Queensland Port Authorities and from older National Mapping Division surveys. Data editing were conducted on 3D point clouds generated with Fledermaus software, and lowest astronomical tide (LAT) to MSL tide corrections applied using the Australian Vertical Datum Transformation Tool (AusCoastVDT).

2.1.3 ENC source data

Electronic Navigational Chart (ENC) spot depths were generated from S-57 files provided by the AHO and broadly cover the entire GBR shelf and the upper slope. These spot depths were extracted from S-57 files using an ESRI file geodatabase and the xyz data imported to Fledermaus software for examining as 3D point clouds. The accepted bathymetry data were then exported from Fledermaus and LAT-MSL adjustment conducted with AusCoastVDT prior to interpolation of the depth model.

2.1.4 ALB source data

Airborne lidar bathymetry (ALB) data were from extensive, AHO-supplied Laser Airborne Depth Sounder (LADS) surveys conducted over the GBR since 1993. Other ALB data were from the Sunshine Coast for the CRC for Spatial Information, and from the Torres Strait using the Fugro SHOALS-1000T system. ALB depths are typically limited to ~40 m. Bathymetry data were imported to Fledermaus software for editing and then LAT-MSL adjustment conducted with AusCoastVDT.

2.1.5 ITEM source data

The ITEM DEM data were derived from the Intertidal Extents Model (ITEM v1.0), a national-scale gridded dataset characterising the spatial extents of the exposed intertidal zone, based upon a full 28 year time series of Landsat observations. ITEM DEM data have 25 m point spacing and have a MSL vertical datum. This version of the gbr30 grid only has ITEM DEM data southwards from latitude 23° South. Future versions of the grid will include ITEM DEM along the remaining intertidal zone.

2.1.6 SDB source data

Satellite derived bathymetry (SDB) data utilise optical imagery and rely on physics- or empirical-based techniques to extract depth data. The Queensland Government-supplied SDB data were created by Earth Observation and Environmental Services (EOMAP) using physics-based Landsat8 for the Gladstone area. EOMAP supplied SDB data using physics-based Landsat8 for offshore Coral Sea reefs. Other SDB data used empirical-based Landsat7/8 data to supplement those reefs on the GBR lacking ALB data. SDB data are limited to ~20 m depth.

2.1.7 Coastline source data

Coastline source data are used to ‘pin’ the bathymetry grid at the coast in order to prevent ‘bleeding’ of land into the water during the grid development phase. Coastline data were only used where the higher priority ITEM DEM data were absent, e.g. the coast northwards of latitude 23° South. The Queensland Government-supplied coastline data were rasterised and converted to 25 m point spacing files, then AusCoastVDT used to apply a mean high water springs elevation value to the data.

2.1.8 SRTM Source data

The 1 arcsec (~27 m) Shuttle Radar Topographic Mission (SRTM) digital surface model (DSM) data were used as land elevation data for the gbr30 model. The DSM data best represents the topography of the mainland and islands, but also includes vegetation features. The 27 m data were resampled to 30 m to match the interpolated bathymetry grid pixel size. During the grid development phase, the SRTM-DSM data were merged onto the interpolated bathymetry grid to complete the gbr30 grid.

2.1.9 Grid development

The final grid development phase was conducted using Generic Mapping Tools (GMT) software (Wessel & Smith, 1991), following the methodology used in Becker et al. (2009). GMT is a Unix-based gridding and plotting software package that can deal with large datasets. This grid development phase is a ‘repair and replace’ method that is widely used for aggregating source bathymetry data for regional-scale and global-scale DEMs, e.g. SRTM30_PLUS (Figure 2).

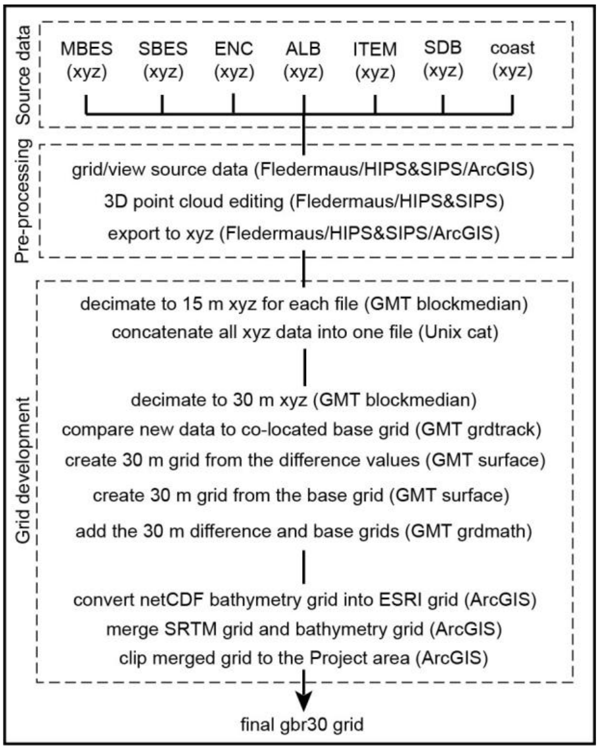

Figure 2: Processing and grid development scheme for the gbr30 grid

The xyz source data were first decimated using GMT blockmedian into individual xyz data files representing single node points at 15 m-resolution. The decimated data files were then concatenated into one large xyz file. Next, GMT blockmedian was conducted on the single large file to decimate the combined data to 30 m-resolution in order to produce one valid depth point for each pixel location to be used in the interpolated bathymetry grid at that same 30 m-resolution.

The 30 m xyz data were then compared with co-located depths from an underlying base grid, in this case the 250 m-resolution AusBathyTopo grid (Whiteway, 2009). The purpose of using a base grid was to flag any new data that may be greatly in error and thus be rejected, and also to provide underlying bathymetry data for pixels that lack coverage by the new source data. The ‘repair and replace’ method repairs the AusBathyTopo grid, replacing pixels with newer, higher-resolution data.

A grid was made with GMT surface using the difference values between the co-located new data and the underlying base data. GMT surface was used to resample the AusBathyTopo grid to 30 m-resolution. The difference grid and the resampled base grid were then added together with GMT grdmath. This resulting netCDF file was converted into an Environmental Systems Research Institute (ESRI) grid. The SRTM-DSM data were then merged with the interpolated bathymetry grid and clipped to produce the final gbr30 bathymetry grid (Figure 3)

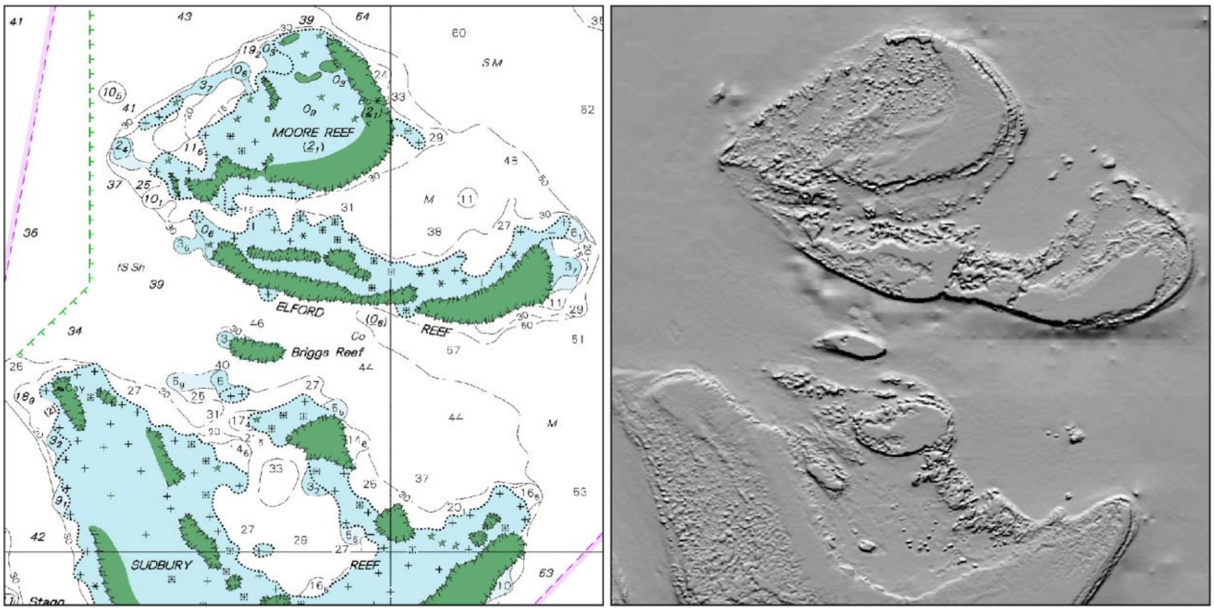

Figure 3: Comparison between chart Aus 830 and the gbr30 grid

2.1.10 Grid delivery

On 19 January 2018, the gbr30 bathymetry grid was publically released by Geoscience Australia on a dedicated page at: http://pid.geoscience.gov.au/dataset/115066
This page provides the data as ESRI grid files, Caris Spatial Archive (CSAR) files and Google Earth kmz files. Also included is the metadata table of all the source bathymetry data surveys used for creating the gbr30 grid. The bathymetry data can be used for marine habitat mapping and improving the accuracy for 3D hydrodynamic modelling of oceanographic data, and including COTS larvae tracking modelling through the reef matrix.

2.2 Spatial datasets of the ‘super spreader’ and tourism reefs

2.2.1 Extracting bathymetry data

For each of the ‘super spreader’ and tourism reefs listed in Table 1, a parent folder was created for each reef using their official name and ID number as they appear on GBRMPA Zoning maps but without spaces, e.g. \ArlingtonReef_16-064. Then within each parent folder, were given seven additional folders for use in the bathymetry data extraction and the resulting files. These folders were: \excel, \fledermaus, \googleearth, \grid, \image, \shape, \xyz.

Initially, a clipping polygon was created and stored in \shape, e.g. ArlingtonReef_clip.shp, which was used to manually pick around the deeper base of each reef at a scale of ~1:20,000 in ArcMap. Care was taken to select points where the gradients change from the relatively steeper reef walls into the surrounding inter-reefal seafloor. The GBRMPA Zoning maps were also used to guide the limits of the clipping polygons, such as where reefs shared common boundaries with other separated named shallow reefs.

The resulting clipping polygon was used to clip an area of the gbr30 grid to be stored inside the folder \grid, and simply called ‘reef’. Some of these reef grids had land elevation (+ve) data within, i.e. Green Island, and as the focus was on the underwater depth (-ve) data, a condition statement was used in ArcMap to restrict depths to <0 m. The output grid was called ‘reef00’ and stored inside \grid. Thus each reef00 grid had an upper limit of ~0 m with the deepest depth corresponding to the base of each individual reef, e.g. reef00 stored in \ArlingtonReef_16-064\grid has a max value of -0.02 m and a min value of -65.27 m.

A condition statement was then used on reef00 to extract all depths greater/equal to -15 m, resulting in a grid named 'reef0015' representing only those pixels between 0 and 15 m depth. Another condition statement extracted pixels from the reef00 grid for the area less than -15 m. This resulted in a grid named 'reef15**' where the ** values correspond to the deepest depth of the original reef00 grid, e.g. for Arlington Reef this grid was called 'reef1565'.

Next, a QPS Fledermaus project was created and named for each reef, e.g. ArlingtonReef_fledermaus.fmproj, and used to import the reef00 grid and then generate a hillshaded Fledermaus SD file at the native horizontal resolution of the grid (~30 m pixel size), e.g. ArlingtonReef_30m.sd stored in the folder \fledermaus. This SD file was then exported as a hillshaded geotif, e.g. ArlingtonReef_30m.tif stored in the folder \image, or exported as a GoogleEarth hillshaded kmz file, ArlingtonReef_30m.kmz stored in the folder \googleearth.

A table of ASCII xyz data (longitude, latitude, depth) were exported from the Fledermaus SD file, e.g. ArlingtonReef_30m.txt stored in the folder \xyz. These xyz data provided the raw values for import into an Excel spreadsheet and insert a histogram chart of the values binned by ~5 m depth bands, e.g. ArlingtonReef_30m.xlsx stored in the folder \excel. Another spreadsheet recorded the descriptive statistics of each of the bathymetry grids (reef00, reef0015 and reef15**) to show the Total No. of pixels, Min depth, Max depth, Mean depth, Proportion by %, and Area in km^2, e.g. ArlingtonReef_statistics.xlsx stored in the folder \excel.

2.2.2 Extracting morphology data

Geomorphology is the interdisciplinary and systematic study of landforms, their landscapes and the earth surface processes that create and change them (IAG/AIG, 2018). Marine geomorphology studies are not as advanced as terrestrial geomorphology, because detailed geomorphic mapping has only recently been addressed through technologies such as multibeam and airborne lidar bathymetry. National seafloor geomorphology mapping workshops are currently being hosted by GA which aim to modify existing mapping schemes for Australia and to develop semi-automated tools to extract morphology from high-resolution bathymetric DEMs, as an essential first step in a mapping scheme.

One such tool is Benthic Terrain Modeler (BTM), a plug-in for ArcGIS used to delineate the benthic zone boundaries of the physical landscape (Wright et al., 2005). BTM uses an input depth grid to generate Bathymetric Position Index (BPI) datasets through a neighbourhood analysis function. Positive cell values within a BPI dataset denote features that are higher than the surrounding area, such as ridges and pinnacles. Negative cell values within a BPI dataset denote features that are lower than the surrounding area, such as canyons and gullies. BPI values near zero are either flat areas where the gradient is near zero, or areas of constant slope where the gradient is significantly greater than zero (Wright, et al., 2005).

Studies of mesophotic coral ecosystems (MCE) on submerged reefs of the GBR shelf point to the importance of depth, location on the shelf and morphology in the distribution of community groups (T. C. L. Bridge et al., 2011; Harris, et al., 2013; Roberts, Moloney, Sweatman, &

Bridge, 2015). T. C. L. Bridge, et al. (2011) found that slope and rugosity values, generated from very high resolution DEMs, accounted for the presence of reef-associated macrofaunal communities. Roberts, et al. (2015) found hard coral cover was highest in groups found on the crests of the submerged reefs. Therefore, the BTM tool can provide a morphology classification to help identify potential deep-water coral habitats from the derived crests and slopes.

A classification dictionary is required for BTM (Table 2). Experiments with the gbr30 grid found a gradient of 3° was useful to delineate sloping areas from flat areas. Shallow and deep areas were delineated at -15 m, and land were pixel values higher than 1 m. Hence, morphology was classified into nine Classes: Crests shallow and deep, Depressions shallow and deep, Flats shallow and deep, Slopes shallow and deep, and Land. For each of the reefs listed in Table 1, the clipping polygons generated above were used to clip the BTM outputs to the reef boundaries, to be stored inside the folder \grid and called 'morph'

Table 2: BTM classification dictionary to specify classes based on ranges of input BPI rasters and slope

Class	Zone	BroadBPI Lower	BroadBPI Upper	FineBPI Lower	FineBPI Upper	Slope Lower	Slope Upper	Depth Lower	Depth Upper
1	Crests shallow	50						-15	1
2	Crests deep	50							-15
3	Depressions shallow		-50					-15	1
4	Depressions deep		-50						-15
5	Flats shallow	-50	50				3	-15	1
6	Flats deep	-50	50				3		-15
7	Slopes shallow	-50	50			3		-15	1
8	Slopes deep	-50	50			3			-15
9	Land							1	

The Class 2-Crests deep and Class 8-Slopes deep were then extracted from the grid 'morph' to identify potential deep-water coral habitats. The output was stored inside the folder \grid and called 'deep_habitat', e.g. Arlington Reef has a grid 'deep_habitat' that has pixels representing only Class 2-Crests deep and Class 8-Slopes deep. Viewing this deep-water habitat grid in ArcMap, allows descriptive statistics such as the number of pixels representing this habitat, the proportion of the area deeper than 15 m with deep-water habitat and a calculation of the area in km^2. The descriptive statistics of deep-water habitat are included in the Excel spreadsheet for each reef, e.g. ArlingtonReef_statistics.xlsx.

Finally, an Adobe Illustrator file was created showing each reef as depicted in the GBRMPA Zoning map, against the equivalent area of the hillshaded gbr30 grid, overlaid by the deep-water habitat grid and coloured by Crests deep and Slopes deep. These side-by-side images give the end-user an appreciation of the topographic detail of each reef that cannot be given by the reef boundary polygons of the GBRMPA Zoning maps alone. The Illustrator files then provided exported jpg images for use in this report, e.g. ArlingtonReef.ai and ArlingtonReef.jpg are stored under the parent folder \ArlingtonReef_16-064.

The following text, figures and tables provide one page for each of the 'super spreader' and tourism reefs starting with a brief introduction of their geographic place and relative size on the

GBR shelf. Figures show the side-by-side comparison between the GBRMPA Zoning map and corresponding gbr30 grid, overlaid by the deep-water habitat grid for each reef. Tables show the extracted descriptive statistics of each reef as depth ranges of the entire reef area, 0-15 m and >15 m depth ranges, together with statistics for the deep-water habitat area for depths >15 m. Histograms show the number of pixels within each ~5 m depth band for each reef.

2.2.3 St Crispin Reef 16-019

St Crispin Reef 16-019 lies on the outer-shelf 57 km northeast of Port Douglas at 16° 06.4'S, 145° 50.1'E. The reef shares a western boundary with Undine Reef 16-020.

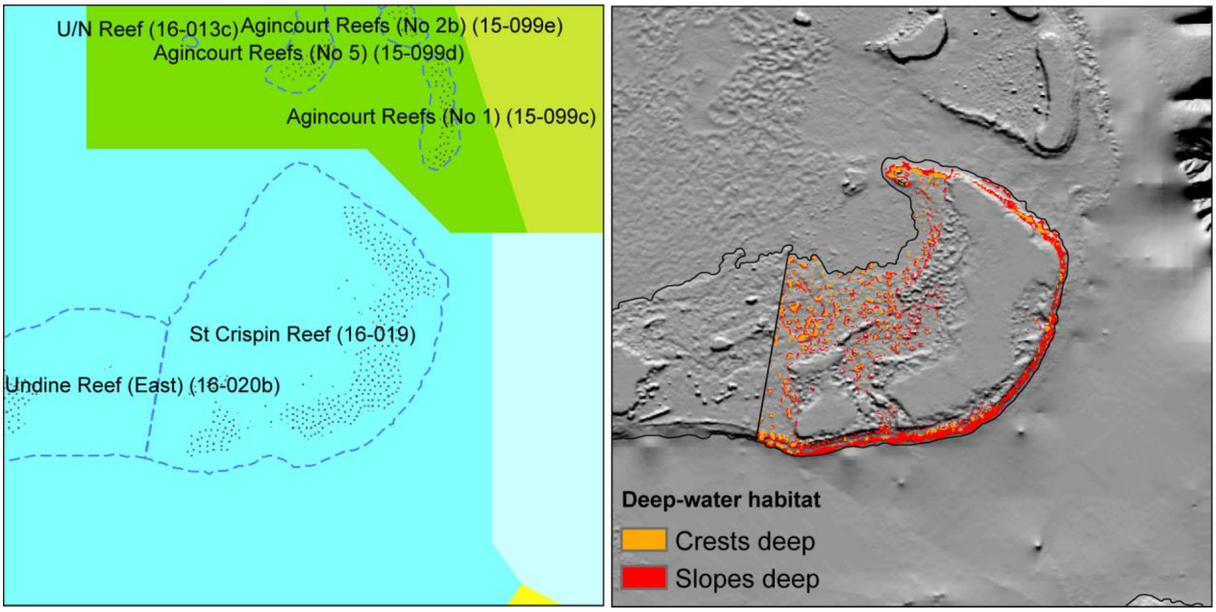

Figure 4: St Crispin Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 3: Descriptive statistics for depth range at St Crispin Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-47 m	Deep-water habitat
Total No. pixels	38505	20335	18170	5833
Min depth (m)	0.00	0.00	-15.00	
Max depth (m)	-47.62	-14.99	-47.62	
Mean depth (m)	-14.50	-5.50	-24.57	
Proportion %	100.00	52.81	47.19	32.10
Area (km^2)	41.26	21.79	19.47	6.25

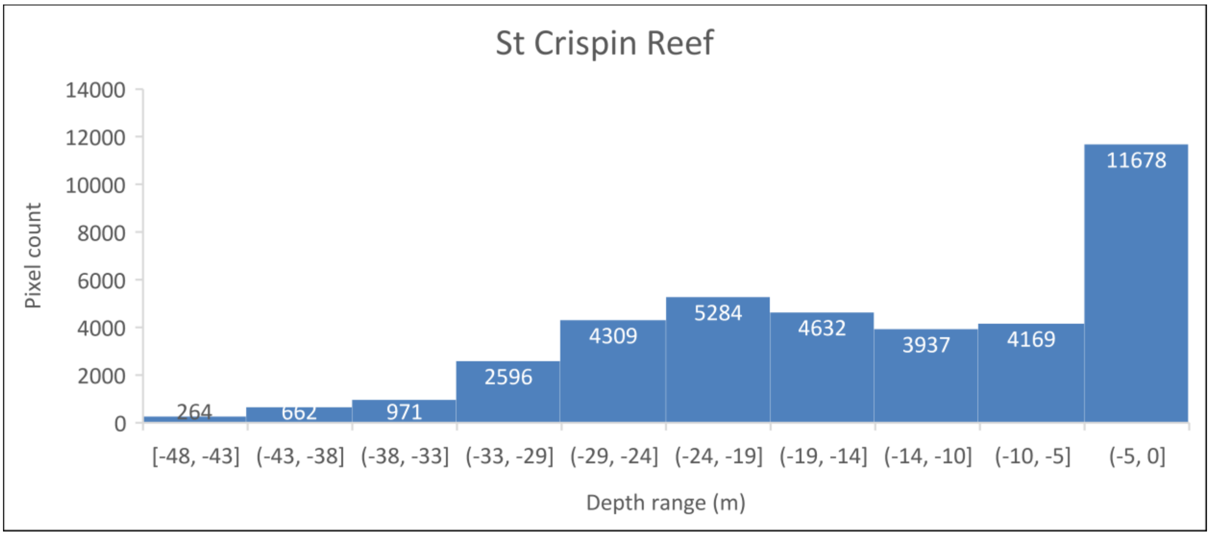

Figure 5: Histogram of depth range at St Crispin Reef

2.2.4 Undine Reef 16-020

Undine Reef 16-020 lies on the mid- to outer-shelf 48 km northeast of Port Douglas at 16° 07.4'S, 145° 44.0'E. The reef shares an eastern boundary with St Crispin Reef 16-019.

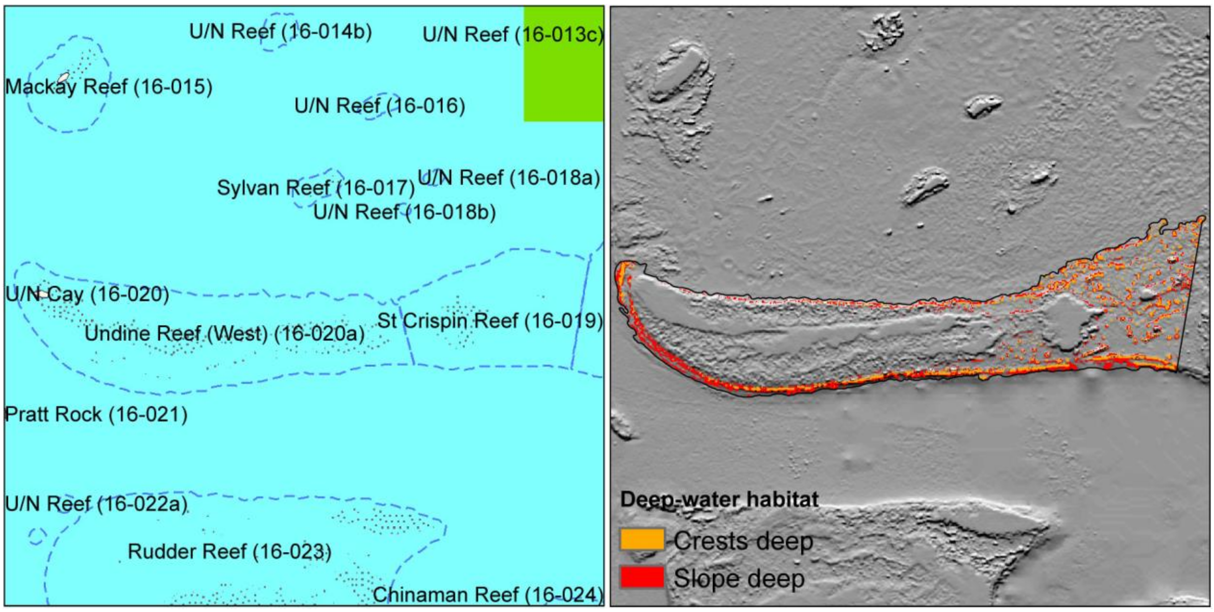

Figure 6: Undine Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 4: Descriptive statistics for depth range at Undine Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-47 m	Deep-water habitat
Total No. pixels	53805	27949	25856	7794
Min depth (m)	-0.04	-0.04	-15.00	
Max depth (m)	-47.33	-15.00	-47.33	
Mean depth (m)	-15.08	-6.76	-24.08	
Proportion %	100.00	51.94	48.06	30.14
Area (km^2)	57.65	29.95	27.70	8.35

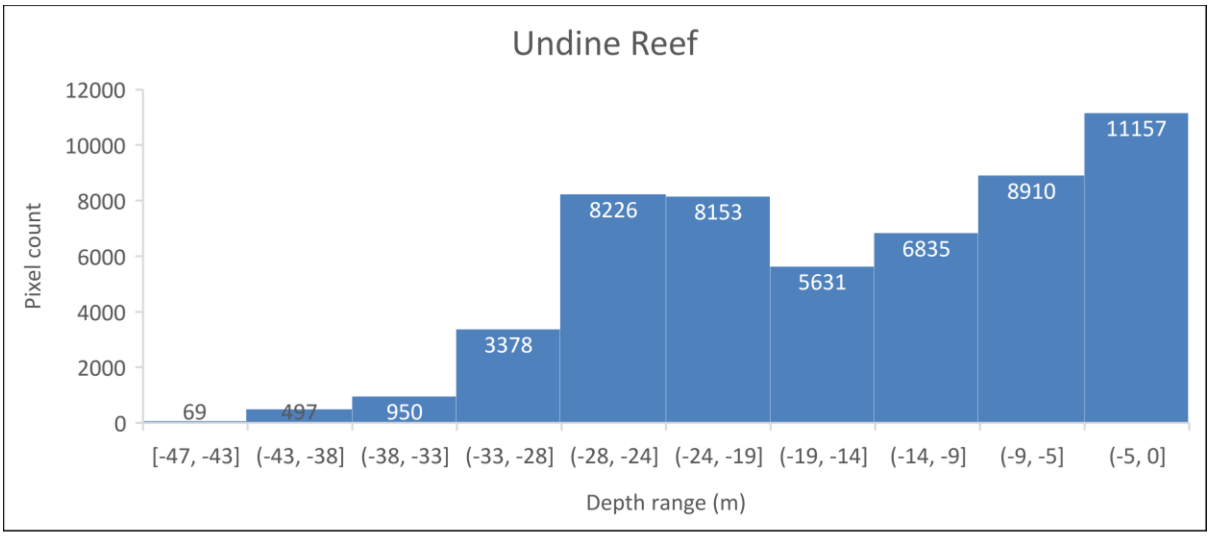

Figure 7: Histogram of depth range at Undine Reef

2.2.5 Rudder Reef 16-023

Rudder Reef 16-023 lies on the mid-shelf 41 km northeast of Port Douglas at 16° 11.4'S, 145° 41.9'E. The reef adjoins two smaller U/N reefs 16-022ab on the northwestern side.

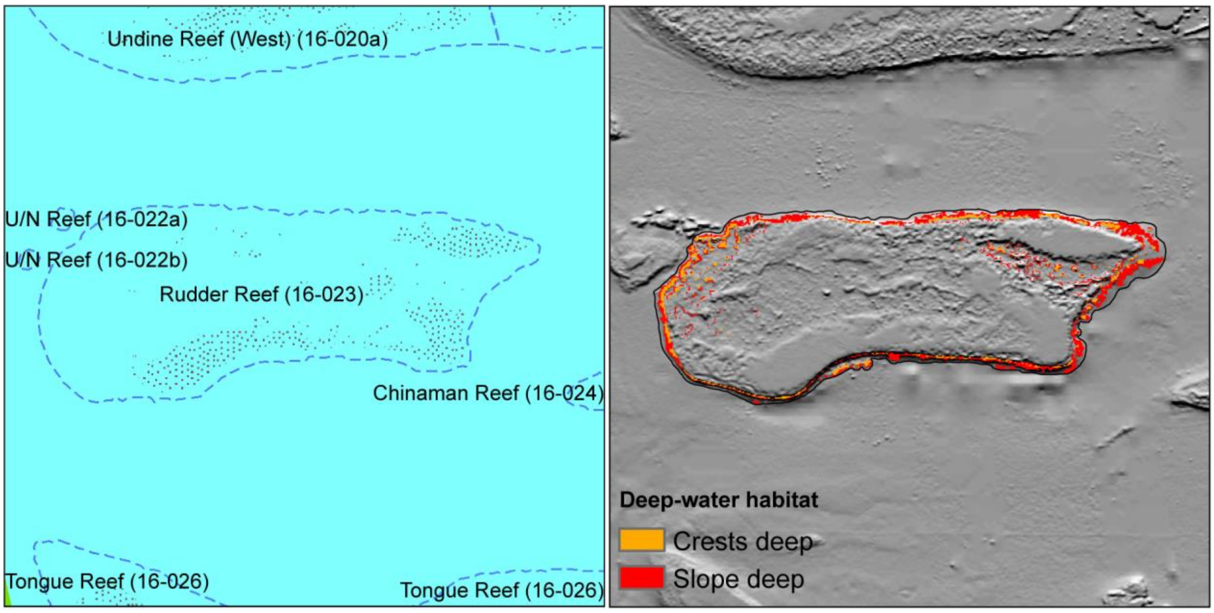

Figure 8: Rudder Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 5: Descriptive statistics for depth range at Rudder Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-48 m	Deep-water habitat
Total No. pixels	45829	32784	13045	4824
Min depth (m)	-0.04	-0.04	-15.00	
Max depth (m)	-48.10	-15.00	-48.10	
Mean depth (m)	-12.31	-7.68	-23.93	
Proportion %	100.00	71.54	28.46	36.98
Area (km^2)	49.08	35.11	13.97	5.17

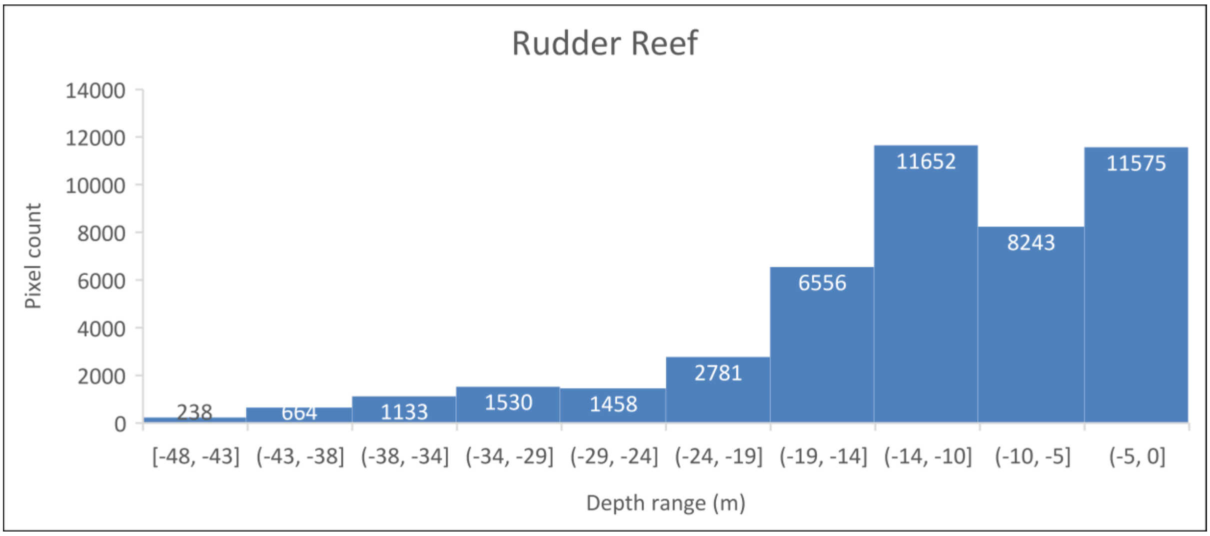

Figure 9: Histogram of depth range at Rudder Reef

2.2.6 Chinaman Reef 16-024

Chinaman Reef 16-024 lies on the mid- to outer-shelf 46 km northeast of Port Douglas at 16° 12.7'S, 145° 47.6'E. The reef is a relatively small patch reef on a deeper bank pedestal.

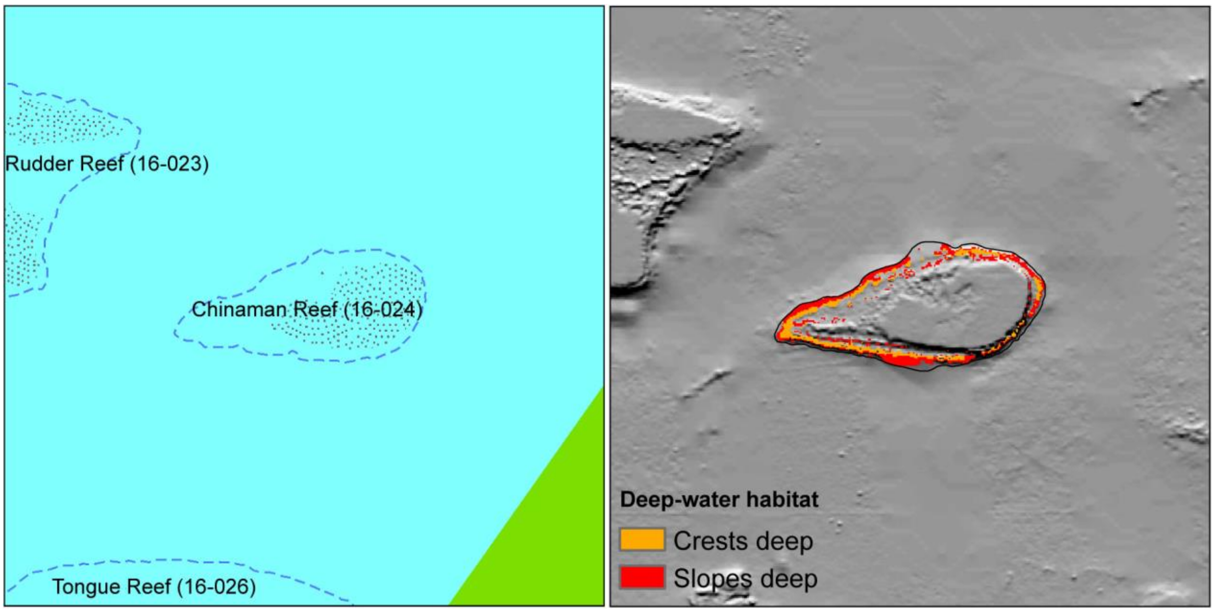

Figure 10: Chinaman Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 6: Descriptive statistics for depth range at Chinaman Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-45 m	Deep-water habitat
Total No. pixels	8033	4566	3467	1779
Min depth (m)	-0.11	-0.11	-15.00	
Max depth (m)	-45.96	-14.99	-45.96	
Mean depth (m)	-13.41	-4.65	-24.96	
Proportion %	100.00	56.84	43.16	51.31
Area (km^2)	8.60	4.89	3.71	1.90

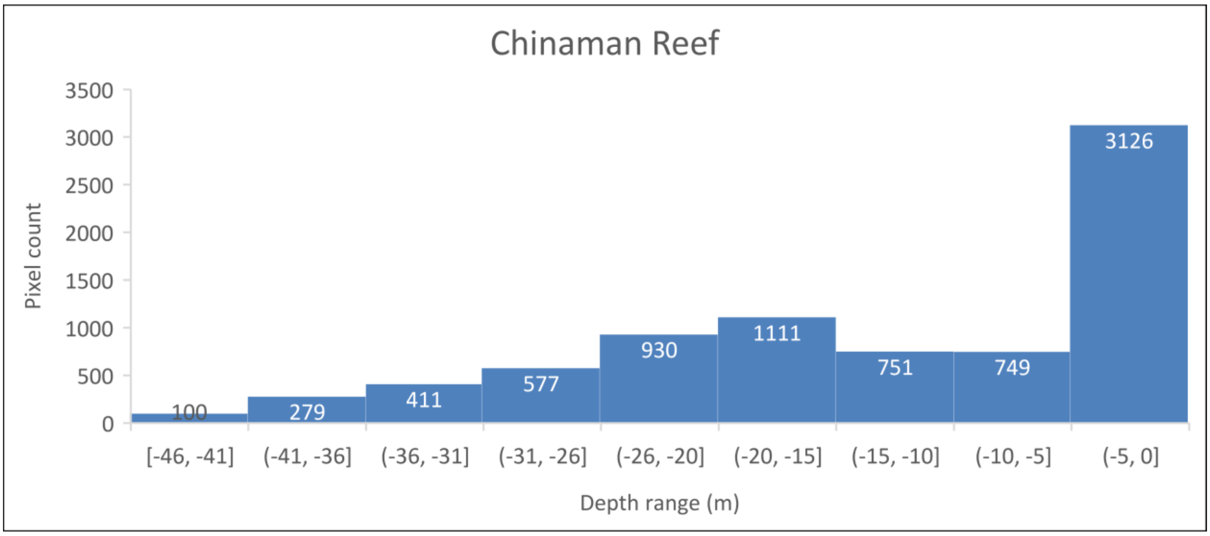

Figure 11: Histogram of depth range at Chinaman Reef

2.2.7 Opal Reef 16-025

Opal Reef 16-025 lies on the outer-shelf 53 km northeast of Port Douglas at 16° 13.6'S, 145° 53.1'E. The reef is a medium sized patch reef on a larger deep bank pedestal.

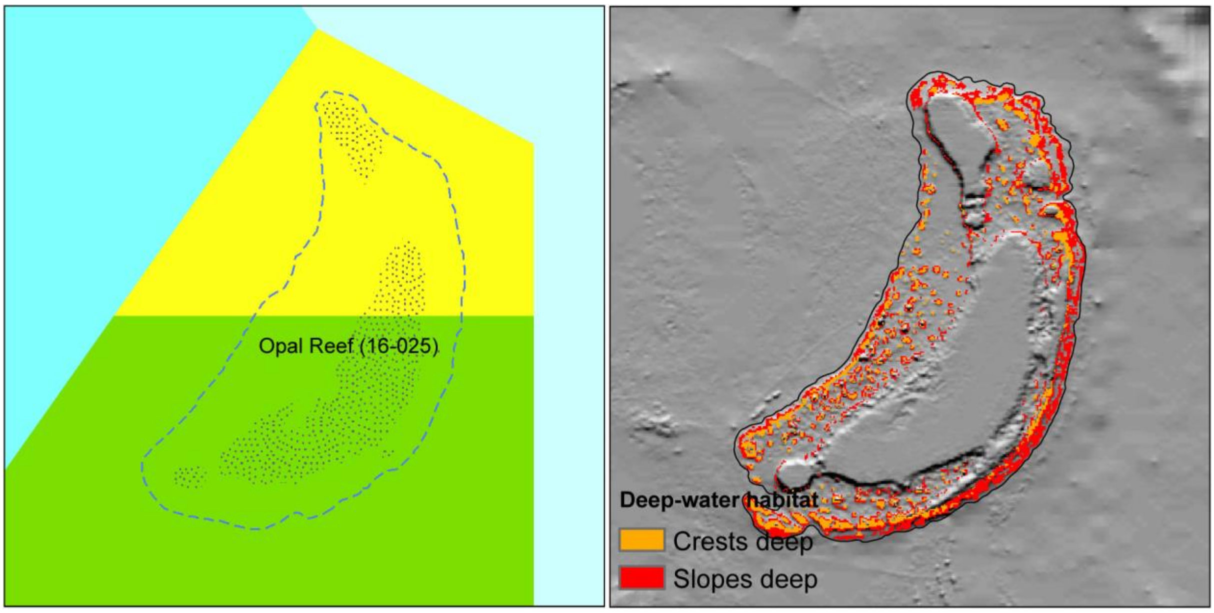

Figure 12: Opal Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 7: Descriptive statistics for depth range at Opal Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-53 m	Deep-water habitat
Total No. pixels	32747	14027	18720	7065
Min depth (m)	-0.01	-0.01	-15.00	
Max depth (m)	-53.06	-15.00	-53.06	
Mean depth (m)	-16.95	-4.64	-26.16	
Proportion %	100.00	42.83	57.17	37.74
Area (km^2)	35.07	15.02	20.05	7.57

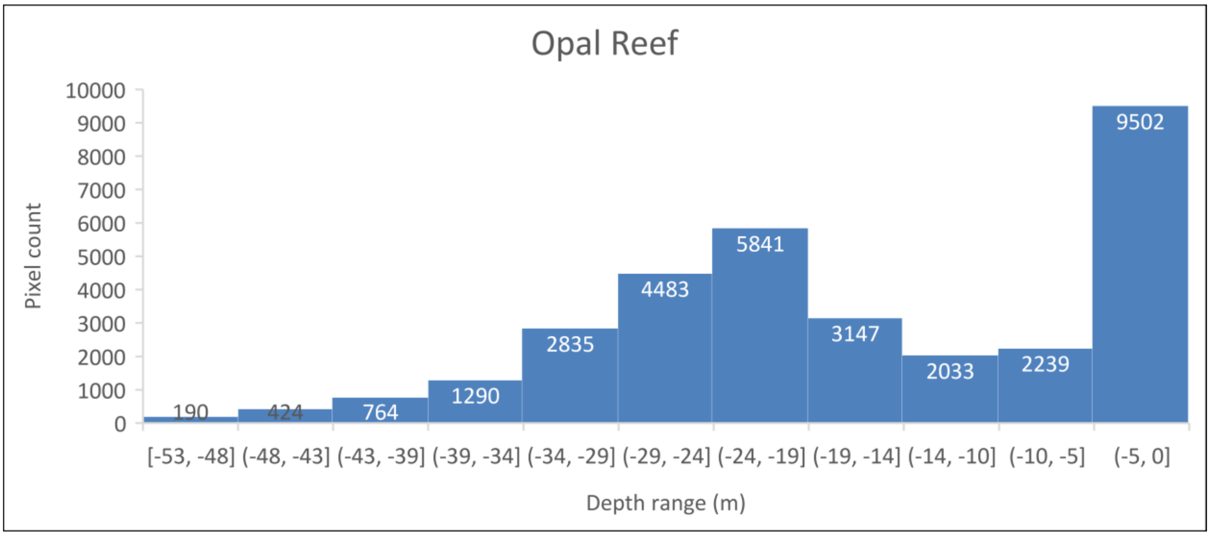

Figure 13: Histogram of depth range at Opal Reef

2.2.8 Tongue Reef 16-026

Tongue Reef 16-026 lies on the mid-shelf 39 km northeast of Port Douglas at 16° 18.2'S, 145° 46.8'E. The reef comprises large patch reefs scattered on an extensive deeper bank.

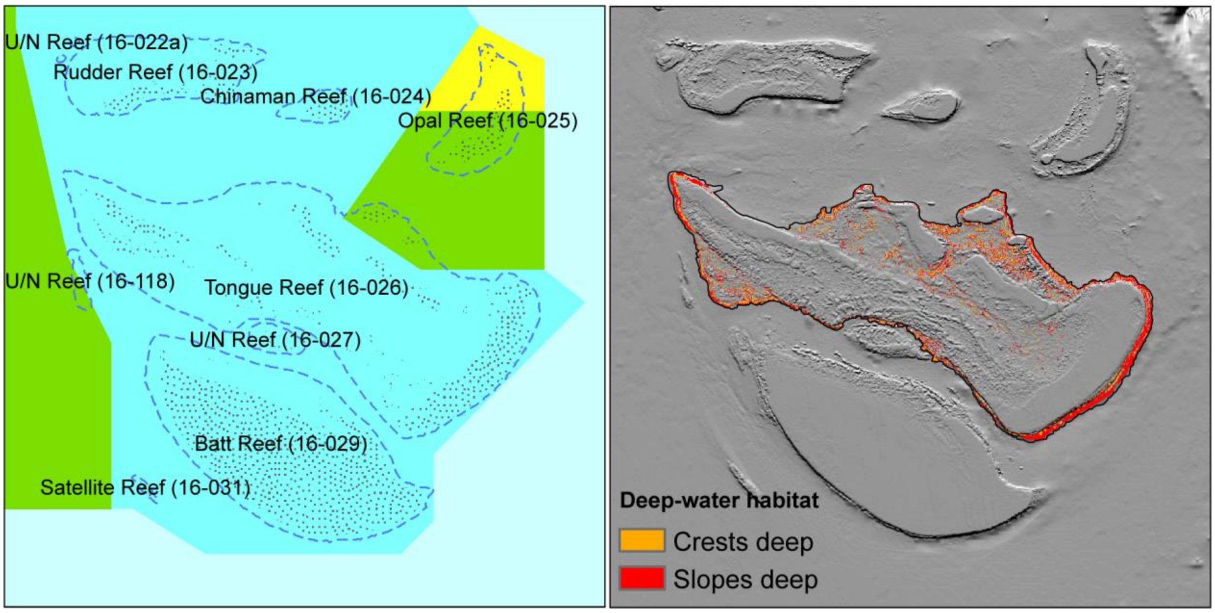

Figure 14: Tongue Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 8: Descriptive statistics for depth range at Tongue Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-66 m	Deep-water habitat
Total No. pixels	240525	156821	83704	23243
Min depth (m)	0.00	0.00	-15.00	
Max depth (m)	-66.03	-15.00	-66.03	
Mean depth (m)	-12.77	-7.40	-22.82	
Proportion %	100.00	65.20	34.80	27.77
Area (km^2)	257.43	167.84	89.59	24.88

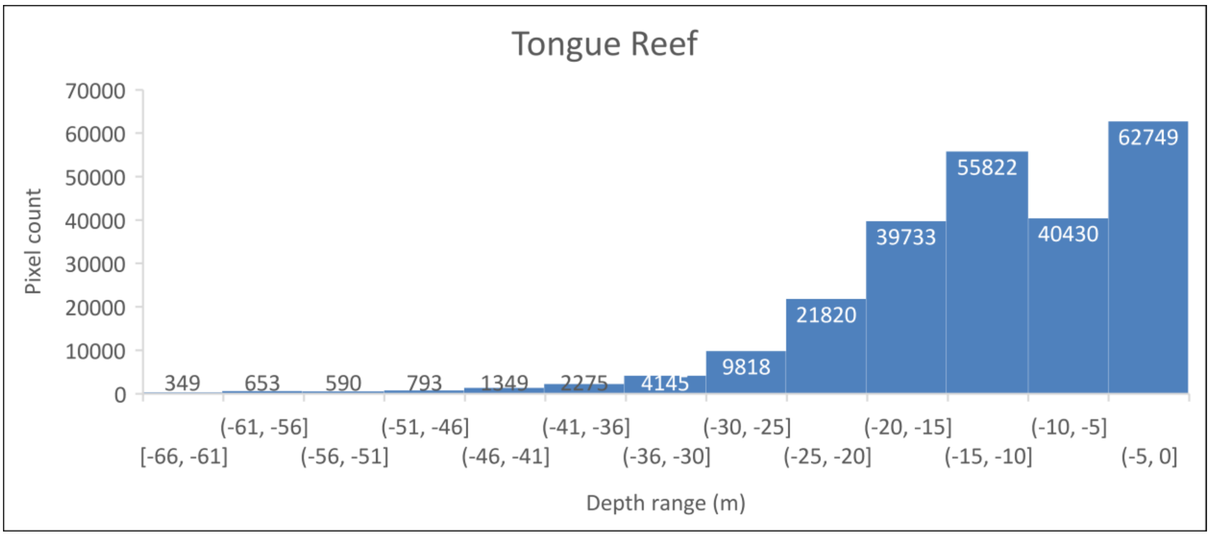

Figure 15: Histogram of depth range at Tongue Reef

2.2.9 Batt Reef 16-029

Batt Reef 16-029 lies on the mid-shelf 33 km east of Port Douglas at 16° 25.1'S, 145° 46.4'E. The reef is a large, extensively shallow patch reef and minor area of deeper bank.

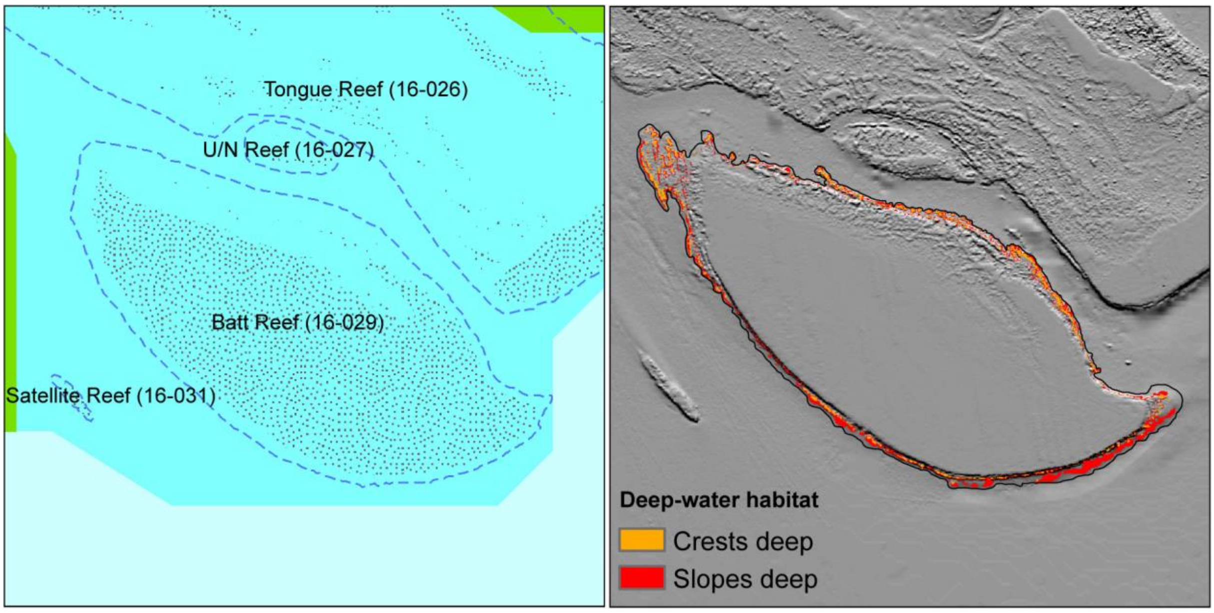

Figure 16: Batt Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 9: Descriptive statistics for depth range at Batt Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-60 m	Deep-water habitat
Total No. pixels	137197	117504	19693	7829
Min depth (m)	0.00	0.00	-15.00	
Max depth (m)	-60.49	-15.00	-60.49	
Mean depth (m)	-6.44	-3.00	-27.01	
Proportion %	100.00	85.65	14.35	39.76
Area (km^2)	146.77	125.70	21.07	8.38

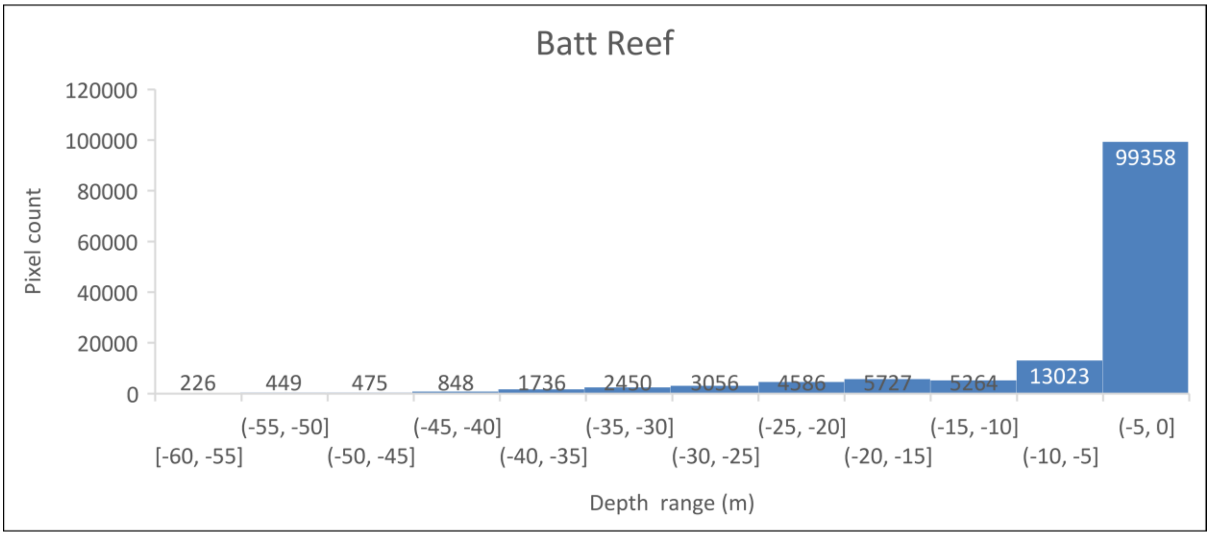

Figure 17: Histogram of depth range at Batt Reef

2.2.10 Low Isles 16-028

Low Isles 16-028 lies on the inner-shelf 15 km northeast of Port Douglas at 16° 23.1'S, 145° 33.9'E. The relative small and shallow reef surrounds sand cays with little or no deeper reef.

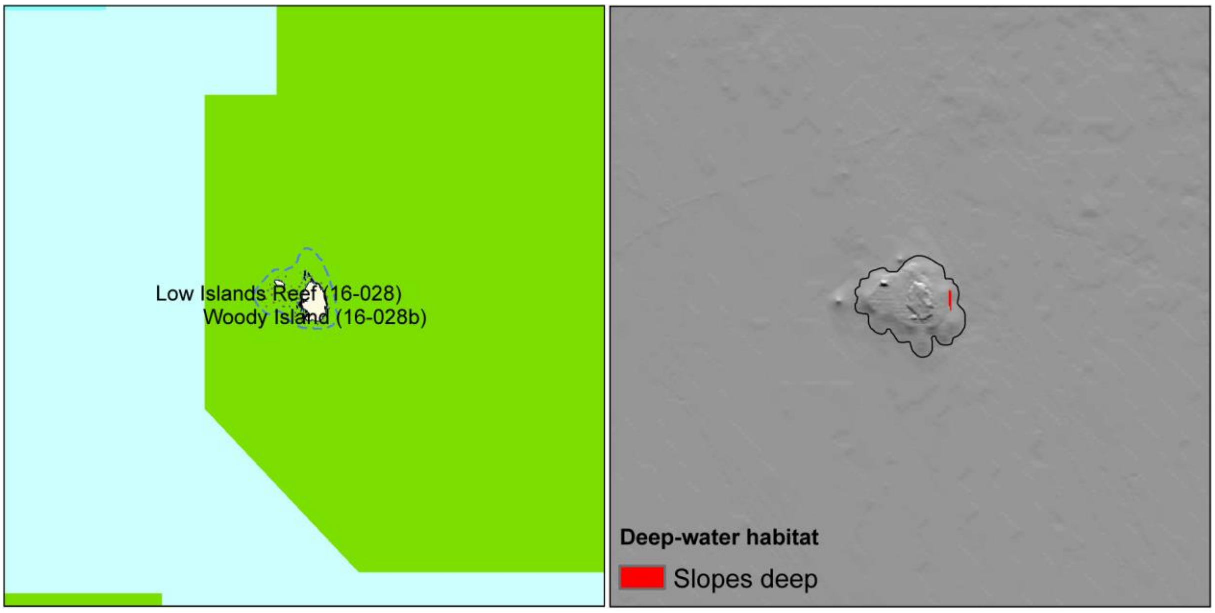

Figure 18: Low Isles in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 10: Descriptive statistics for depth range at Low Isles. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-24 m	Deep-water habitat
Total No. pixels	4148	3460	688	31
Min depth (m)	-1.61	-1.61	-15.01	
Max depth (m)	-24.68	-15.00	-24.68	
Mean depth (m)	-8.84	-6.88	-18.70	
Proportion %	100.00	83.41	16.59	4.51
Area (km^2)	4.44	3.70	0.74	0.03

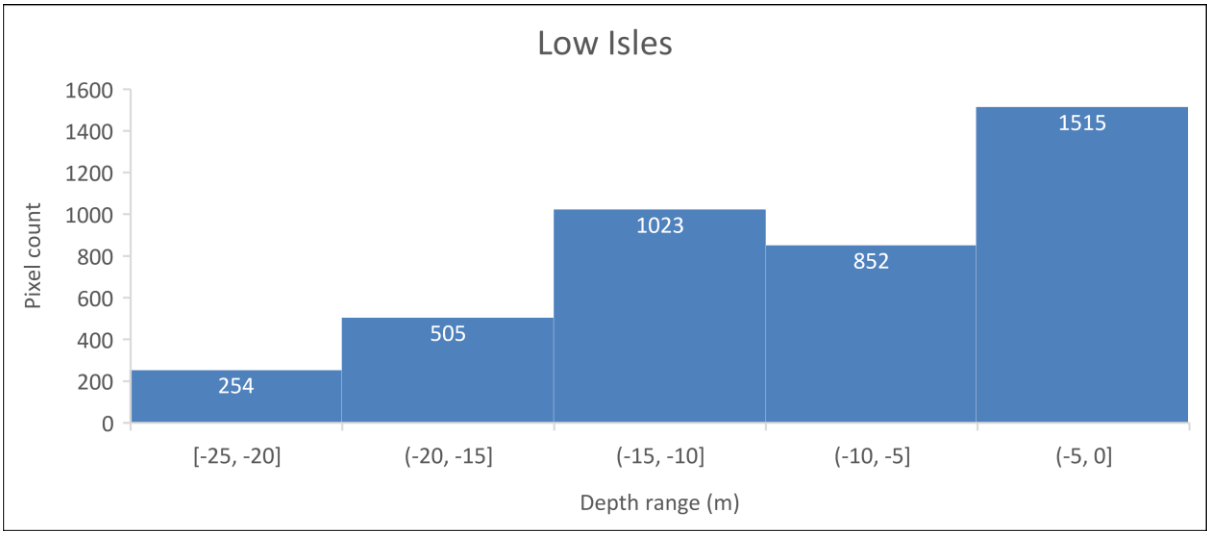

Figure 19: Histogram of depth range at Low Isles

2.2.11 Norman Reef 16-030

Norman Reef 16-030 lies on the outer-shelf 57 km east of Port Douglas at 16° 25.7'S, 145° 59.8'E. This relatively small patch reef sits on top of a much larger deep bank.

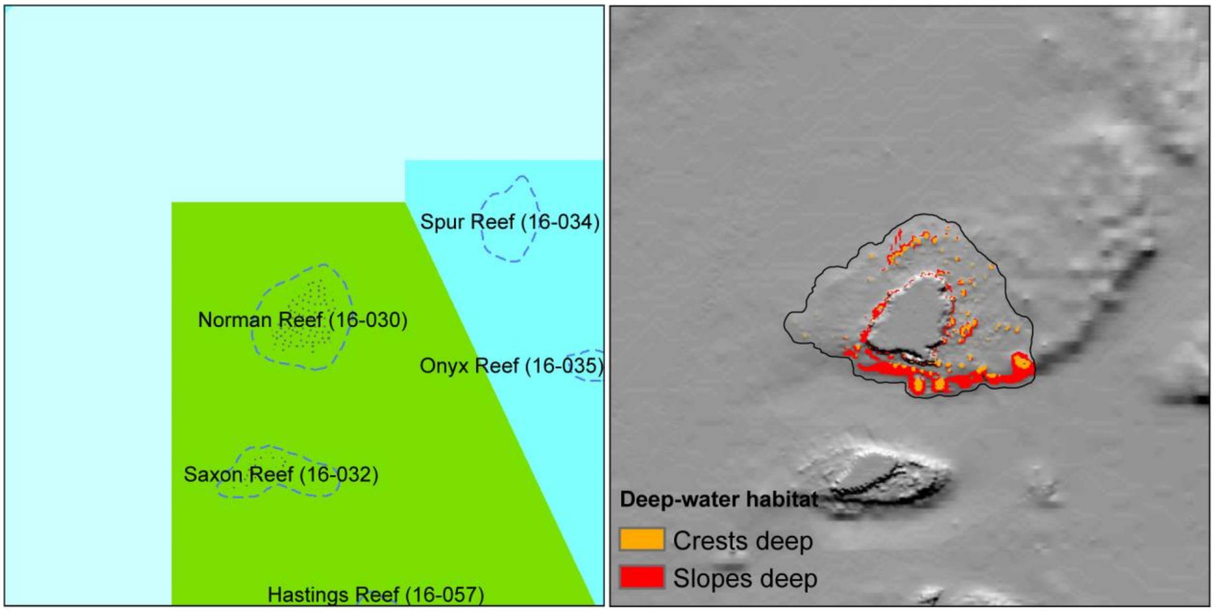

Figure 20: Norman Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 11: Descriptive statistics for depth range at Norman Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-66 m	Deep-water habitat
Total No. pixels	18808	3122	15686	2986
Min depth (m)	-0.45	-0.45	-15.00	
Max depth (m)	-66.14	-14.99	-66.14	
Mean depth (m)	-32.25	-3.63	-37.94	
Proportion %	100.00	16.60	83.40	19.04
Area (km^2)	20.12	3.34	16.78	3.19

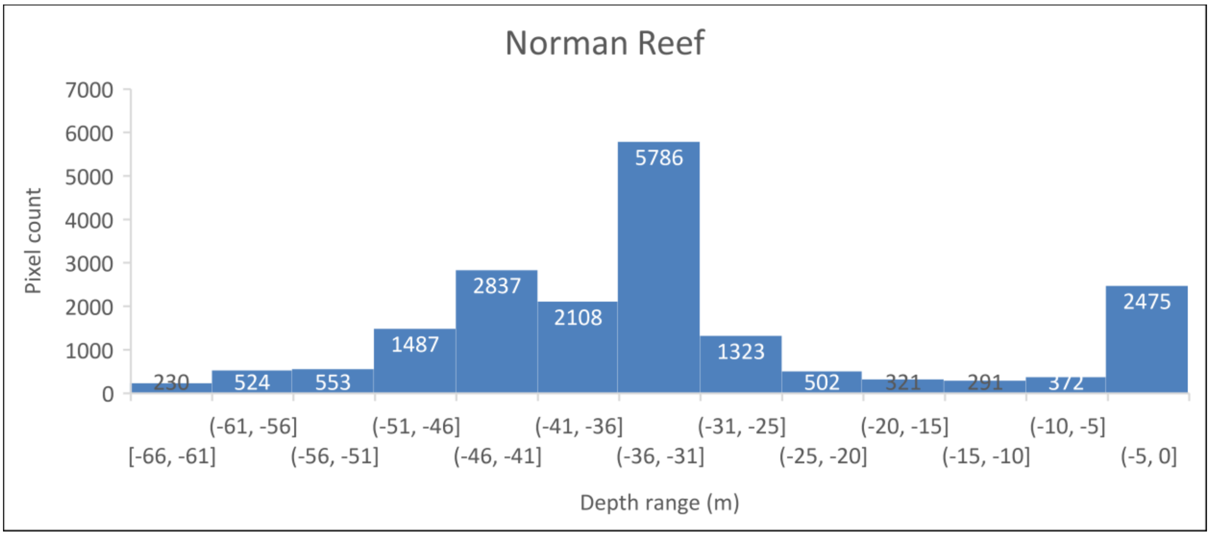

Figure 21: Histogram of depth range at Norman Reef

2.2.12 Saxon Reef 16-032

Saxon Reef 16-032 lies on the outer-shelf 56 km east of Port Douglas at 16° 27.9'S, 145° 59.3'E. This relatively small patch reef sits on top of a larger and deeper bank.

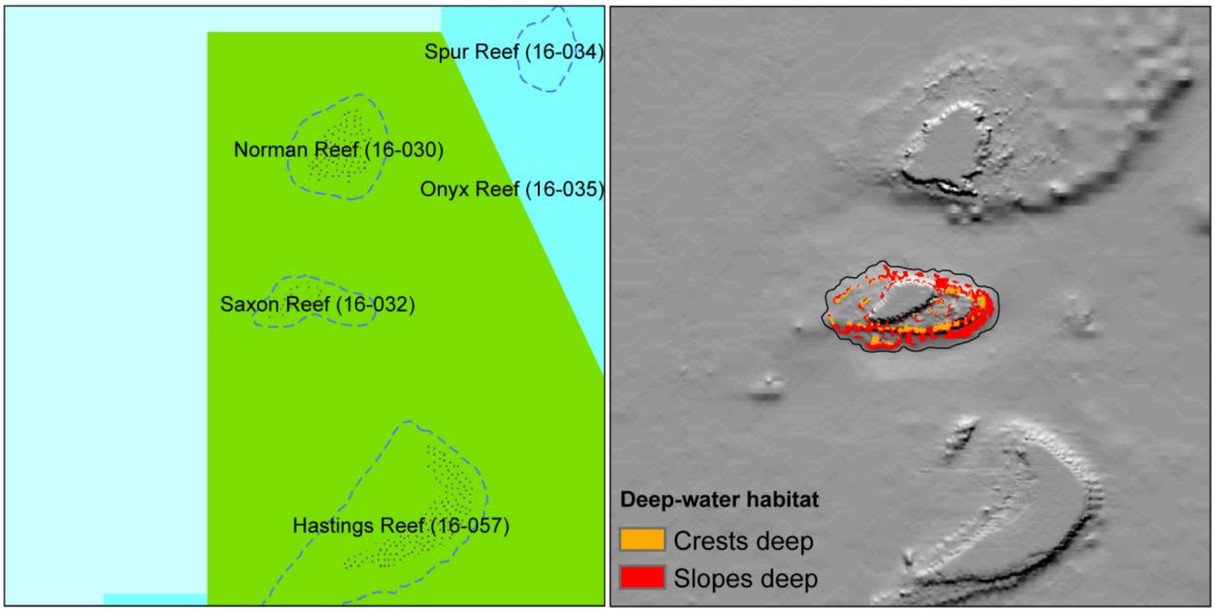

Figure 22: Saxon Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 12: Descriptive statistics for depth range at Saxon Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-71 m	Deep-water habitat
Total No. pixels	7556	1397	6159	2414
Min depth (m)	-0.41	-0.41	-15.01	
Max depth (m)	-71.08	-14.98	-71.08	
Mean depth (m)	-32.96	-4.87	-39.33	
Proportion %	100.00	18.49	81.51	39.19
Area (km^2)	8.08	1.49	6.59	2.58

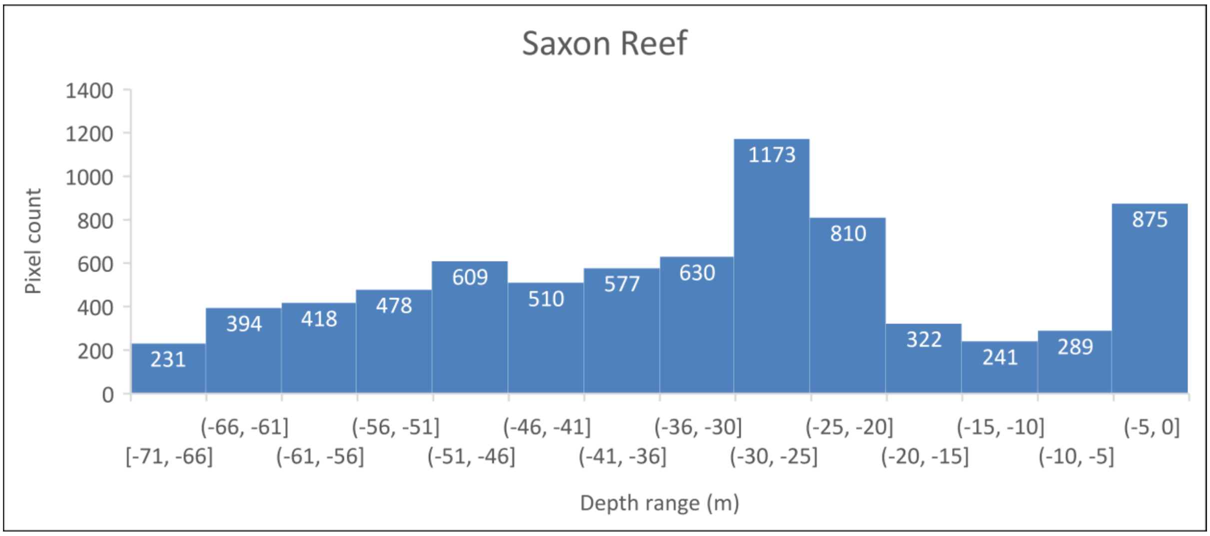

Figure 23: Histogram of depth range at Saxon Reef

2.2.13 Hastings Reef 16-057

Hastings Reef 16-057 lies on the outer-shelf 51 km northeast of Cairns at 16° 31.2'S, 145° 00.8'E. This medium sized patch reef sits on a larger and deeper bank.

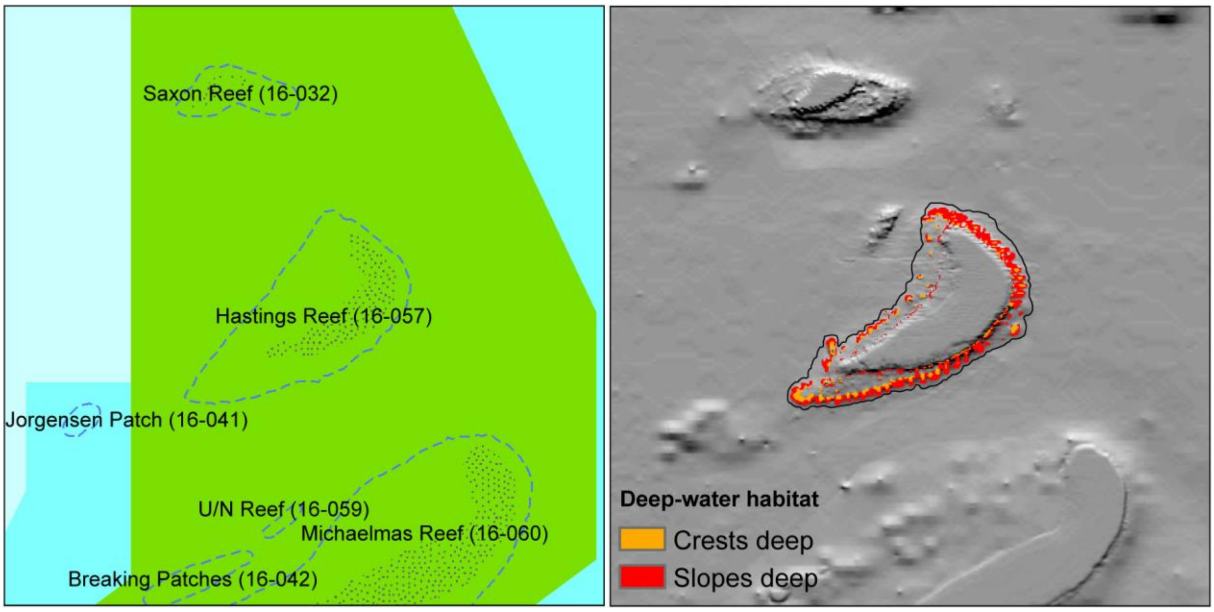

Figure 24: Hastings Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 13: Descriptive statistics for depth range at Hastings Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-58 m	Deep-water habitat
Total No. pixels	15663	7043	8620	3142
Min depth (m)	-0.63	-0.63	-15.01	
Max depth (m)	-58.35	-15.00	-58.35	
Mean depth (m)	-19.25	-4.26	-31.50	
Proportion %	100.00	44.97	55.03	36.45
Area (km^2)	16.75	7.53	9.22	3.36

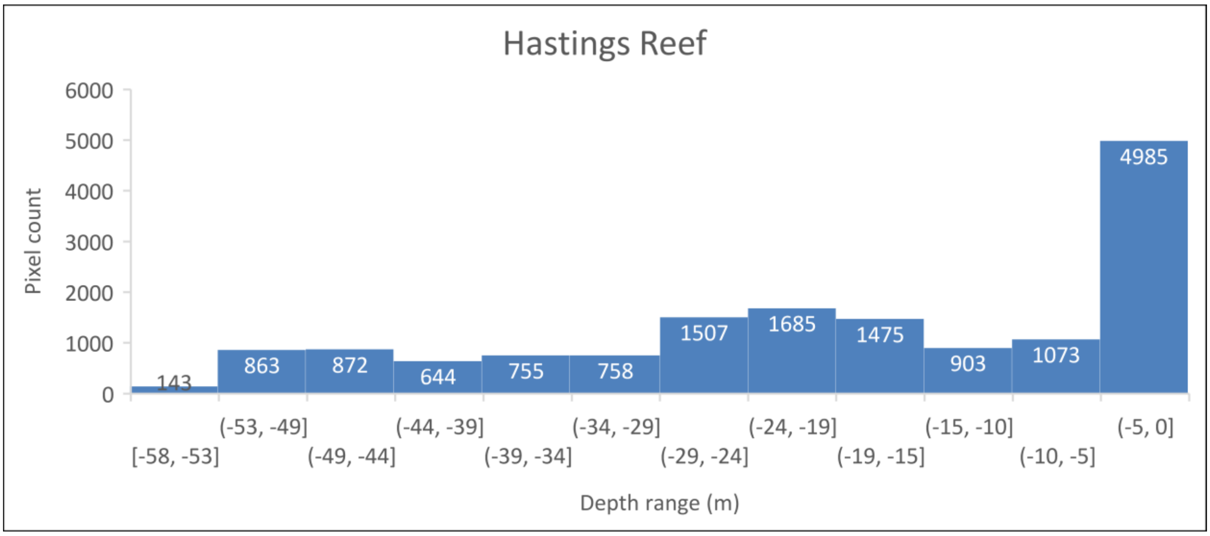

Figure 25: Histogram of depth range at Hastings Reef

2.2.14 Michaelmas Reef 16-060

Michaelmas Reef 16-060 lies on the mid- to outer-shelf 45 km northeast of Cairns at 16° 34.9'S, 146° 01.1'E. This medium sized patch reef sits on a larger and deeper bank.

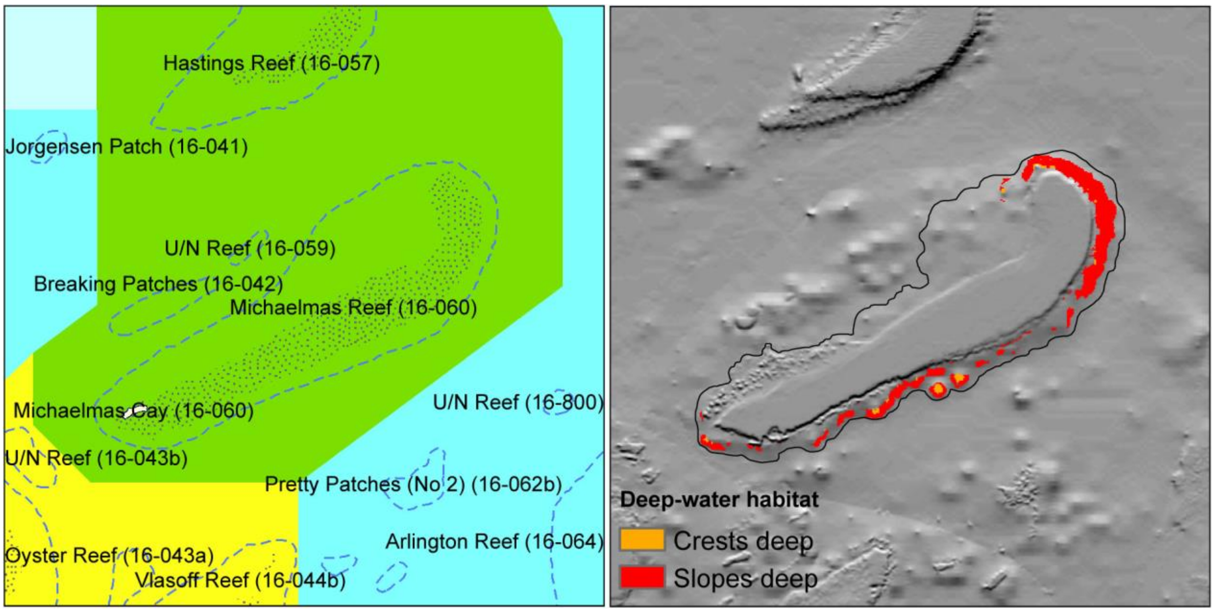

Figure 26: Michaelmas Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 14: Descriptive statistics for depth range at Michaelmas Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-62 m	Deep-water habitat
Total No. pixels	36211	26323	9888	3564
Min depth (m)	-0.29	-0.29	-15.00	
Max depth (m)	-62.52	-15.00	-62.52	
Mean depth (m)	-11.60	-5.34	-28.25	
Proportion %	100.00	72.69	27.31	36.04
Area (km^2)	38.71	28.14	10.57	3.81

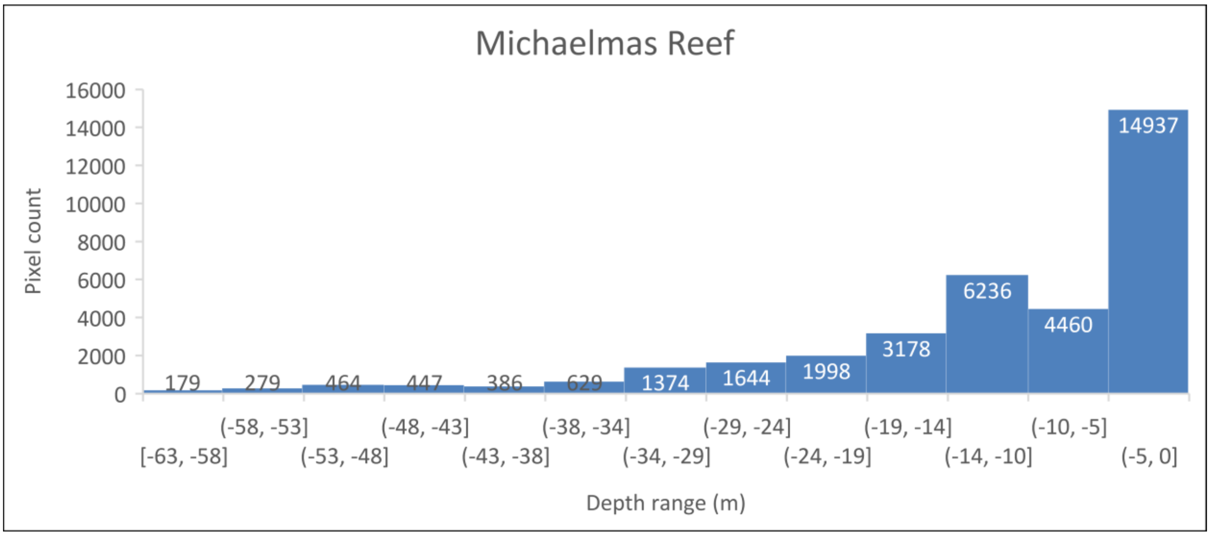

Figure 27: Histogram of depth range at Michaelmas Reef

2.2.15 Green Island Reef 16-049

Green Island Reef 16-049 lies on the mid-shelf 39 km northeast of Cairns at 16° 46.1'S, 145° 59.9'E. This medium sized patch reef surrounds a sand cay on a larger and deeper bank.

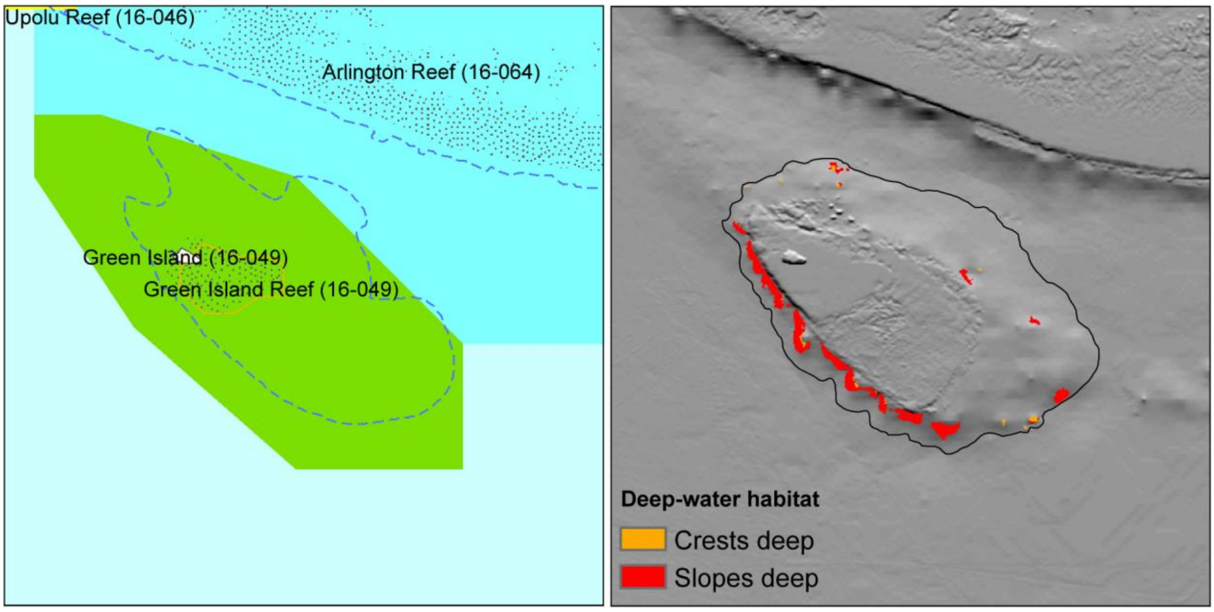

Figure 28: Green Island Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 15: Descriptive statistics for depth range at Green Island Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-49 m	Deep-water habitat
Total No. pixels	44635	24282	20353	2026
Min depth (m)	-0.03	-0.03	-15.00	
Max depth (m)	-49.41	-15.00	-49.41	
Mean depth (m)	-17.25	-6.65	-29.90	
Proportion %	100.00	54.40	45.60	9.95
Area (km^2)	47.65	25.92	21.73	2.16

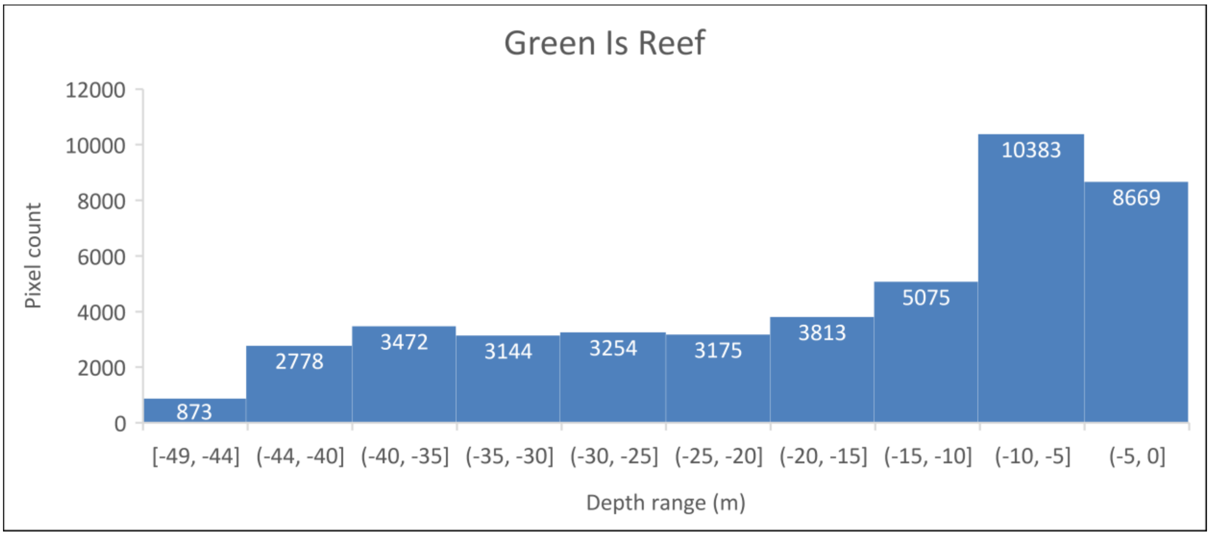

Figure 29: Histogram of depth range at Green Island Reef

2.2.16 Arlington Reef 16-064

Arlington Reef 16-064 lies on the mid- to outer-shelf 37 km northeast of Cairns at 16° 42.7'S, 146° 02.2'E. This large reef adjoins Upolu and Oyster reefs on a larger bank.

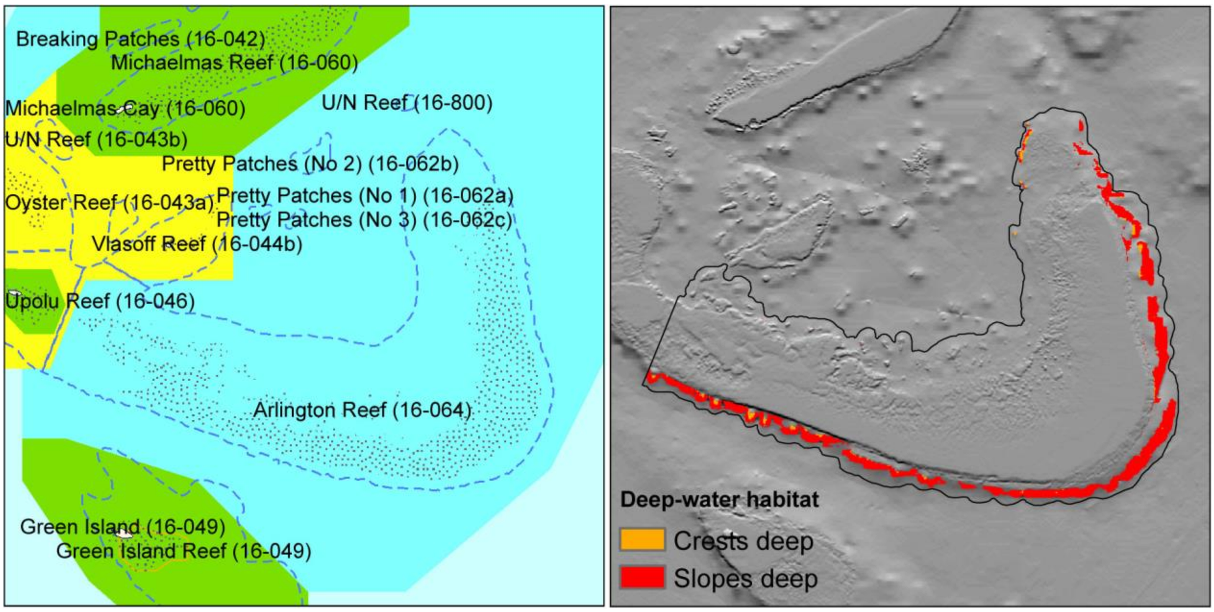

Figure 30: Arlington Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 16: Descriptive statistics for depth range at Arlington Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-65 m	Deep-water habitat
Total No. pixels	144973	105429	39544	11946
Min depth (m)	-0.02	-0.02	-15.00	
Max depth (m)	-65.27	-15.00	-65.27	
Mean depth (m)	-11.85	-4.89	-30.40	
Proportion %	100.00	72.72	27.28	30.21
Area (km^2)	154.87	112.63	42.24	12.76

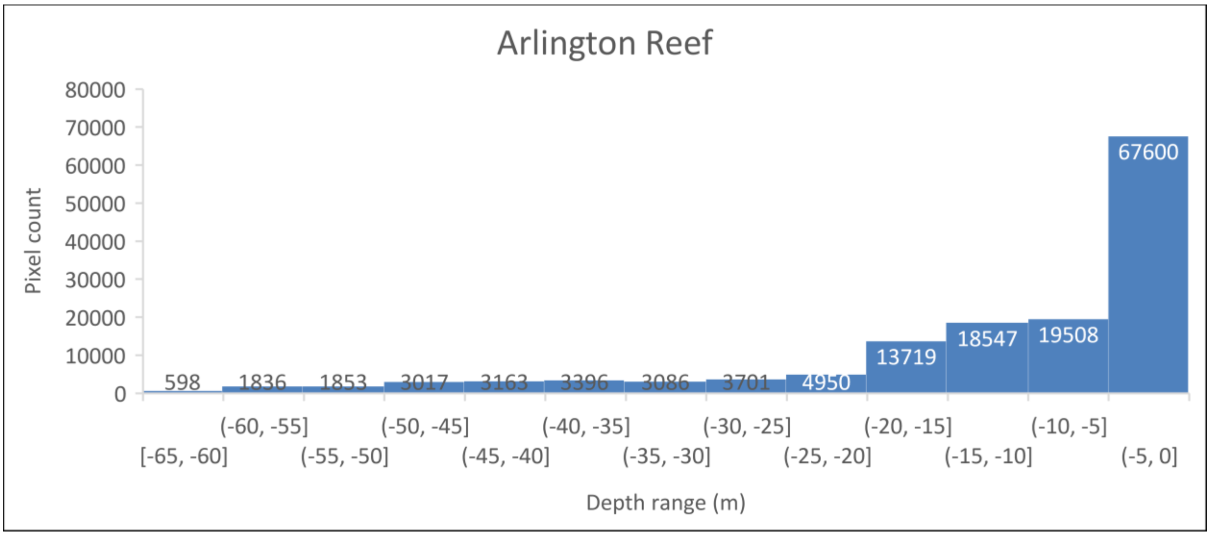

Figure 31: Histogram of depth range at Arlington Reef

2.2.17 Flynn Reef 16-065

Flynn Reef 16-065 lies on the outer-shelf 58 km east-northeast of Cairns at 16° 43.9’S, 146° 16.4’E. This medium-sized reef sits on a larger and deeper bank.

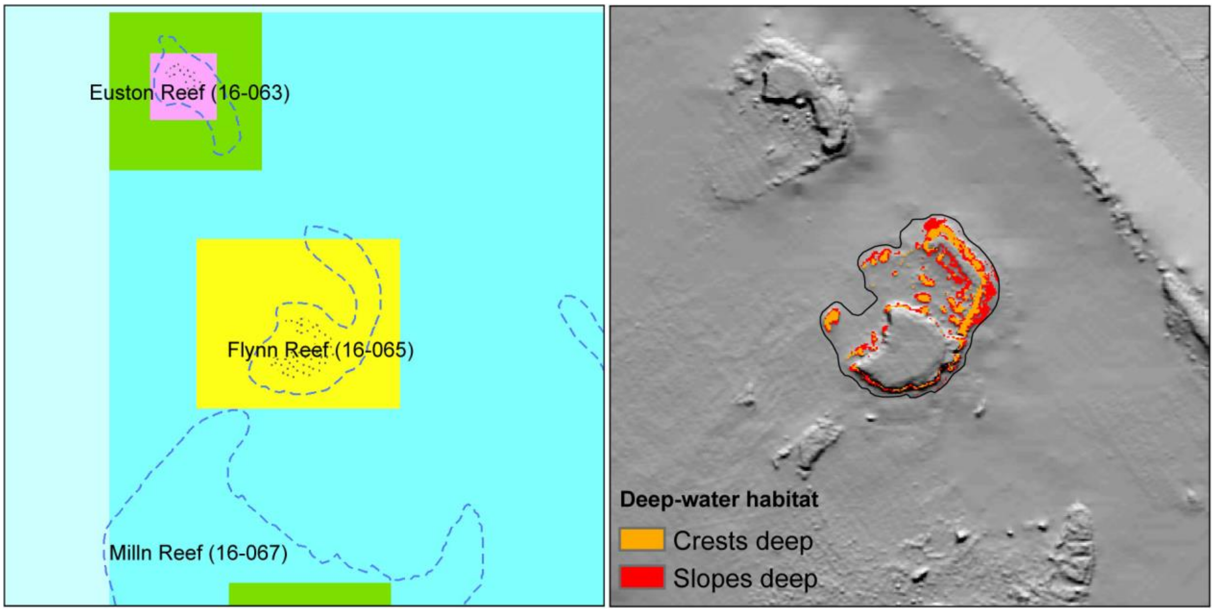

Figure 32: Flynn Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 17: Descriptive statistics for depth range at Flynn Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-51 m	Deep-water habitat
Total No. pixels	7461	2063	5398	1859
Min depth (m)	-0.03	-0.03	-15.04	
Max depth (m)	-51.74	-14.99	-51.74	
Mean depth (m)	-25.94	-5.03	-33.93	
Proportion %	100.00	27.65	72.35	34.44
Area (km^2)	7.95	2.20	5.75	1.98

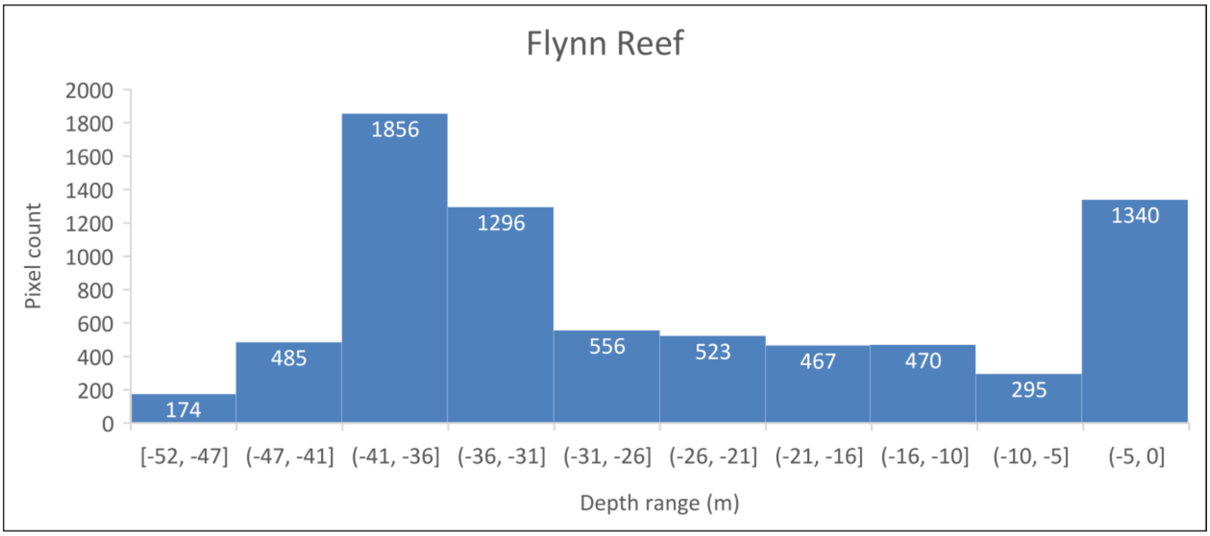

Figure 33: Histogram of depth range at Flynn Reef

2.2.18 Milln Reef 16-060

Milln Reef 16-060 lies on the outer-shelf 58 km east-northeast of Cairns at 16° 47.1'S, 146° 16.2'E. This medium-sized reef sits on a much larger and deeper bank.

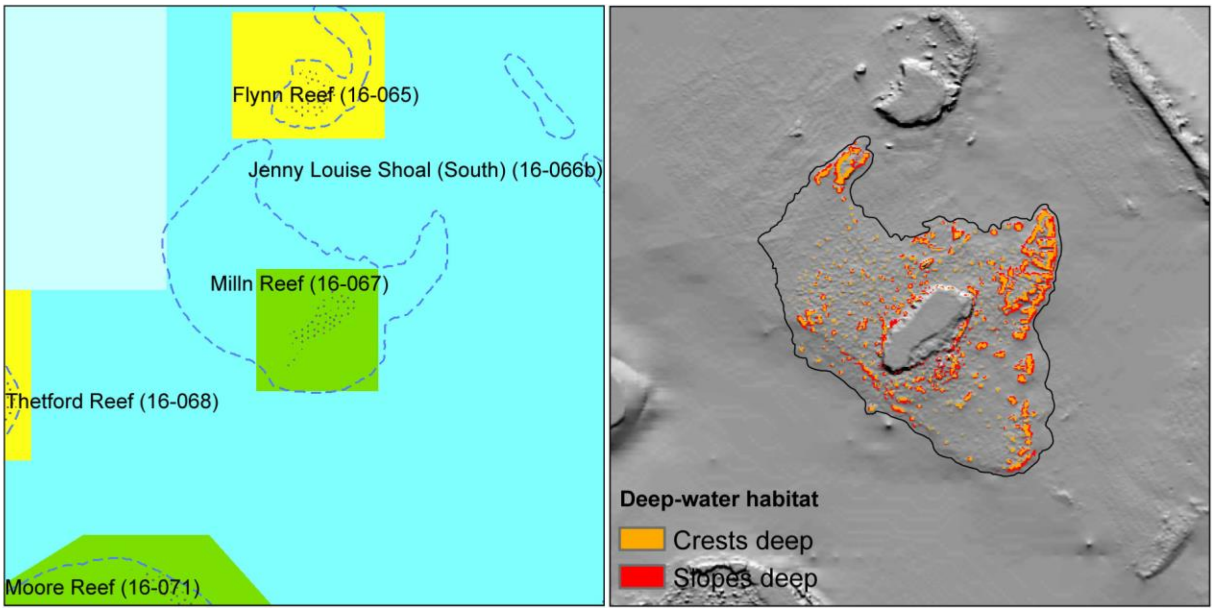

Figure 34: Milln Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 18: Descriptive statistics for depth range at Milln Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-54 m	Deep-water habitat
Total No. pixels	37658	2915	34743	5888
Min depth (m)	-0.16	-0.16	-15.00	
Max depth (m)	-54.80	-14.98	-54.80	
Mean depth (m)	-33.28	-4.63	-35.69	
Proportion %	100.00	7.74	92.26	16.95
Area (km^2)	40.21	3.11	37.10	6.29

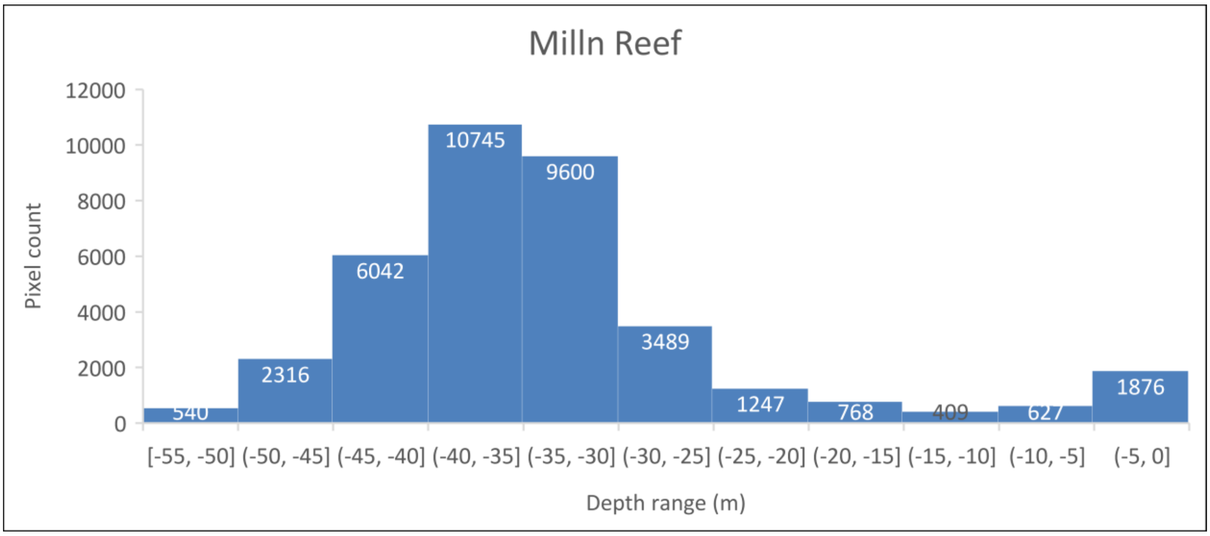

Figure 35: Histogram of depth range at Milln Reef

2.2.19 Thetford Reef 16-068

Thetford Reef 16-068 lies on the mid-shelf 46 km east-northeast of Cairns at 16° 48.1'S, 146° 10.9'E. This medium-sized reef sits on a much larger and deeper bank.

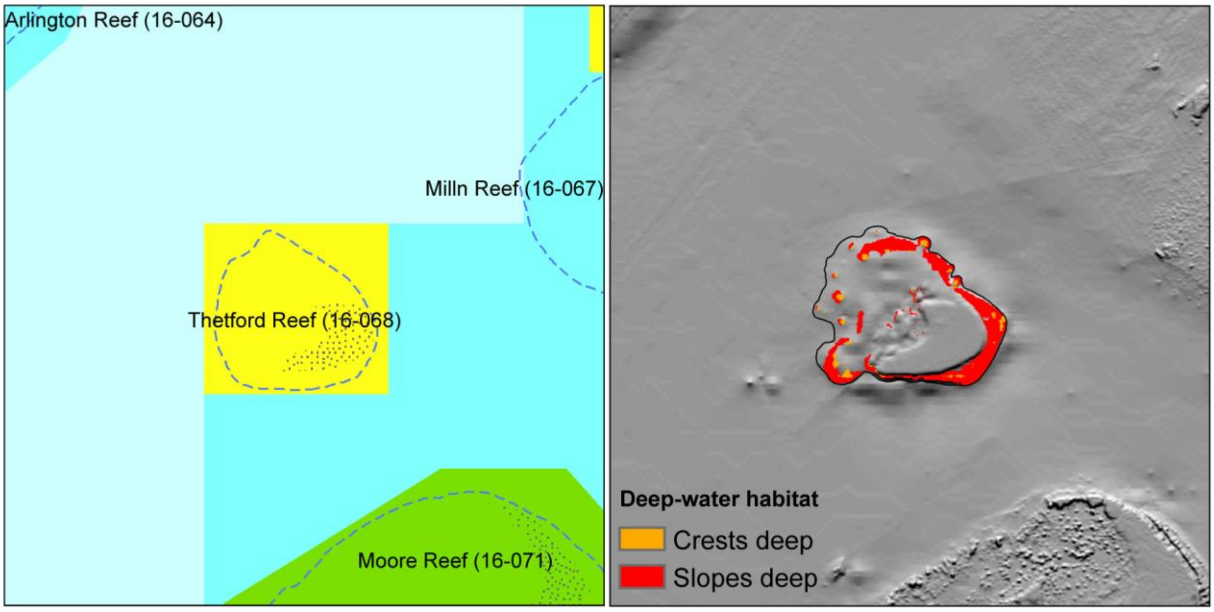

Figure 36: Thetford Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 19: Descriptive statistics for depth range at Thetford Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-57 m	Deep-water habitat
Total No. pixels	14100	5119	8981	3529
Min depth (m)	-0.97	-0.97	-15.00	
Max depth (m)	-57.46	-15.00	-57.46	
Mean depth (m)	-20.64	-6.59	-28.65	
Proportion %	100.00	36.30	63.70	39.29
Area (km^2)	15.05	5.47	9.59	3.77

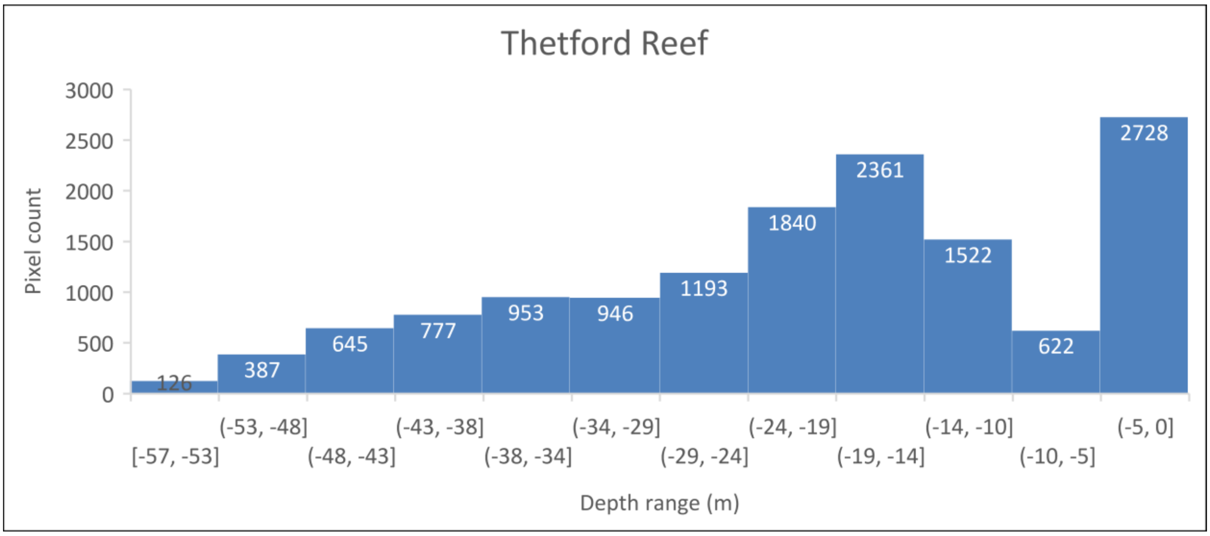

Figure 37: Histogram of depth range at Thetford Reef

2.2.20 Moore Reef 16-071

Moore Reef 16-071 lies on the mid-shelf 47 km east of Cairns at 16° 52.3'S, 146° 12.6'E. This medium-sized reef adjoins Elford Reef and sits on a much larger and deeper bank.

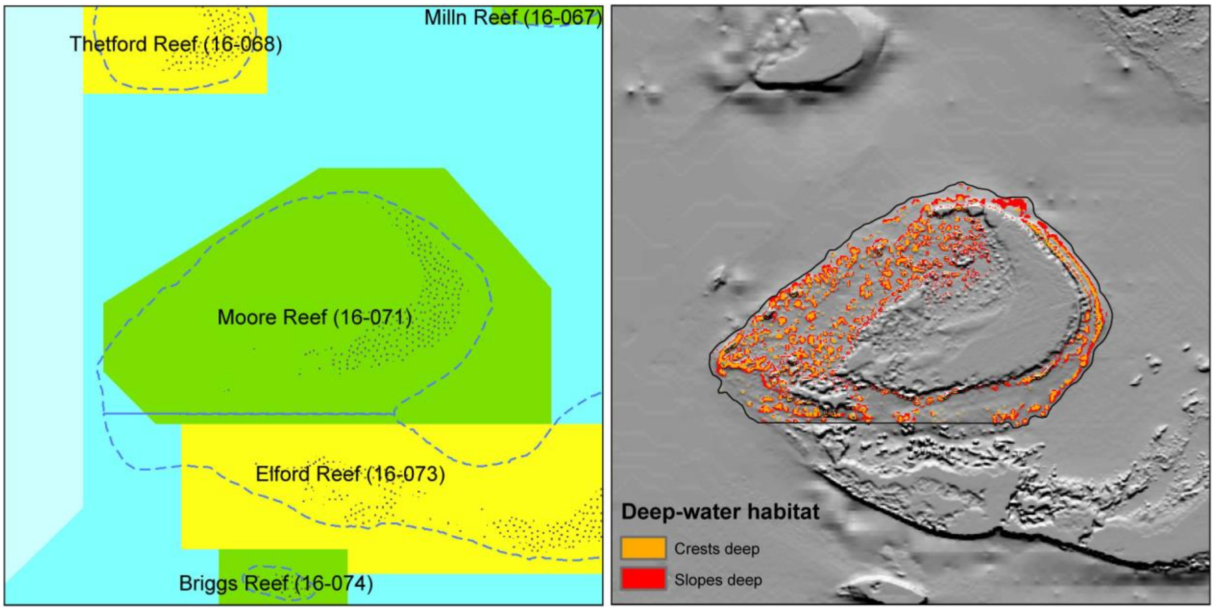

Figure 38: Moore Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 20: Descriptive statistics for depth range at Moore Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-59 m	Deep-water habitat
Total No. pixels	43409	16880	26529	8109
Min depth (m)	-0.08	-0.08	-15.00	
Max depth (m)	-59.96	-14.99	-59.96	
Mean depth (m)	-20.02	-5.97	-28.87	
Proportion %	100.00	38.89	61.11	30.57
Area (km^2)	46.33	18.02	28.31	8.65

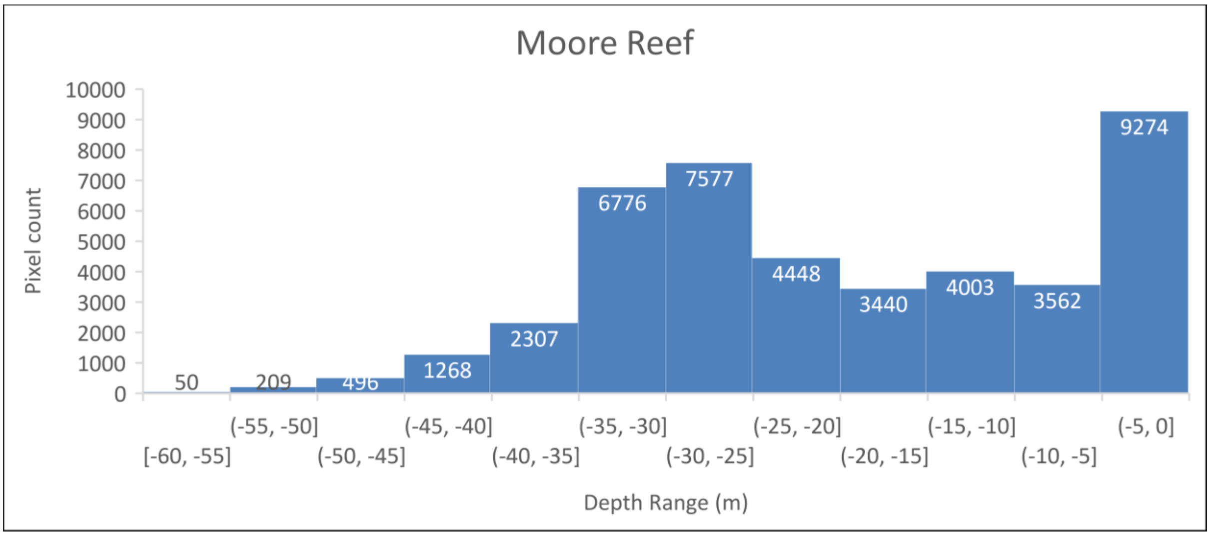

Figure 39: Histogram of depth range at Moore Reef

2.2.21 Briggs Reef 16-074

Briggs Reef 16-074 lies on the mid-shelf 47 km east of Cairns at 16° 56.3'S, 146° 12.4'E. This relatively small reef is mostly shallow reef on a minor area of deeper bank.

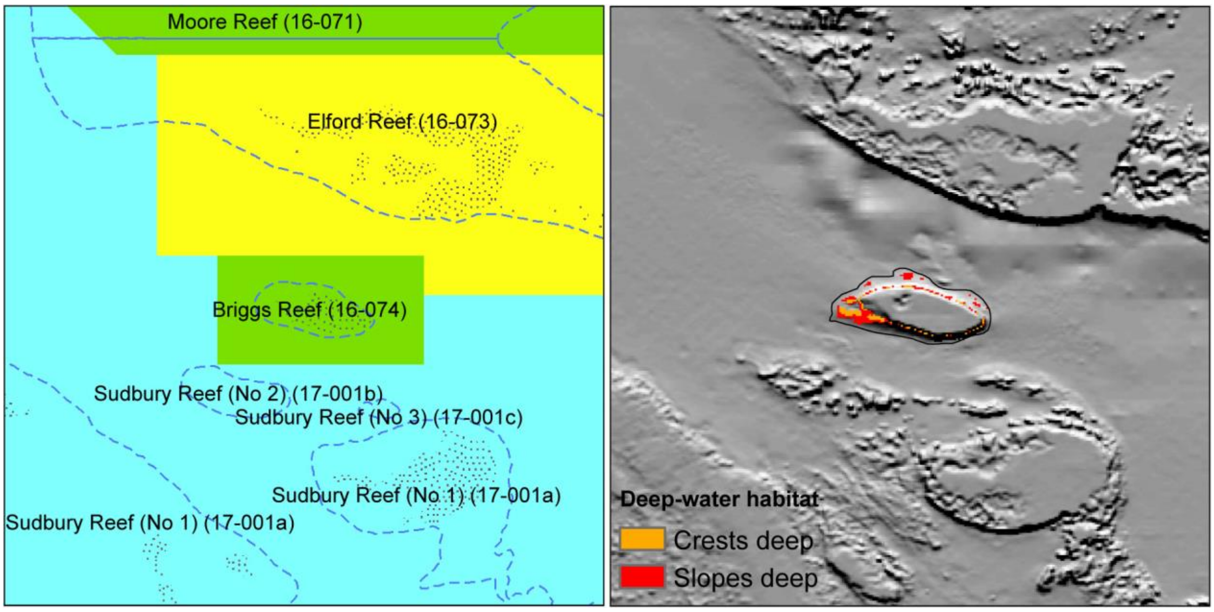

Figure 40: Briggs Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 21: Descriptive statistics for depth range at Briggs Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-48 m	Deep-water habitat
Total No. pixels	1989	955	1034	289
Min depth (m)	-0.02	-0.02	-15.05	
Max depth (m)	-48.39	-14.98	-48.39	
Mean depth (m)	-19.88	-3.09	-35.39	
Proportion %	100.00	48.01	51.99	27.95
Area (km^2)	2.12	1.02	1.10	0.31

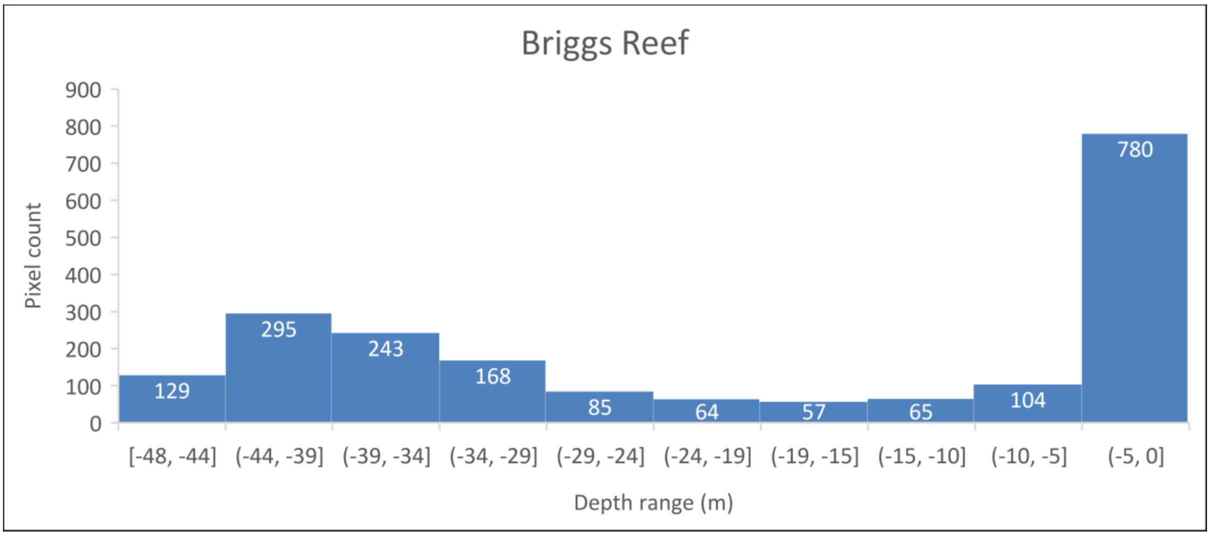

Figure 41: Histogram of depth range at Briggs Reef

2.2.22 Fitzroy Island Reef 16-054

Fitzroy Island Reef 16-054 lies on the inner-shelf 24 km east of Cairns at 16° 55.9'S, 145° 59.6'E. This fringing reef is relatively narrow with little to no deeper reef area.

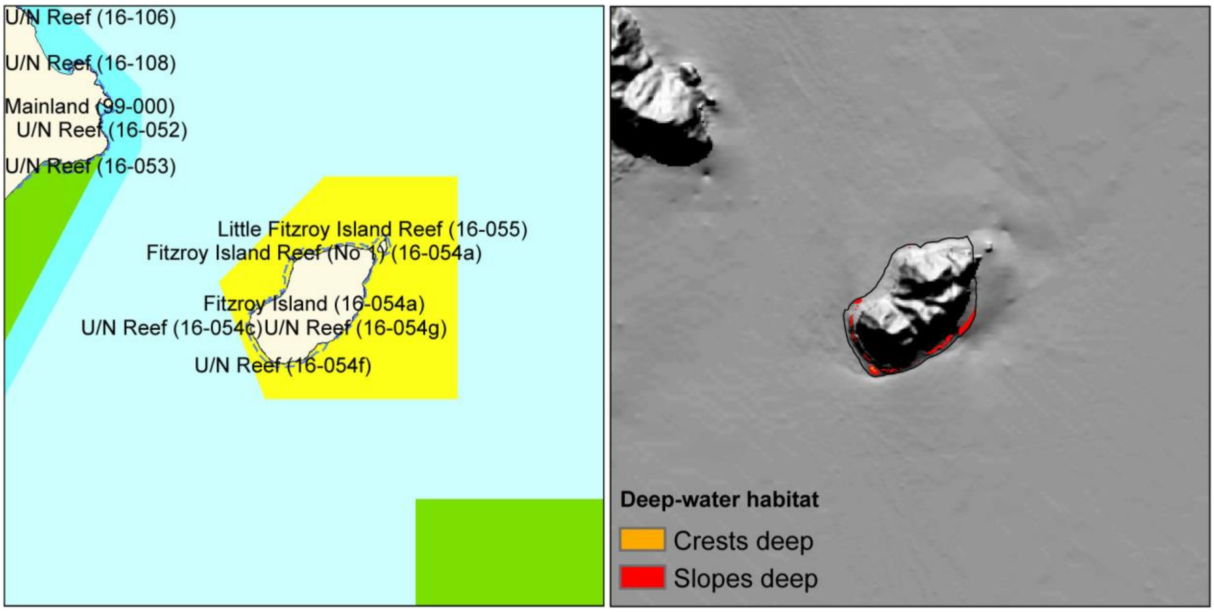

Figure 42: Fitzroy Island Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 22: Descriptive statistics for depth range at Fitzroy Island Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-38 m	Deep-water habitat
Total No. pixels	1653	1011	642	174
Min depth (m)	-0.01	-0.01	-15.00	
Max depth (m)	-38.15	-15.00	-38.15	
Mean depth (m)	-13.28	-7.00	-23.17	
Proportion %	100.00	61.16	38.84	27.10
Area (km^2)	1.76	1.08	0.68	0.19

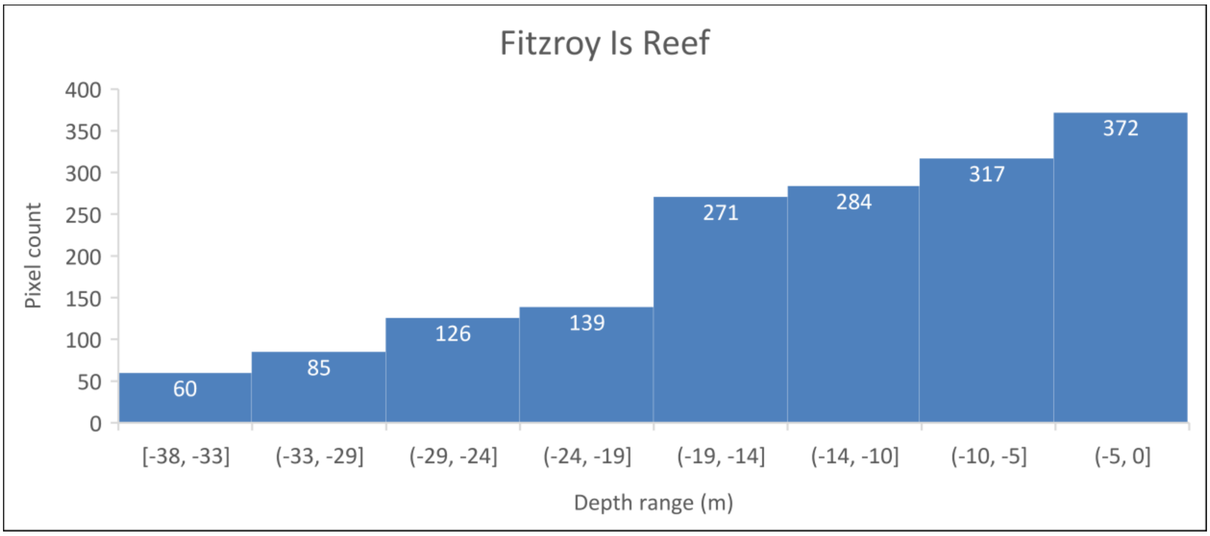

Figure 43: Histogram of depth range at Fitzroy Island Reef

2.2.23 Elford Reef 16-073

Elford Reef 16-73 lies on the mid-shelf 50 km east of Cairns at 16° 54.7’S, 146° 14.2’E. This medium-sized reef adjoins Moore Reef and sits on a much larger and deeper bank.

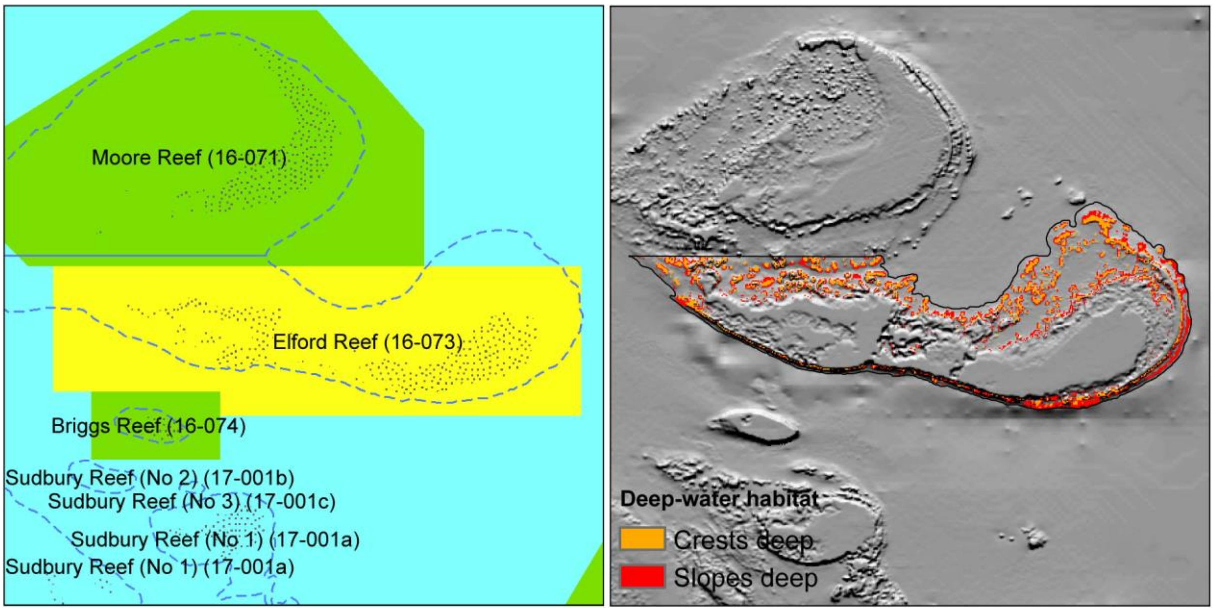

Figure 44: Elford Reef in Cairns Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 23: Descriptive statistics for depth range at Elford Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-54 m	Deep-water habitat
Total No. pixels	38499	18918	19581	6405
Min depth (m)	-0.34	-0.34	-15.00	
Max depth (m)	-54.62	-14.99	-54.62	
Mean depth (m)	-17.22	-5.00	-29.03	
Proportion %	100.00	49.14	50.86	32.71
Area (km^2)	41.08	20.19	20.89	6.83

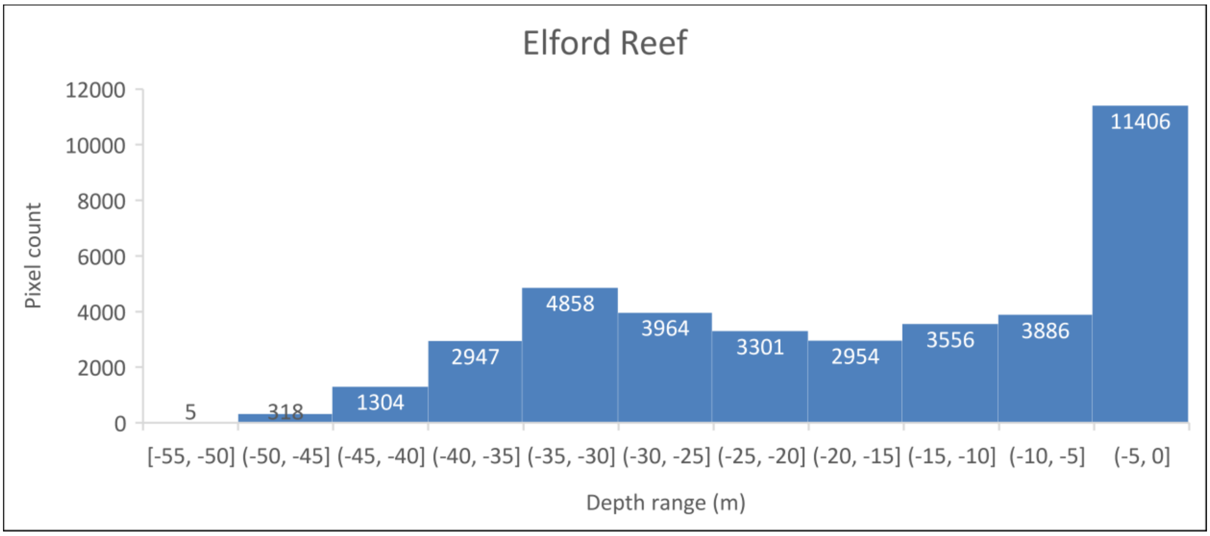

Figure 45: Histogram of depth range at Elford Reef

2.2.24 Rib Reef 18-032

Rib Reef lies on mid-shelf 57 km east of Lucinda at 18° 28.7'S, 146° 52.4'E. The relatively small reef is mostly shallow reef surrounded by a narrow area of deeper bank.

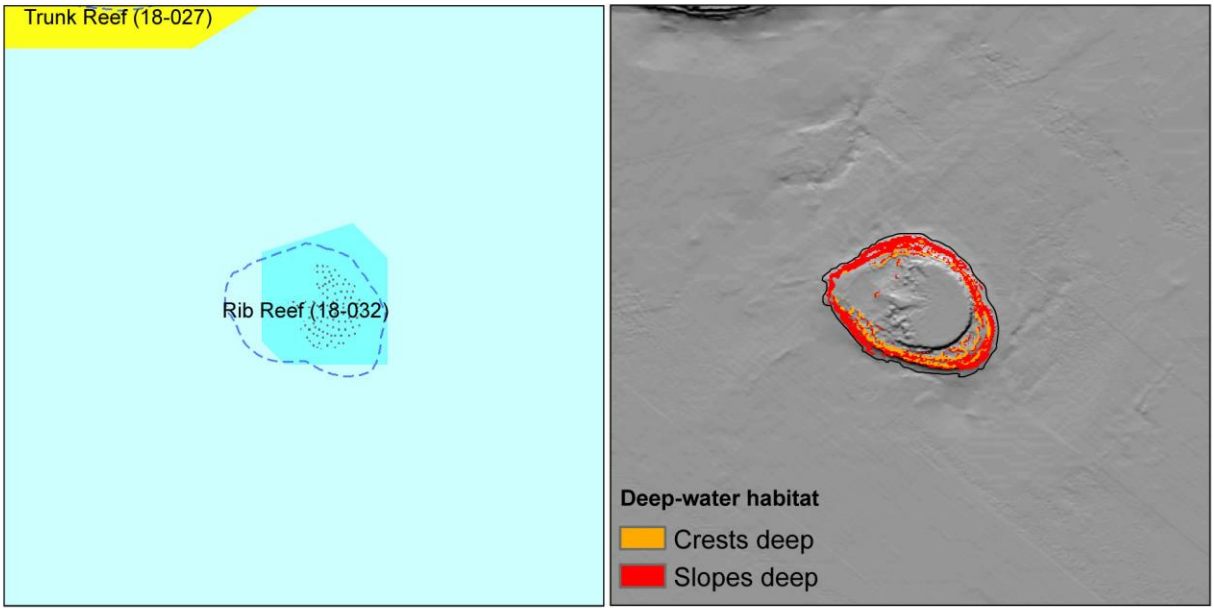

Figure 46: Rib Reef in Townsville Zoning map vs gbr30 grid with clipping polygon and deep-water habitat

Table 24: Descriptive statistics for depth range at Rib Reef. Deep-water habitat is only for depths >15 m

	Full reef	Reef 0-15 m	Reef 15-55 m	Deep-water habitat
Total No. pixels	11370	4368	7002	3532
Min depth (m)	-1.03	-1.03	-15.00	
Max depth (m)	-55.05	-14.99	-55.05	
Mean depth (m)	-21.65	-5.43	-31.77	
Proportion %	100.00	38.42	61.58	50.44
Area (km^2)	12.03	4.62	7.41	3.74

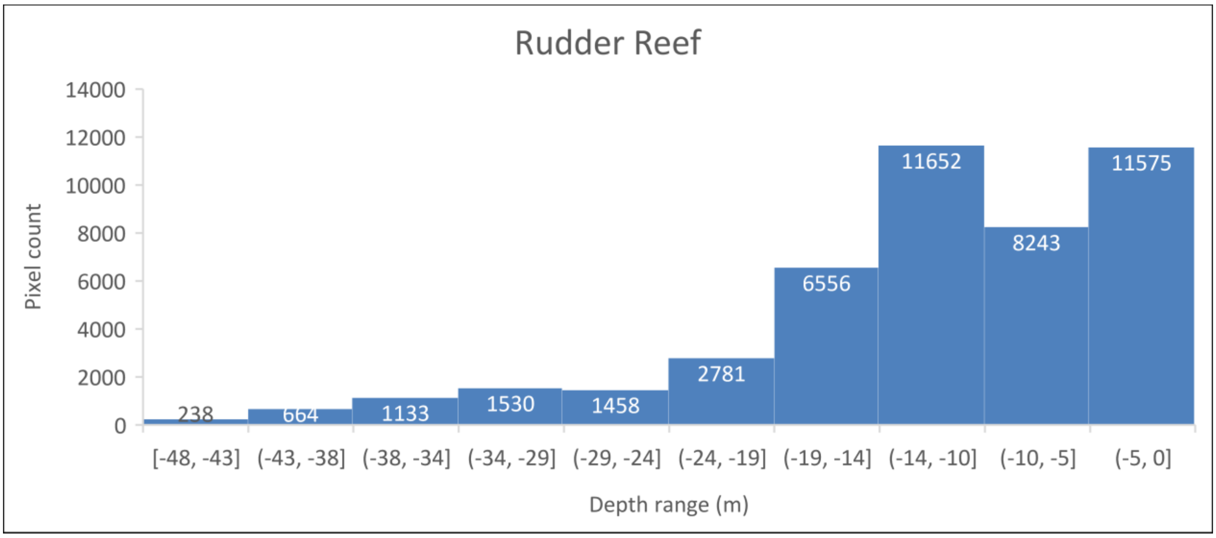

Figure 47: Histogram of depth range at Rib Reef

3.0 DISCUSSION

3.1 gbr30 bathymetry grid

The development of the gbr30 bathymetry grid is a major step forward in the regional-scale spatial datasets available for the GBR. Elevation and bathymetry (depth) are recognised as one of the ten most important fundamental spatial data themes and are included in the Australian Foundation Spatial Data Framework (ICSM, 2017). Elevation and depth data provide a common reference and base framework for the assembly and maintenance of other information themes, thus making digital elevation models (DEMs) one of the most widely used data themes across a variety of purposes (ICSM, 2017).

The ~30 m pixel resolution bathymetry grid provides an accurate digital representation of the seabed surface, revealing the finer-scale detail of the coral reefs, deeper banks and inter-reefal areas. When viewed in a geographic information system (GIS), the gbr30 grid can be spatially analysed to generate artificially hillshaded seafloor to highlight features, contoured within particular depth intervals, or to select depth values directly off targeted sites. Moreover, the gbr30 grid is accessible online and usable within government and the wider community for purposes beyond seafloor morphology. These purposes may include hydrodynamic modelling, natural hazard assessment, plan and build offshore infrastructure, benefit tourism and fishing.

3.2 Deep-water banks

With the exception of Low Isles and Fitzroy Island Reef, all the ‘super spreader’ and tourism reefs in this study are Type 1 banks using the Harris, et al. (2013) classification of geomorphic bank features (Figure 48). A geomorphic bank is an underwater feature defined by the International Hydrographic Organisation (IHO and IOC, 2013) as “isolated (or group of) elevation(s) of the seafloor, over which the depth of water is relatively shallow, but sufficient for safe surface navigation”. The Type 1 banks are the most common on the GBR, generally having the largest surface area and also supporting near-sea-surface (NSS) coral reefs (Harris, et al., 2013).

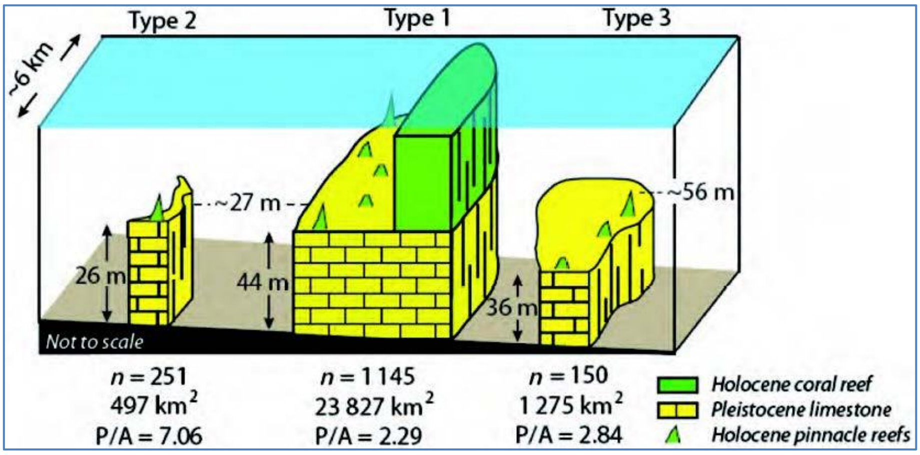

Figure 48: Conceptual diagram of the three types of banks on the GBR shelf. Most of the reefs in this study are Type 1 banks. From Figure 4 in Harris, et al. (2013)

Of the 20 Type 1 banks, the mean area of the banks at their full extent where they merge into the surrounding inter-reefal seafloor is ~51 km^2. Individually, the bank areas range from a low 2.12 km^2 for Briggs Reef to a very large 257.43 km^2 for Tongue Reef (Appendix 1). Focussing on the NSS coral reefs supported by these banks and assuming these lie in depths shallower than 15 m, then the percentage area of these shallow reefs range from only 7.74% in the case of Milln Reef up to high 85.65% for Batt Reef (Appendix 1). The average percentage area of NSS reefs (i.e. found in depths <15 m) is ~48%. Conversely, the average percentage area of deeper banks (>15 m) is ~52%, so there is more deep-water bank area than NSS coral reefs.

The larger surface area of these deep-water banks, compared to their shallower NSS reefs, is due to sea-level highstand reef growth during the ~7 interglacial periods since the onset of the GBR, suggested as Marine Isotope Stage (MIS) 15, or around 600 ka (Humblet & Webster, 2017). Therefore, each subsequent interglacial reef growth occurs on the antecedent surface of the previous interglacial reef. There was significant reef growth in the southern GBR during the Last Interglacial between ~129-121 ka (Dechnik et al., 2017), then subaerial exposure of the banks as sea levels dropped to full lowstand during the Last Glacial Maximum (LGM), around 20 ka (Webster et al., 2018). The NSS reefs supported by these banks have only grown since ~8 ka when deglacial sea levels stabilised during the mid-Holocene (Hopley, et al., 2007).

The exceptions of Low Isles and Fitzroy Island Reef not being considered deep-water banks, are because Low Isles is an inner-shelf coral cay rising up from a relatively shallow surrounding seafloor at 24 m maximum depth. There is also no evidence that Low Isles is formed on an older Pleistocene bank (Hopley, et al., 2007). Fitzroy Island Reef is a fringing reef formed around an inner-shelf continental island, likely Holocene in age (Hopley, et al., 2007), and also rising up from a relatively shallow maximum depth. Nonetheless, these are important tourism sites with coral and included in this study because they have permanent COTS control sites.

3.3 Deep-water coral habitats

Population outbreaks of adult COTS require zooxanthellate scleractinian coral colonies for their food and shelter. A question is, how much scleractinian coral habitat exists in these deep-water environments? So within the context of the COTS control program on the GBR, which is limited to diver-restricted depths of about 15 m, how much scleractinian coral exists in depths below about 15 m that stretches into the mesophotic (twilight) zone depths where mesophotic coral ecosystems (MCEs) occur? MCEs, as a definition, includes both zooxanthellate and azooxanthelate coral communities living within the intermediate depths of ~30-150 m of the photic zone (T. Bridge & Guinotte, 2013).

Studies on MCEs have taken on more importance due to their potential as refugia areas from environmental disturbance and climate change (T. Bridge & Guinotte, 2013). On the GBR, MCE research has largely focussed on the submerged reefs found on the outer-shelf (Type 3 banks in Harris, et al. (2013). Early submersible observations in 1984 found submerged reefs were occupied by diverse mesophotic coral communities with living corals being found to a depth of 100 m (Hopley, et al., 2007). More recent studies of MCEs with autonomous underwater vehicle (AUV) transects across submerged reefs, have revealed clear patterns in the zonation of sessile benthic megafauna along depth gradients (T. C. L. Bridge, et al., 2011).

T. C. L. Bridge, et al. (2011) found reef-associated macrofaunal communities occurred in three distinct depth zones, shown in Figure 49: (1) a shallow (<60 m) community dominated by photosynthetic scleractinian corals, zooxanthellate octocorals and photosynthetic sponges; (2) a transitional community (60-75 m) of both zooxanthellate taxa and azooxanthellate taxa (gorgonians and antipatharians), and (3) an entirely azooxanthellate community (>75 m). The micro-topography of the submerged reefs have a major influence on the presence of MCEs, as well as providing the hard substrate required for their attachment. MCE diversity was highest on steep, rugose reef habitats. Conversely, diversity was lower on the flatter, more sediment-covered non-reef substrate, which may serve to suppress coral attachment.

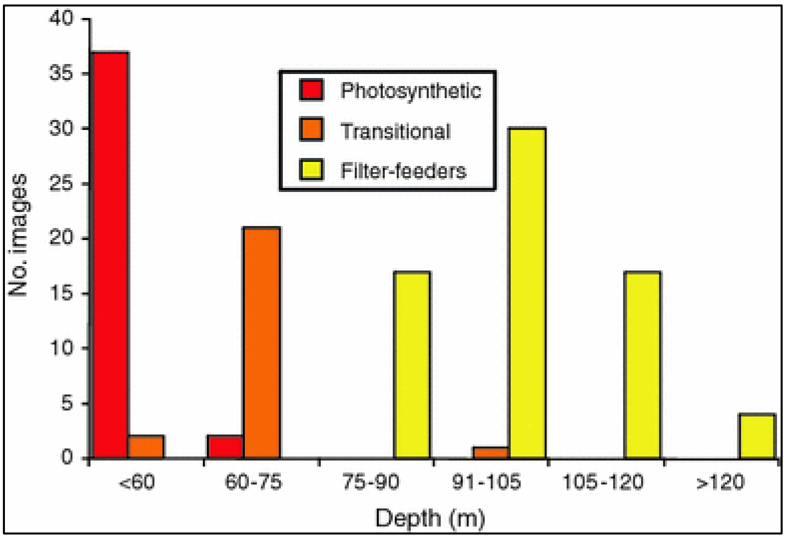

Figure 49: Depth zonation of reef-associated groups at Hydrographers Passage. The zooxanthellate group is dominant above 60 m. Taken from Figure 6 in T.C.L. Bridge, et al. (2011)

For this report, the BTM plugin to ArcGIS (Wright, et al., 2005) was used to identify potential deep-water coral habitat for areas deeper than 15 m, extracting the two morphology classes likely to influence coral habitat: Crests deep and Slopes deep. Appendix 2 records a summary of deep-water habitat area when these two classes are combined. Excluding the non-Type 1 banks (Low Isles and Fitzroy Island Reef), the average proportion of deep-water habitat is 32.96% or an area of 6.10 km^2. So on average, nearly a third of bank area deeper than 15 m is potential deep-water coral habitat, with the remaining area comprising of flats and depressions that are less likely to have deep-water coral habitat.

The highest area of deep-water habitat is 24.88 km^2 at Tongue Reef, a very large bank, and the smallest area is 0.31 km^2 at Briggs Reef, a correspondingly small bank. However, some smaller-sized banks do record some of the highest proportions of deep-water habitat: Chinaman Reef and Rib Reef with 51.31% and 50.55%, respectively. So for some banks, around half the bank area deeper than 15 m is potential deep-water coral habitat, with remainder being flats and depressions between the high proportion of crests and slopes. For the two non-Type 1 banks, Low Isles and Fitzroy Island Reef, even they record some minor deep-water habitat area, mainly due to the steeper gradients found around their edges.

When taken together, depth and terrain attributes derived from DEMs, such as crests, slopes and rugosity, combined with ground truth imagery/samples may be used to help understand benthic community patterns and generate predictive habitat maps. For example, T. Bridge, Beaman, Done, & Webster (2012) used the BTM outputs from high-resolution bathymetry grids combined with extensive AUV stereo imagery over deep-water banks and reefs to understand MCE community structure to a depth of ~110 m (Figure 50). The gbr100 bathymetry grid was then used to scale-up predictive habitat maps to the broader GBR extent (T. Bridge, et al., 2012). Predictive habitat maps are beyond the scope of this report, which require ground truth imagery/samples on these ‘super spreader’ and tourism reefs. However, the potential deep-water coral habitat maps provided here may be used to target sites for future ground truthing.

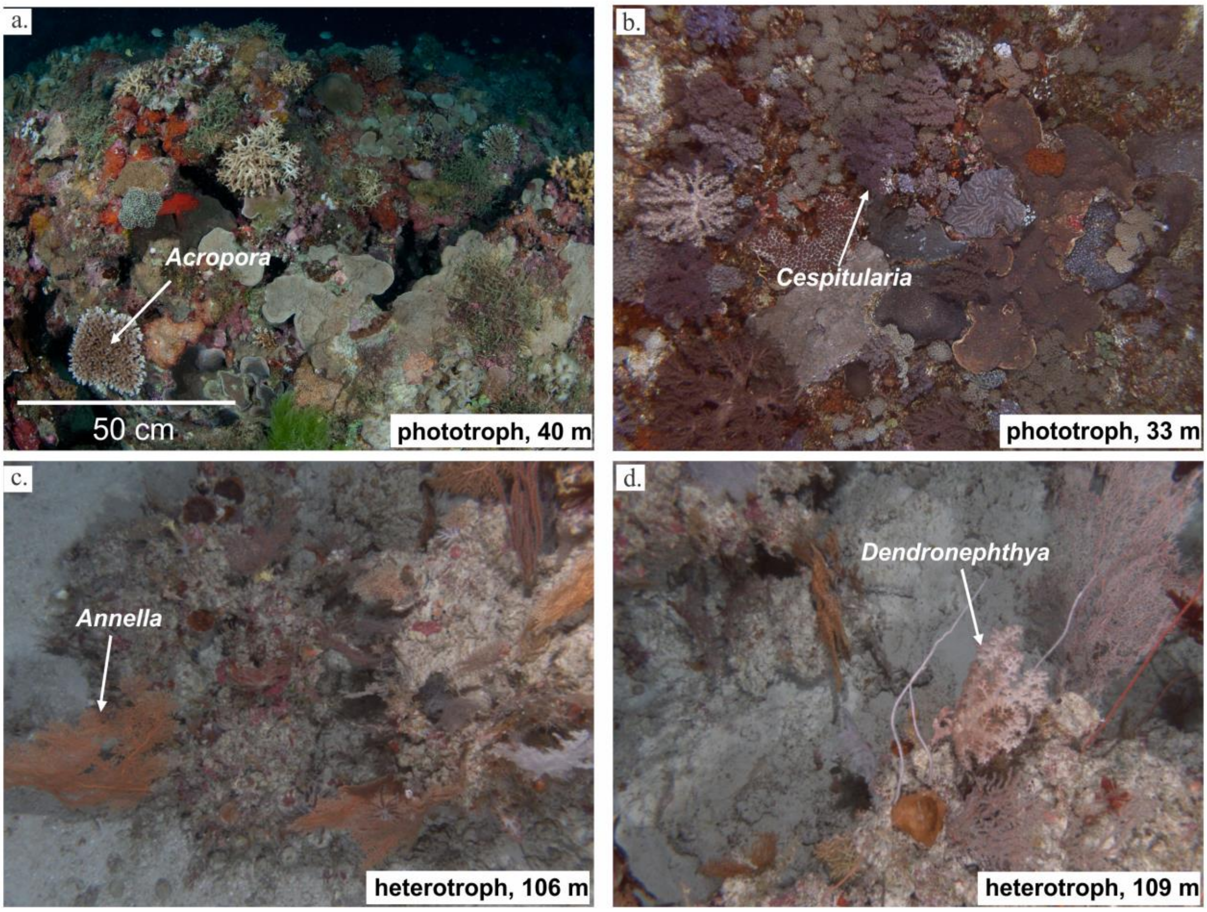

Figure 50: Examples of phototrophic and heterotrophic mesophotic communities on the GBR. Taken from Figure 2 in T. Bridge, et al. (2012)

3.4 Assessment of adult COTS risk

There are anecdotal reports that adult COTS move into shallower areas from deeper habitat. The scientific literature provides more nuanced detail on depth trends for outbreaks. A well-studied outbreak in Moorea found aggregations consistently starting at the deepest locations of the outer reef and progressing upward with the migration of seastars along the reef-slope (Kayal et al., 2012). The outer reef habitat of Moorea typically extends from the water surface down to a depth of ~35 m where sand plains begin. A peak in diversity and coral coverage is typically observed at the 10-20 m depth range (Kayal, et al., 2012). Hence, the outbreaks were rising from the relatively deeper habitat around 10-20 m where the coral cover is greatest.

Early studies of COTS outbreaks in the GBR, observed that most of the juvenile seastars were found in the top 3 m of water on windward reef slopes while the small adults were confined to deeper waters along the reef edge (Laxton, 1974). The coral colonies growing in shallow water habitats exposed to marked wave action had frequently survived the starfish invasions (Endean & Stablum, 1973). It was surmised that COTS larvae appear to settle in the top 3 m on the windward side of reefs or on exposed coral patches in deeper water behind the main reef (Laxton, 1974). As they grow and change diet from algae to living coral, they migrate downwards away from the turbulent surface waters into the deeper water at the bottom of the reef slope (Laxton, 1974). Note, the 'deeper' water referred to in these studies was relative to the shallow surface waters and were limited to a maximum depth of ~15 m.

Large-scale field studies of COTS outbreak behaviour on the GBR in the 1980s found patterns consistent across reefs. Adult seastars preferred habitats on the leeward margins of reefs and on the steeper (but not vertical) reef slopes (De'ath & Moran, 1998a). Motion increased with depth for all seastars (De'ath & Moran, 1998a), within the context that observations were split into depth bands <3 m and >3 m, but were all found within the zone of highest coral cover typically below the wind-generated wave base. Seastars also preferred tabular *Acropora* as prey over other coral genera and morphology forms, with these preferences not greatly influenced by factors such as seastar density, time of day or depth (De'ath & Moran, 1998b).

The picture emerges that COTS outbreaks are not found in depths significantly below the zone of highest coral cover on emergent reefs, and that any reference to 'deeper' depths are relative to the shallow water experienced by snorkelers and divers. For the GBR outer-shelf, in general, the living hard coral cover on emergent reefs is greatest to ~10-15 m, then gradually reduces in coverage (Dinesen, 1983). On the GBR mid-shelf, living hard coral cover is greatest to ~10 m, then more rapidly reduces in coverage (Dinesen, 1983). Similarly, the COTS preferred prey of tabulate *Acropora* is generally found as the dominant hard coral community type in depths to ~10-12 m on mid- and outer-shelf emergent reefs (Done, 1982). Hence, the zones of highest coral coverage on emergent reefs should be the target of COTS control measures.

Further, an extensive study of submerged reefs in the central GBR quantified coral cover and community groups to 30 m (Roberts, et al., 2015). The distribution of community groups was best explained by depth and shelf location (Roberts, et al., 2015). Even though hard coral cover was high in groups on the crests of the submerged reefs on the mid- and inner-shelf (~10 m), and even relatively high on lower reef slopes (20-30 m) in places, few COTS were observed nor any feeding scars found. This study occurred while there was an active outbreak occurring at adjacent emergent reefs. The assessment of this report is that there is a low risk of adult COTS outbreaks in deep-water habitats below the zone of highest coral cover.

3.5 Assessment of larval COTS risk

There is little evidence of COTS migrating across the deeper inter-reefal seafloor between reefs. Inter-reefal depths on the mid- to outer-shelf range from ~40-70 m and may stretch for several km between emergent reefs or adjacent banks. The inter-reefal seabed is relatively smooth with relict low dunes, occasional pockmarks and localised limestone pinnacles with a surficial cover of muddy sand (Carter, Larcombe, Dye, Gagan, & Johnson, 2009). Indeed, COTS appear not to prefer being on sand and will move relatively quickly towards hard physical substrate when placed on sand (Pratchett et al., 2017). Hence, there is a consensus that outbreaks on reefs are due to the earlier settlement of COTS larvae brought by currents to those reefs (Wolfe, Graba-Landry, Dworjanyn, & Byrne, 2017).

However, an earlier deep-water recruitment hypothesis raised questions on where the mass settlement of COTS larvae occurs (Johnson, Sutton, Olson, & Giddins, 1991)? Coral rubble and crustose coralline algae (CCA) were shown to induce settlement and metamorphosis of COTS larvae. According to the deep-water hypothesis, the paucity of juveniles found on the GBR is due to the mass recruitment of COTS being more likely to occur in deep rather than in shallow water (Johnson, et al., 1991). The preferred species of CCA were considered most abundant in deep-water and dominate the CCA flora below 50-60 m where they may form extensive beds of coral rubble or rhodoliths at the base of reef slopes (Johnson, et al., 1991).

As the proponents of this hypothesis acknowledged, the species of preferred CCA is also found in shallow water and where coral rubble also accumulates. Studies on the ubiquitous spur and groove morphology from emergent reefs in the southern GBR show the depths of this zone ranges from 0-19 m and is generally floored with coral rubble or CCA (Duce et al., 2016). Much progress has since been made in detecting these small and cryptic post-settlement juveniles. A recent study of the growth curves of juvenile COTS in the GBR, collected over 3000 individuals across 64 reefs by scuba divers inspecting CCA encrusted pieces of dead coral and live coral colonies in shallow waters (J. Wilmes et al., 2017).

Parsimony would suggest that tiny larvae are not settling in deep-water, then crawling many metres vertically to then appear as small coral-eating juveniles in shallow waters, only to move vertically downwards as larger adults searching for their coral prey. Juvenile COTS are also likely to be found close to where they first settled (J. C. Wilmes et al., 2018). Hence, the growing consensus is that pelagic larvae initially settle in shallow waters (below wave base) to feed on CCA encrusted coral and shelter within the coral rubble until they reach the coral-eating phase. The assessment of this report is that there is a low risk of larval COTS to be found in deep-water habitats on emergent reefs below the zone of highest coral cover.

4.0 RECOMMENDATIONS AND CONCLUSION

(1) This project integrated all the available source bathymetry data currently used within the latest gbr100 grid and generated a much higher-resolution gbr30 bathymetry grid (~30 m pixel spacing) over the GBR shelf area. The gbr30 grid is publically available for download on the Geoscience Australia website at: http://pid.geoscience.gov.au/dataset/115066

The gbr30 grid is recommended for use as a spatial dataset to feed into the Local and Regional Decision Support Tool (DST) being developed by CSIRO for Integrated Pest Management. Other uses of the grid may extend beyond COTS control efforts to include hydrodynamic modelling, natural hazard assessment, to plan and build offshore infrastructure, and to benefit tourism and fishing.

(2) The gbr30 grid was used to generate spatial datasets and descriptive statistics of the 22 ‘super spreader’ and tourism reefs, to better understand the extent of deep-water habitat at these sites. Output files included Fledermaus 3D visualisation files, Google Earth kmz, ESRI raster grids, hillshade geotifs, ESRI shapefiles, Excel spreadsheets and histograms, xyz files.

These spatial datasets are recommended for operational use in helping with COTS control at these 22 ‘super spreader’ and tourism sites by understanding the topographic variability and overall depth distribution of each reef. Benthic Terrain Modeler was used to extract the crest and slope areas deeper than 15 m, which are likely to be potential deep-water coral habitats.

(3) An assessment was conducted on whether submerged banks or deeper reefs may provide deep-water coral habitat for COTS, and the implications for the design of the control program. Extensive mesophotic (twilight zone) coral ecosystems have been described on these banks and deeper reefs with zooxanthellate corals found to ~60 m. However, the scientific literature does not record any evidence of COTS outbreaks being found in depths significantly below the zone of highest coral cover on emergent reefs, which generally peak at ~10-15 m.

The assessment concluded there is a low risk of adult COTS outbreaks in deep-water habitats below the zone of highest coral cover. The assessment also discounted the deep-water recruitment hypothesis for larvae settling in deep-water on the basis of observations of COTS movements over their lifecycle. The assessment concluded there is low risk of larval COTS to be found in deep-water habitats on emergent reefs below the zone of highest coral cover.

The recommendation is that COTS control efforts should continue in the relatively shallow waters of emergent reefs, and to not expend resources searching for COTS outbreaks in deeper waters significantly below the zone of highest coral cover.

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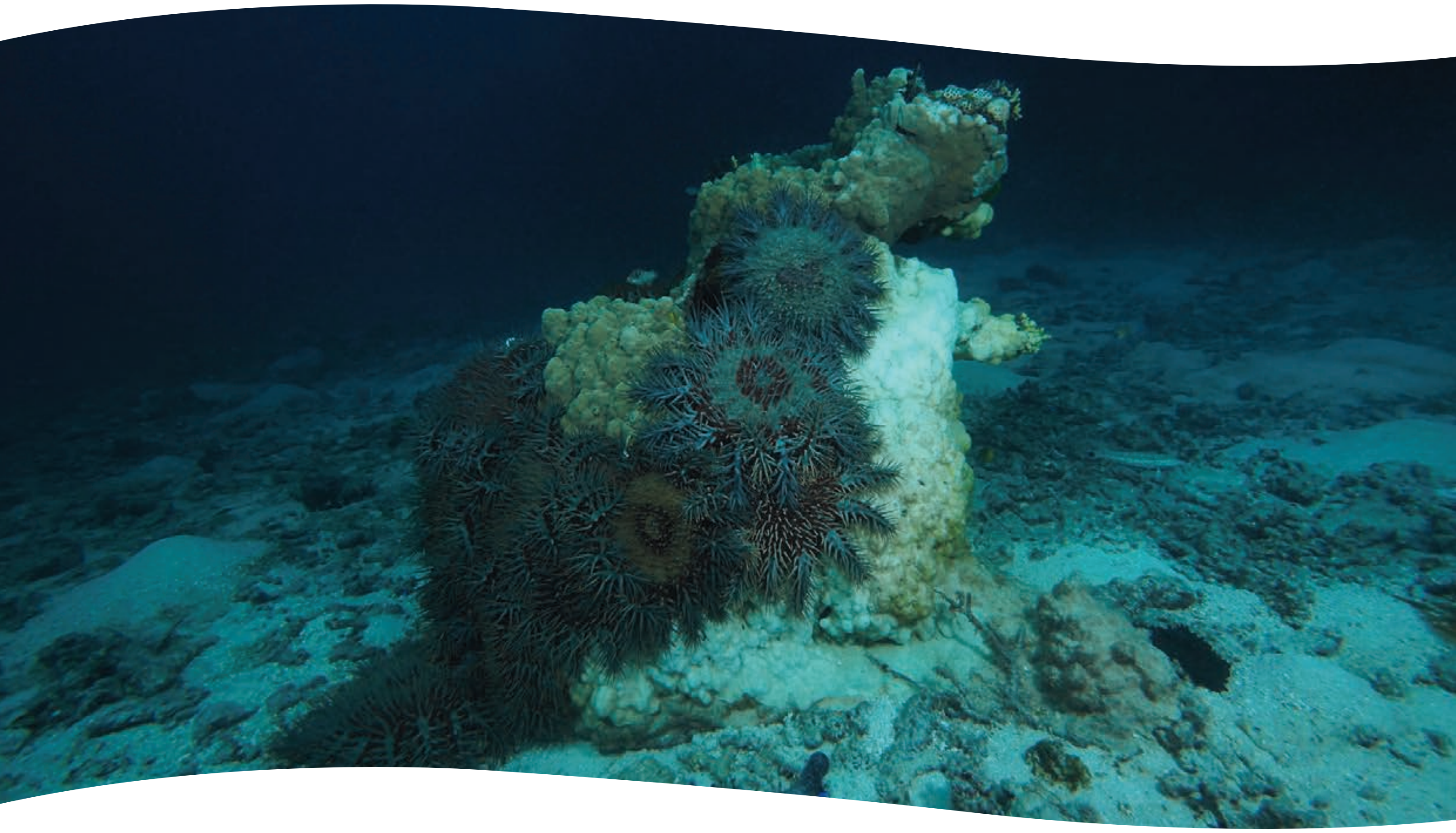
APPENDIX 1: SURFACE AREA OF REEFS WITHIN 0-15 M AND >15 M DEPTH BANDS

Reef name	Total area (km^2)	Area 0-15 m (km^2)	Area >15 m (km^2)	Proportion 0-15 m (%)	Proportion >15 m (%)
StCrispinReef_16-019	41.26	21.79	19.47	52.81	47.19
UndineReef_16-020	57.65	29.95	27.70	51.94	48.06
RudderReef_16-023	49.08	35.11	13.97	71.54	28.46
ChinamanReef_16-024	8.60	4.89	3.71	56.84	43.16
OpalReef_16-025	35.07	15.02	20.05	42.83	57.17
TongueReef_16-026	257.43	167.84	89.59	65.20	34.80
BattReef_16-029	146.77	125.70	21.07	85.65	14.35
LowIsles_16-028	4.44	3.70	0.74	83.41	16.59
NormanReef_16-030	20.12	3.34	16.78	16.60	83.40
SaxonReef_16-032	8.08	1.49	6.59	18.49	81.51
HastingsReef_16-057	16.75	7.53	9.22	44.97	55.03
MichaelmasReef_16-060	38.71	28.14	10.57	72.69	27.31
GreenIsReef_16-049	47.65	25.92	21.73	54.40	45.60
ArlingtonReef_16-064	154.87	112.63	42.24	72.72	27.28
FlynnReef_16-065	7.95	2.20	5.75	27.65	72.35
MillnReef_16-060	40.21	3.11	37.10	7.74	92.26
ThetfordReef_16-068	15.05	5.47	9.59	36.30	63.70
MooreReef_16-071	46.33	18.02	28.31	38.89	61.11
BriggsReef_16-074	2.12	1.02	1.10	48.01	51.99
FitzroyIsReef_16-054	1.76	1.08	0.68	61.16	38.84
ElfordReef_16-073	41.08	20.19	20.89	49.14	50.86
RibReef_18-032	12.03	4.62	7.41	38.42	61.58

APPENDIX 2: SURFACE AREA OF POTENTIAL DEEP-WATER HABITAT >15 M DEPTH

Reef name	Area >15 m (km^2)	Proportion >15 m (%)
StCrispinReef_16-019	6.25	32.10
UndineReef_16-020	8.35	30.14
RudderReef_16-023	5.17	36.98
ChinamanReef_16-024	1.90	51.31
OpalReef_16-025	7.57	37.74
TongueReef_16-026	24.88	27.77
BattReef_16-029	8.38	39.76
LowIsles_16-028	0.03	4.51
NormanReef_16-030	3.19	19.04
SaxonReef_16-032	2.58	39.19
HastingsReef_16-057	3.36	36.45
MichaelmasReef_16-060	3.81	36.04
GreenIsReef_16-049	2.16	9.95
ArlingtonReef_16-064	12.76	30.21
FlynnReef_16-065	1.98	34.44
MillnReef_16-060	6.29	16.95
ThetfordReef_16-068	3.77	39.29
MooreReef_16-071	8.65	30.57
BriggsReef_16-074	0.31	27.95
FitzroyIsReef_16-054	0.19	27.10
ElfordReef_16-073	6.83	32.71
RibReef_18-032	3.74	50.55



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