Facing Island Reef Surveys

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BMT Eastern Australia Pty Ltd Level 8, 200 Creek Street Brisbane Qld 4000 Australia PO Box 203, Spring Hill 4004 Tel: +61 7 3831 6744 Fax: + 61 7 3832 3627 ABN 54 010 830 421 www.bmt.org		
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	Title:	Facing Island Reef Surveys
	Project Manager:	Conor Jones
	Author:	Conor Jones
	Client:	Gladstone Ports Corporation
	Client Contact:	Dr Megan Ellis
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Synopsis: An assessment of reef communities adjacent to Facing Island, located near Gladstone on the central Queensland coast.

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Executive Summary

Background

An extensive network of nearshore reefs occurs on the eastern side of Facing Island. This reef system is located more than 5 km from the East Banks Spoil Disposal Site (EBSDS). To meet conditions of the sea dumping permit for maintenance material, GPC monitors the condition of reef assemblages at Facing Island every five years. Monitoring tests the impact hypothesis that maintenance dredging activities have not affected adjacent reef communities. Reefs in the study area were previously surveyed in 2011, 2012, 2013 and 2014, thereby providing a (recent) historical data-set to assess changes over time.

The overall aim of this study was to characterise patterns in the structure and condition of benthic reef communities along Facing Island and 'control' sites at Rundle Island, and trial the use of various technologies for future monitoring studies.

Approach

Three sampling techniques were used in the present study:

- using high-resolution multispectral satellite imagery to provide broad-scale mapping of reefs and to investigate opportunities for more frequent monitoring
- quantitative sampling of epibenthic reef communities – diver-based sampling to characterise the benthic community structure and condition of reefs for comparisons with previous surveys.
- trial 3D photogrammetry mapping – diver-based sampling to construct 3D images of the seafloor, which was undertaken for the purposes of stakeholder engagement and as a potential monitoring tool.

Reef Mapping

Remotely-sensed data based on high-resolution multispectral satellite imagery greatly improved the accuracy of reef extent. In total, 21.71 km^2 of reefs were mapped, compared with 13.90 km^2 that were digitised in the previous mapping using aerial imagery alone. This was due to better resolution of the interface between deep reef and sands using remote sensing data.

The multispectral data also provided a basis for classifying the broad-scale distribution of dominant reef communities. The classification was most successful east of Facing Island, followed by the Seal Rocks Reef area, and was least successful at Rundle Island. This was likely due to differences in optical water types, especially turbidity conditions. This trial has provided improved habitat mapping at Facing Island and Seal Rocks but suggests that object-based classification of water-column corrected high-resolution multispectral data would be required for objective change detection over broad spatial scales.

Reef Community Monitoring

The results of the present study indicate that there were strong spatial gradients in epibenthic community structure and condition throughout the study area. The sites differ in their exposure to anthropogenic and catchment disturbance, and the revised design attempted to partition these processes as much as practical. Revised treatments include the harbour entrance (potentially affected by catchment processes and dredging), eastern Facing Island (potentially affected by dredged material placement), and Rundle Island (serving as a broad-scale environmental control). In summary:

- Hard coral cover was greatest at Rundle Island and sites along the eastern side of Facing Island, and the lowest cover was recorded at sites in the harbour entrance treatment.
- Macroalgae cover showed an inverse relationship to coral cover – sites with low coral cover had the highest algae cover.
- Harbour entrance sites had greatly reduced in coral cover between 2013 and 2014, and do not appear to have recovered substantially between 2014 and 2018.
- While the spatial patterns in hard coral and macroalgal cover are consistent with catchment disturbances, the relative influence of dredged material placement impacts cannot be completely partitioned. However, based on dredge plume monitoring, modelling studies, and the 2018 cover data, it is considered extremely unlikely that sediment plumes created by maintenance dredging are driving these spatial patterns. Both monitoring and modelling indicate that sediment plumes created by material placement are short term features (measurable for < 1 hour) that do not have significantly large enough concentrations to impact reef communities.
- A large degree of uncertainty exists regarding temporal changes in community mainly to do with low levels of replication and a lack of raw data. Future monitoring should consider the use of photo-quadrat data as the unit of replication, rather than transects to improve the potential to detect changes. This can be done with the raw data collected by BMT in 2018, and using Gladstone Healthy Harbour Partnership (GHHP) data, provided GHHP increases point ID frequency above 20.

3D Imaging

Four 3D models were produced over 100 m^2 sites using diver-based photogrammetry techniques. They allow the user to observe the site from a variety of perspectives in space. The technique potentially allows visualisation of small changes in benthic cover over a reasonably large area that may not be encompassed in point-based or line-intercept monitoring approaches. Observing orthomosaics side by side provides an opportunity to assess cover without the difficulties of measurement in a highly rugose 3D environment. Benthic cover classifications could be performed over the orthomosaics to determine percent cover of particular groups using image analysis software.

The disadvantages of this form of monitoring are that the ability to build these models is underpinned by the heterogeneity of the substrate. Substrates with a highly repetitive pattern, or that move through time are difficult to match using pixel matching algorithms. These limitations mean that data collection and model outputs are vulnerable to missing data. The risk of missing data increases with substrate heterogeneity and turbidity, as capture frames become smaller with less overlap, and fewer features for pixel matching algorithms.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

1.1.1 Project Need

The East Banks Sea Disposal Site (EBSDS) has a long history of use for the disposal of uncontaminated capital and maintenance dredged material, and is currently used by Gladstone Ports Corporation (GPC) exclusively for the disposal of maintenance dredged material. Fine sediments within EBSDS are re-mobilised and transported by waves and currents, and as such functions as a dispersive site.

The closest coral reef receptor to the EBSDS is the network of nearshore reefs located on the eastern side of Facing Island. This reef system is located more than 5 km from the EBSDS (Figure 1-1).

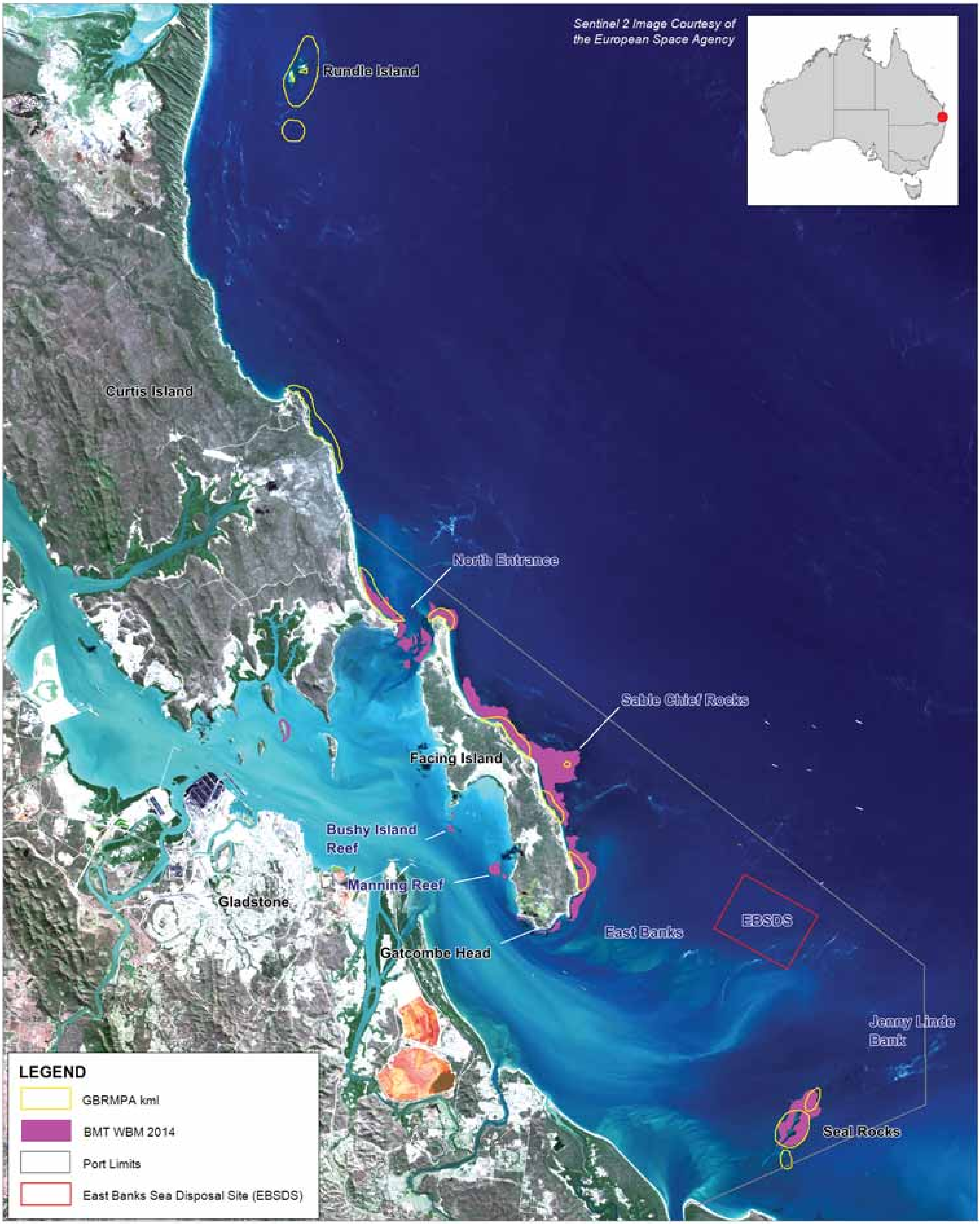
The Port of Gladstone sea dumping permit for maintenance material prescribes a Long Term Monitoring and Management Plan for Maintenance Dredging Sea Disposal (2015-2018). The reef monitoring aspect of this plan seeks to test the impact hypothesis that Maintenance dredging activities do not result in long-term changes to adjacent reef communities. This is established by reef condition surveys conducted every 5 years in accordance with Technical Advisor Consultative Committee recommendations.

The study area for this project includes reefs located on the eastern side of Facing Island and Rundle Island to the north of Facing Island (Figure 1-1). Some of the reefs in the study area were surveyed in 2011, 2012, 2013 and 2014; providing a (recent) historical data-set to assess changes over time. The 2013 data (Sea Research 2013) was the most recent study to include all monitoring program sites. These reef systems were found to support rich and abundant epibenthic communities comprised of hard and soft corals, macroalgae and a wide range of other invertebrate fauna (Sea Research 2013; BMT WBM 2014).

1.1.2 Aim and Objectives

The overall aim of this study is to characterise patterns in the structure and condition of benthic epibenthic reef communities along Facing Island and ‘control’ sites at Rundle Island. The specific objectives of this study were to:

- compare spatial patterns in the structure and condition of epibenthic reef communities at Facing Island and Rundle Island as a part of 5-yearly compliance monitoring
- assess changes in epibenthic reef communities using sea floor imagery at representative sites over time.
- based on the above, describe spatial and temporal patterns in within the context environmental variability and potential human impacts.
- Build upon the reef mapping work of BMT WBM (2014), by using remote sensing techniques to describe the distribution of nearshore reefs at Facing Island.
- trial remote sensing and 3D mapping technologies as ways of performing more accurate and regular monitoring of benthic reef communities.



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Study Area and Previous Reef Mapping

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1.2 Monitoring Design Considerations

Effective environmental monitoring and interpretation relies on an understanding of natural gradients, confounding processes, as well as the intensity, duration, and geographical extent of the putative anthropogenic impacts to be assessed. In this case, putative anthropogenic impacts include plumes generated by material placement and resuspension from the EBSDS. These issues need to be considered in the design and interpretation of the monitoring program, and are discussed in more detail below.

1.2.1 Reef Locations and Physical Setting

Prior to BMT WBM (2014), the most comprehensive spatial layers describing reefs within Port Curtis and surrounding Facing Island was the Great Barrier Reef Marine Park's Google Earth layer for reefs of the marine park (Lawrey and Stewart 2016). This area was updated by BMT WBM (2014) based on manual digitisation from aerial imagery and ground surveys. Maps from the two data sources are shown in Figure 1-1. *Note: The present survey updated the reef mapping based on interpretation of 10 m resolution multispectral Sentinel-2 imagery (see Section 3.1).*

The existing (2014) mapping illustrates that an extensive reef system occurs along almost the entire length of the eastern side of Facing Island. Smaller offshore reefs systems occur to the south (Seal Rocks) and north (Rundle Island) of Facing Island. These reef systems differ greatly in terms of their physical setting, including reef size, water depth, geological setting, wave exposure, and hydrodynamic setting (exposure to currents). These reefs also have different water quality characteristics and vulnerabilities to flood plumes, as described below.

1.2.2 Water Quality Characteristics

BMT's hydrodynamic model provides a basis for predicting suspended sediment concentrations associated with dredged material placement at the EBSDS (initial plumes and subsequent remobilisation), and concentrations of suspended sediment and salinity during ambient conditions and major flood events. A summary of relevant findings from various technical reports is provided below.

Dredged Material

Sediment movements associated with dredged material placement at the EBSDS was simulated for placement associated with the maintenance dredging, where 340,000 m^3 of material would be placed on the EBSDS (BMT WBM 2017). The 95th percentile exceedance plot shows where concentrations of total suspended solids (TSS) would be exceeded for the worst 4-day period(s) in the simulation (Figure 1-2). This plot shows that plumes emanating from the EBSDS are generally low in TSS concentration, with the worst-affected reef being those surrounding Sable Chief Rocks (6-7 mg/L TSS). Reefs between Sable Chief Rocks and Gatcombe Head would experience 5 mg/L TSS or less, and North Point Reef, near North Entrance, would experience 2-3 mg/L TSS peak levels.

The increase in TSS due to spoil placement was relatively minor compared to ambient wind-generated resuspension and TSS released by flood plumes (BMT WBM 2017).

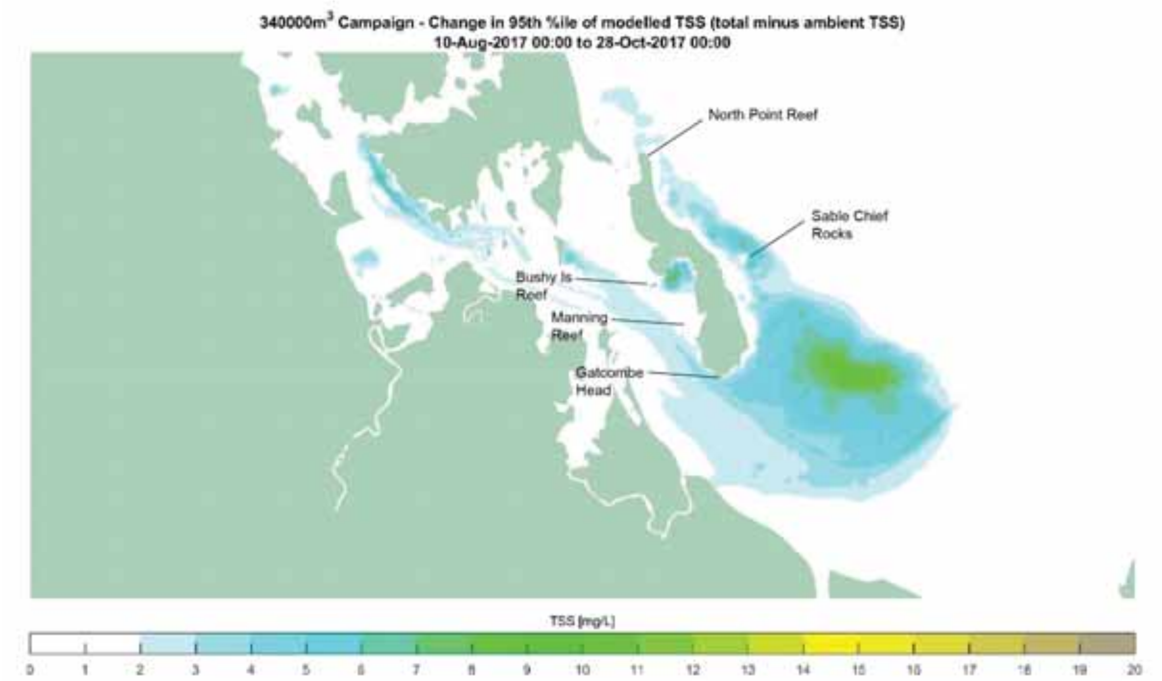


Figure 1-2 95th percentile TSS for a 2.5 month simulation of spoil placement at the EBSDS

The reef remediation prioritisation study (BMT WBM 2014), developed a catchment model for integration with the Port Curtis hydrodynamic model. This was used to hindcast the changes in turbidity and salinity that may have affected corals during the 2013 flood event. Total suspended solids generated from major floods are orders of magnitude higher than disposal plumes associated with dredged maintenance material disposal.

The effects of the simulated 2013 flood were consistent with catastrophic impact to all reefs west of Gatcombe Head and inside North Entrance, attributable to drastic reductions in salinity. The 2013 model showed significant bodies of freshwater developed west of Facing Island and a plume with salinity well below 20 ppt extended into Rodds Bay and over Seal Rocks reefs. Salinities of approximately 15 ppt or less were experienced for three days in the cluster of reefs around North Entrance, while Bushy Island and Manning Reef experienced salinities less than 10 ppt. Measured time-series data from an instrument located between Bushy Island and Manning Reef, showed that salinity fell below 5 ppt at the peak of the 2013 event.

Berkelmans *et al.*, (2012) suggested a salinity dose-time threshold for acroporid corals, based on observed responses to the Fitzroy River 2010-2011 flood plume and its effects on reefs in the Keppel group. The Keppel reefs are the nearest significant inshore coral community to Port Curtis, and acroporid corals (among the more sensitive genera) have a dose-time linear threshold of 22 PSU (roughly equivalent to PPT) for three days grading to 28 PSU over 16 days (Berkelmans *et al.,* 2012).

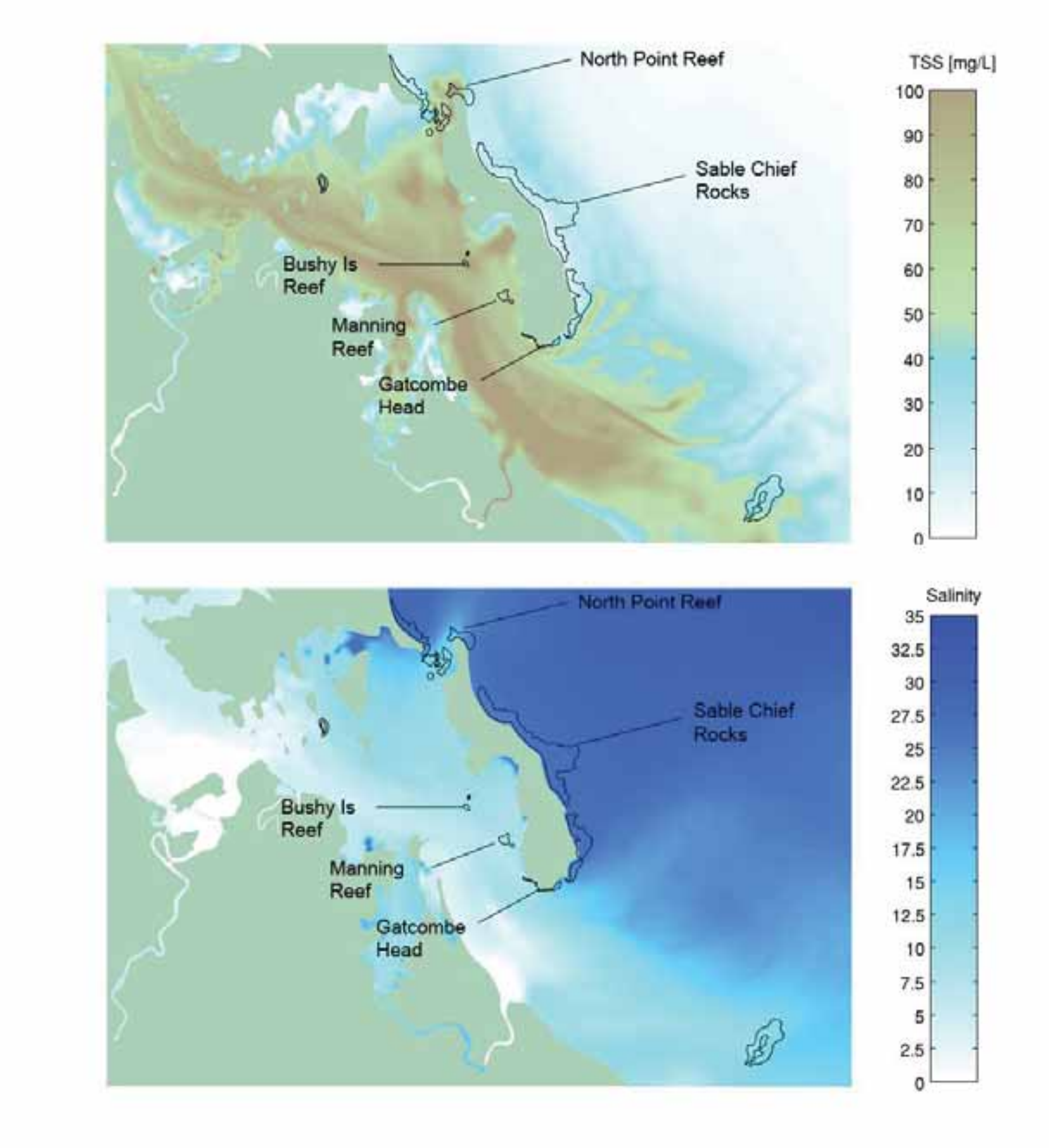


Figure 1-3 Hindcast median TSS (above) and 95th percentile salinity (below) from the 2013 floods (BMT WBM 2014)

BMT visited a selection of sites from the original monitoring program in 2014, but not all 2013 monitoring sites, because the objective was to prioritise remediation sites, not execute the monitoring program. The remediation prioritisation study identified major declines in coral cover between 2013 and 2014, and also between 2009 and 2014, using data collected at sites not included in the monitoring program from BMT WBM (2009). Sites that experienced major reductions in coral cover fell within the Berkelmans *et al.,* (2012) salinity threshold, applied to the 2013 model hindcast. The loss of hard coral was likely the result of freshwater flows from the Boyne and Calliope Rivers, leaving parts of eastern Facing Island relatively unaffected.

Thermal Bleaching

Reefs in the monitoring program are also at risk of thermal bleaching, like the rest of the Great Barrier Reef (GBR). Degree heating weeks (DHW) showing the number of weeks that the summer average sea surface temperature were exceeded for the three world-scale mass-bleaching events are shown in (Hughes *et al.,* 2017).

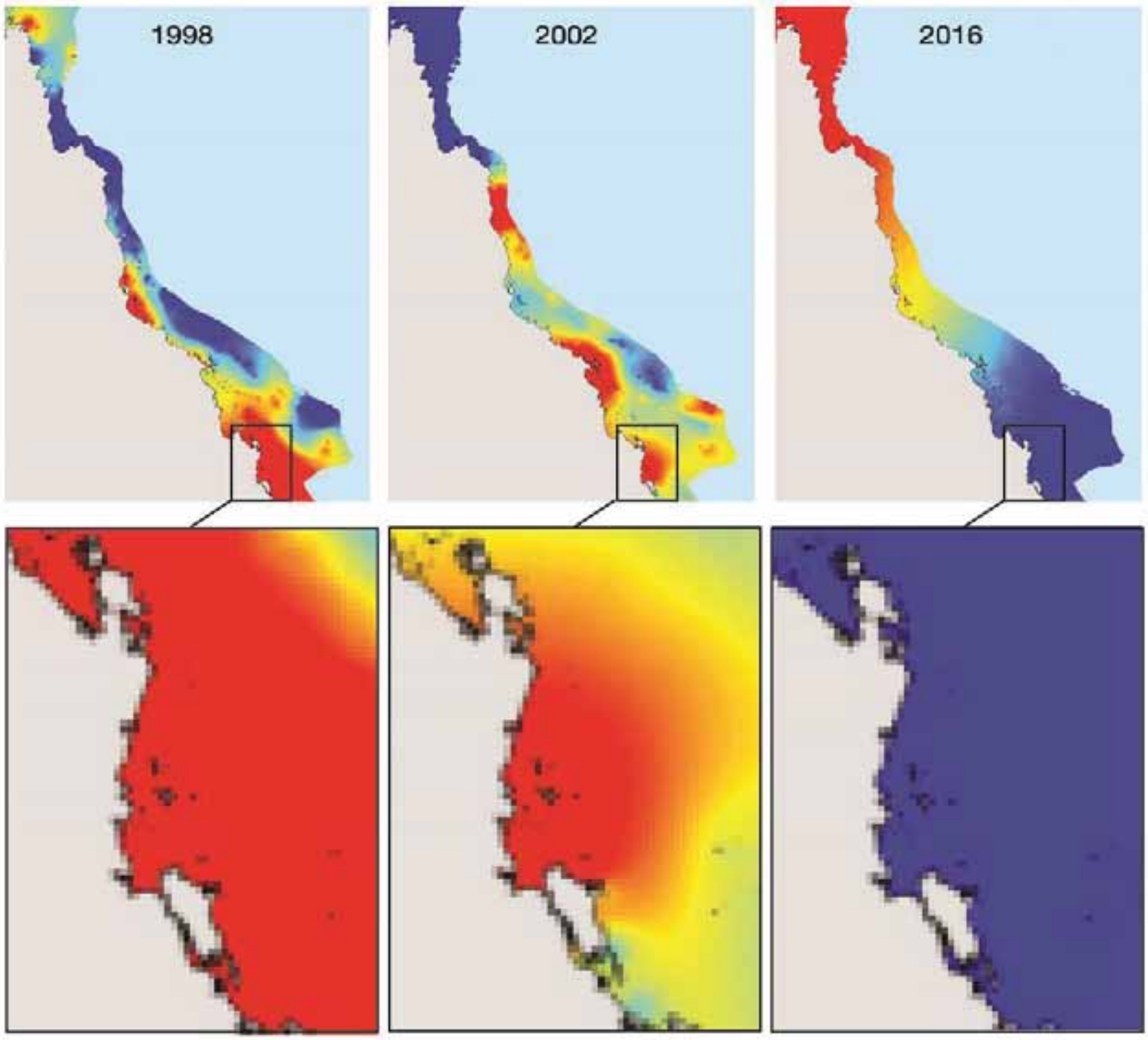


Figure 1-4 Spatial heat stress for bleaching events in 1998 (left) 2002 (middle) and 2016 (right). Dark blue shading indicates 0 Degree heating weeks (DHW), and red is the maximum DHW for each year (7, 10 and 16, respectively). Hughes *et al.,* (2017)

The study area is shown as insets the bottom of each pane in Figure 1-4. The reefs within the monitoring program have experienced variable temperature stress in each of these events, with blue shading indicating zero DHW, and red shading being the maximum DHW for each bleaching event. Other colours are shown as a continuous colour spectrum between the zero and maximum DHW extremes. In the 1998 event, all reefs experienced extreme warming, in the 2002 event there was a north-south gradient in temperature stress, and in 2016, none of the reefs experienced sustained warming above the average sea surface temperature. This shows that unlike catchment impacts, where there are clearly defined spatial gradients in impact, thermal stress varies inconsistently, and is often consistent throughout the study area.

1.2.3 Original Monitoring Program Design

The past monitoring design (last implemented by Sea Research, 2013) consisted of a control-impact framework, with sites east of Facing Island considered to be 'impact', and sites at Rundle Island considered to be 'control' (Figure 1-5). Putative impact was considered the movement of dredged material placed on the EBSDS (Figure 1-1). At each site, four line-intercept transects were taken over 50 m belts, giving four replicates per site. The design had seven impact sites and three control sites.

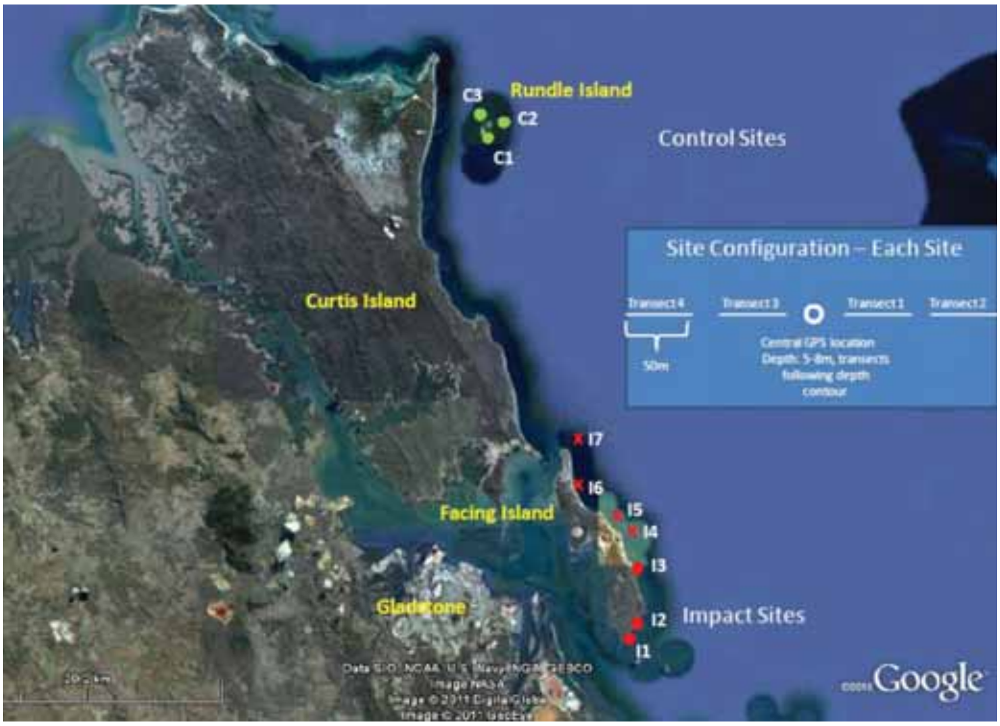


Figure 1-5 Monitoring design last implemented by Sea Research (2013)

Ideally more control sites at alternative locations would be employed to better encompass site-specific variability, but suitable sites (located inshore, with hard coral communities, at similar depths) were not available. Alternative sites investigated on the east coast of Curtis island were dominated by sponges and not appropriate controls for eastern Facing Island (Sea Research 2012) and eventually removed from the monitoring program.

1.2.4 Revised Nomenclature and Design

The original design included three sites in the 'impact' treatment that experience chronic and acute water quality stress from turbid (and occasionally fresh) water from Port Curtis. As described earlier (Sea Research 2013, BMT WBM 2014), these benthic communities also have very different composition, and are dominated by different species subject to prevailing water quality conditions.

For these reasons, a revised design that includes three treatments: harbour entrance; outer Facing Island; and Rundle Island is presented in Table 1-1 and Figure 1-6.

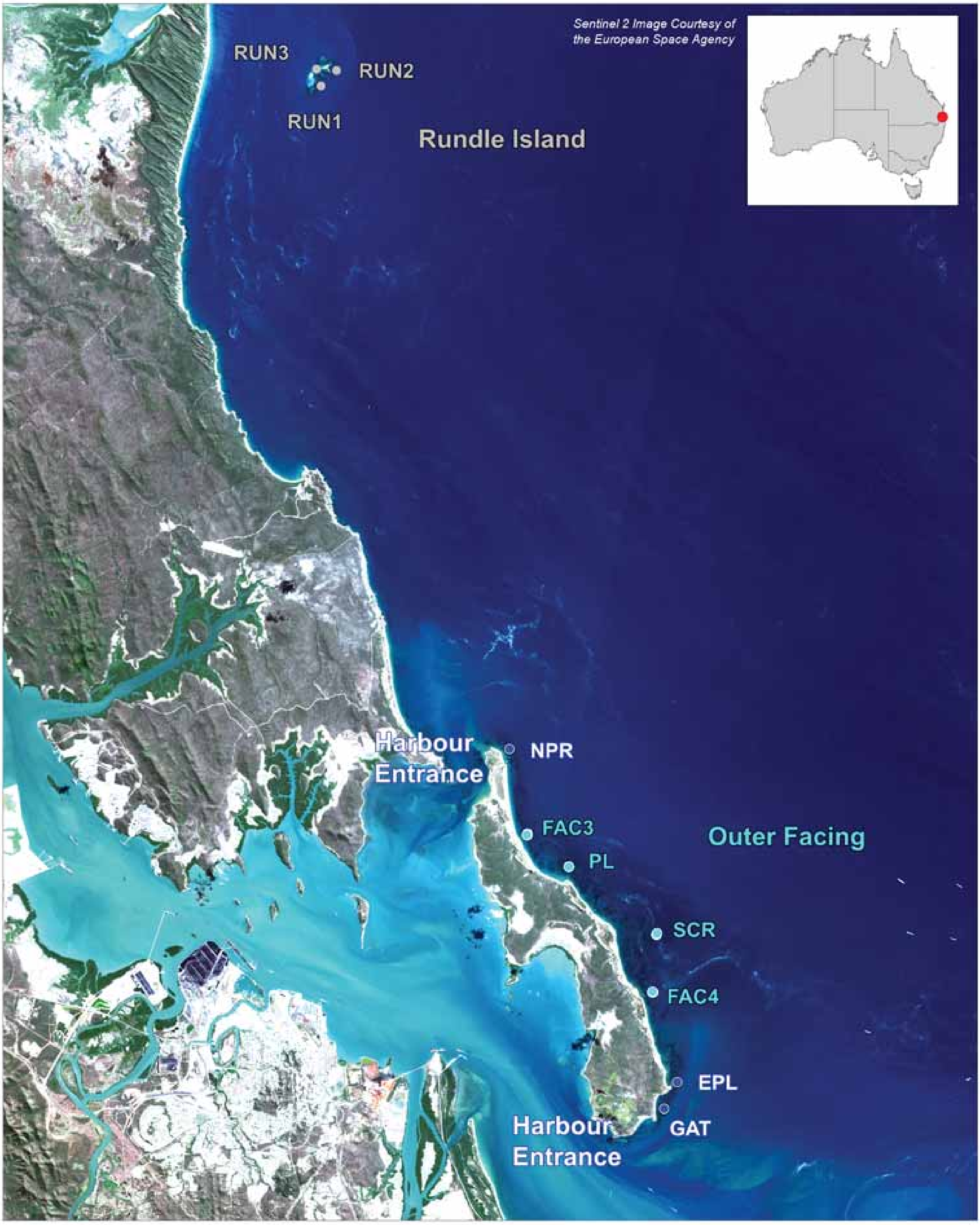
Ideally the study terminology would follow the naming convention applied by the GBRMPA spatial layer. However, individual reefs mapped by GBRMPA form a contiguous fringing reef in front of Facing Island, while other monitoring sites exist over reefs that are not mapped or named. The site labels adopted in Table 1-1 endeavour to follow GBRMPA terminology where possible within the limitations stated above.

The revised design groups sites into the following treatments:

- Background sites (RUN1, RUN2, and RUN3 in Figure 1-6) - Reefs at Rundle Island represent control sites in the context of assessing potential dredging impacts. These sites are also not as strongly influenced by catchment runoff as the harbour entrance treatment.
- Harbour entrance sites (NPR, EPL, and GAT in Figure 1-6) – these sites are more strongly influenced by fluvial discharges than the other two treatments. Two of the sites in this treatment (GAT, EPL) are also closest to the EBSDS.
- Outer Facing Island (FAC3, PL, SCR, and FAC4 in Figure 1-6) – these sites are not predicted to be grossly affected by fluvial discharges and are >10 km from EBSDS, representing putative material placement impacts.

Table 1-1 Revised and previous designs, and terminologies

BMT WBM 2014 site (GBRMPA reef Name)	2014 Data Availability	Sea Research Sites (2013)	2018 site terminology	2018 Treatments
Gatcombe East (Facing Island #6)	Assessed	Impact 1	**GAT** (Gatcombe)	harbour entrance
East Point Ledge (Facing Island #5)	Assessed	Impact 2	**EPL** (East Point Ledge)	harbour entrance
Facing Island #4 (Facing Island #4)	Assessed	Impact 3	**FAC4** Facing Island #4	outer Facing
Sable Chief Rocks Reef (Sable Chief Rocks)	Assessed	Impact 4	**SCR** (Sable Chief Rocks)	outer Facing
Pearl Ledge (Facing Island #3)	Assessed	Impact 5	**PL** (Pearl Ledge)	outer Facing
North Facing Island (not charted or named)	Not assessed	Impact 6	**FAC3** (Facing Island #3)	outer Facing
North Entrance (North Point Reef/ Facing Island #1)	Not assessed	Impact 7	**NPR** (North Point Reef)	harbour entrance
Rundle Island 1 (Rundle Reef)	Not assessed	Control 1	**RUN1** (Rundle Reef)	Rundle Island
Rundle Island 2	Not assessed	Control 2	**RUN2** (Rundle Reef)	Rundle Island
Rundle Island 3	Not assessed	Control 3	**RUN3** (Rundle Reef)	Rundle Island



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2 Methods

Three sampling techniques were used in the present study:

- quantitative (transect-based) sampling of epibenthic reef communities as a part of 5-yearly compliance monitoring
- broad-scale mapping of reefs using high-resolution multispectral satellite imagery
- trial photogrammetry to produce 3D models.

Transect-based methods were used to perform 5-yearly reef monitoring, while remote sensing and 3D modelling methodologies were used to provide more accurate reef mapping, and as trial methodologies for potential for more regular monitoring.

2.1 Remote Sensing Analysis

Multispectral remotely sensed imagery was analysed by calculating the benthic reflective index (BRI), and the depth invariant index (DII) for Sentinel-2 scenes encompassing the study area. The depth invariant index has been used extensively for benthic classification of coral reef environments, while the benthic reflective index can have better classification efficacy in turbid-water environments (Sagawa *et al.,* 2010). Scenes of the study area from August 11th and September 15th 2017 were downloaded and processed, with the latter scene offering the best visibility, but poorer atmospheric conditions. Of the imagery available in the last two years, the two scenes chosen had the best combination of water and atmospheric clarity.

The DII (Lyzenga 1981) was calculated from atmospherically corrected, de-glinted images. Scenes were atmospherically corrected using the Sentinel application platform (SNAP 6.0) and de-glinted using the procedures outlined in Hedley *et al.,* (2005). Shallow-water signals for use in both procedures were obtained from sandy areas east of Facing Island known to be devoid of marine plants or reef based on ground-truthing in 2014 and 2018. The BRI was calculated using a 10 m resolution bathymetric grid, developed by BMT and GPC for hydrodynamic modelling purposes. For the DII, the coastal band 1 (0.443 µm central wavelength, 60m resolution) was resampled to 10 m and used with the blue band (0.490 µm) and green band (0.560 µm) as band pairs to provide maximum signal penetration in turbid waters.

The DII was visualised as a, false colour RGB image with the B1-B2 band combination as the red channel, the B2-B3 combination as the green channel, and the B1-B3 combination as the blue channel. Results for the August capture were not presented or further processed due to poor visibility, particularly at North Entrance and Gatcombe Head, where reefs were partially or fully obstructed by turbidity.

The results of the DII and BRI indices were classified using Maximum Likelihood methods for pixels (Foody *et al*., 1992) in Arcmap 10.5. Polygon areas over dense *Acropora* stands at Facing Island and Rundle Island were used as training polygons for coral habitat, while macroalgal dominated reef at Gatcombe Head, North Entrance, and Seal Rocks Reef were used to train macroalgal reef polygons. Habitat classification signature files were used to classify the BRI and DII indices. Classifications for the DII were attempted with five band pairs, and three band pairs; both of which produced classification results inferior to the BRI. Therefore, the classification based on BRI is presented in section 3.1.

2.2 Coral Monitoring Transects

2.2.1 Data Collection

The 10 sites surveyed by Sea Research (2013) were revisited in the present survey (Figure 1-6) between May 31st and June 4th, 2018. The 2013 survey used a line intercept approach over a 50 m transects, with four replicate samples collected at each site. The present survey was designed to be compatible with the original sampling program, but able to be improved in the future by using photo-quadrats (taking random photos along a fixed transect) to increase sample replication and sample precision. Photo-quadrat methods are also similar to those used in the Long-term Inshore Reef Monitoring Program by AIMS and are compatible with the transect data collected by the GHHP.

The start of each transect location was marked with a shot line and located using a waterproof GPS unit tied to the diver's surface float. Start and finish points for each transect were determined from point tracking on the diver tether.

Each location was surveyed along the -3 to -5 m lowest astronomical tide (LAT) contour or as appropriate given site conditions. Transects occasionally became shallower or deeper while following available reef habitat. A 20 m transect tape was lain on the substrate, and a diver swam over the substrate underneath using paired high-definition underwater cameras capturing still images (every second) and video. Distance from the tape varied depending on visibility and macroalgal canopies encountered; however, a distance of 15-50 cm was generally adhered to as per procedures used by AIMS and the Hawaii Coral Reef Assessment and Monitoring Program. Incidence of coral disease and numbers of coral recruits were quantified within 34 cm of the transect tapes from video footage taken over the entire transect.

All diving was undertaken by BMT marine scientists with ADAS commercial dive qualifications aboard the 2c certified vessel *Candela*.

2.2.2 Data Analysis

The video footage was used to assist in identification, and for coral health, recruitment counts, and general observation purposes. Still imagery was quantified to determine benthic cover and community composition. Coral Point Count was used to quantify photo-quadrats, with coral and algae identified to the lowest practical level (typically genus). Twenty-point identifications were made per photo. Photos were selected randomly (10 per transect), giving a total of 200 point IDs per transect, or 40 photo-quadrat samples per site.

Raw data from Sea Research (2013) were unavailable; therefore, qualitative temporal comparisons between 2013 and 2018 were made. Approximate means and standard errors for sites were digitised from the original report and re-apportioned into sites within the 2018 treatment groups by averaging means and errors in the new treatment groups. Transect-level means and standard errors were visually compared between the four sites that were surveyed in both 2014 (BMT WBM 2014) and 2018 (present study).

Differences among sites and treatments in 2018 were explored at the photo-quadrat level, to increase replication and improve power. A chi-squared test was conducted to test the differences in coral cover among different sites and treatment groups within a generalised linear model. Patterns in quantitative community attributes (such as cover) using photo-quadrats as replicates were explored using generalised linear modelling in R. Percent cover data converted to proportions best fit the Poisson distribution, and this was used as the error structure in linear modelling with the Chi-squared test statistic. This approach mitigated the need to comply with standard ANOVA assumptions.

Patterns in assemblage structure at different sites were analysed using the non-metric muti-dimensional scaling plots (nMDS), Similarity Percentages (SIMPER), and Analysis of Similarity (ANOSIM) routines using Primer 7 software package. ANOSIM and nMDS routines were used to identify differences in assemblage structure among sites and among treatments. SIMPER and shade plots were used to identify taxa contributing to differences among sites and treatments and to identify possible drivers of these patterns.

2.3 3D Mapping

Three-dimensional mapping of reefs was trialled at three sites; North Point Reef (NPR), Facing Island #3 (FAC3), and Sable Chief Rocks (SCR). Imagery was also collected from Seal Rocks Reef, but was not able to be built into a 3D model due to a dynamic algal canopy that prevented photo-matching during photogrammetry.

At each site, 500-800 georeferenced photos were taken using a wide-angle still camera interfaced with a surface RTK GPS. Photos and positions were built into 3D models using proprietary techniques involving:

- Batch processing of photos to remove poorly focused images.
- Colour correction to bring up red tones and reduce green and blue levels.
- Removal of lens vignetting to homogenise lighting across the field of view.
- Photogrammetry using tie points at precisely known locations.
- Generation of 3D models and orthomosaics from aligned imagery.

3 Results and Discussion

3.1 Remote Sensing

3.1.1 Facing Island

False-colour imagery of the DII at Facing Island shows shallow-water reef communities resolved as bright pink regions (Figure 3-1). Turbidity and other water-column effects make the reef-sand boundary difficult to distinguish just north of Pearl Ledge, but a clear sand (black) versus reef (pink) boundary is present over much of the image. The previous mapping polygons from BMT WBM (2014) and GBRMPA are shown as blue and yellow polygons, respectively.

The delineation between reef edge and sand (dark pixels) is clear along most of Eastern Facing Island area except the area of reef near Pearl Ledge, where water column artefacts are difficult to distinguish from reef. The DII mapping is mostly consistent with the BMT WBM (2014) reef extent, but there are some areas previously mapped as reef that appear to be sand, and there are other areas of reef beyond the 2014 extent that should be included. These differences in extent are presumably methodological. Increases in reef extent include the following areas:

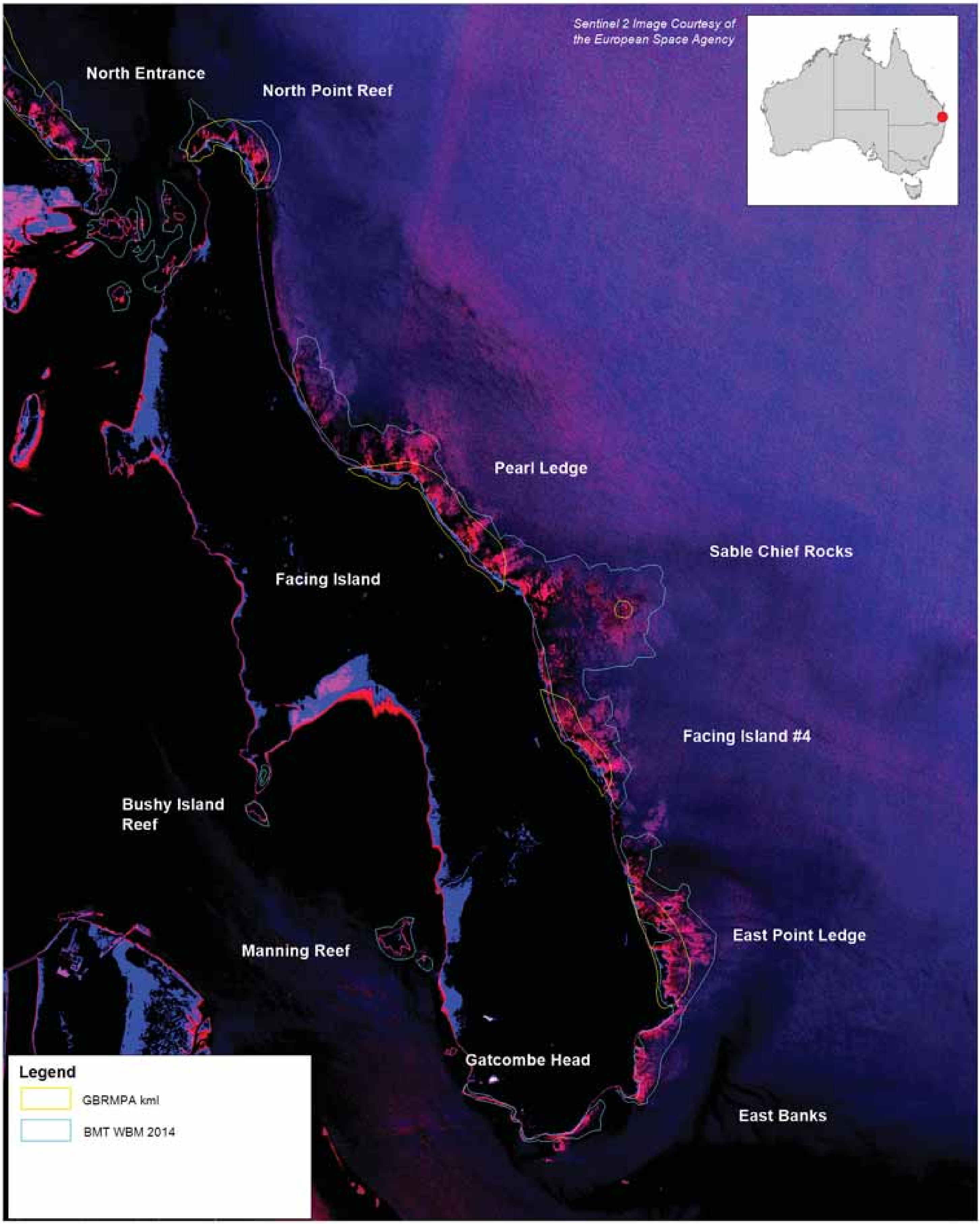
- close to the shore between North Point Reef and FAC3.
- near Pearl Ledge.
- south-east of Sable Chief Rocks.
- between East Point Ledge and Facing Island #4.

Reductions in the BMT WBM (2014) reef extent are between Pearl Ledge and FAC3, near Gatcombe Head, and between Gatcombe Head and East Point Ledge.

The maximum likelihood classification of eastern Facing Island using the BRI has produced a map of coral and macroalgal dominated reefs along its length (Figure 3-2). This map was produced using ground-truthing data where coral was the dominant cover form (polygon areas at Rundle Island and Sable Chief Rocks) and where macroalgae was the dominant cover (reefs at East Point Ledge, and Gatcombe Head). The maximum likelihood method predicts classes based on training samples and does not provide quantitative cover data for coral or macroalgae. The map shows that reefs from East Point Ledge south, and inside North Entrance are macroalgal dominated, while communities between Sable Chief Rocks and North Entrance re dominated by coral.

This map largely agrees with ground-truthing observations conducted in 2014 and 2018; however, several anomalous classifications have been produced, including patches of macroalgal dominated reef inside Port Curtis and patches of coral-dominated habitat on East Banks. The anomalies appear to be the result of turbidity and/or seagrass patches. Reefs such as Manning Reef and Bushy Island are poorly characterised by this classification.

Interestingly, the area of reef between Pearl Ledge (more specifically FAC3) and North Entrance was not ground-truthed in 2014 or 2018, yet both the DII and BRI classifications suggest that reef exists in this area.



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Facing Island Depth Invariant Index

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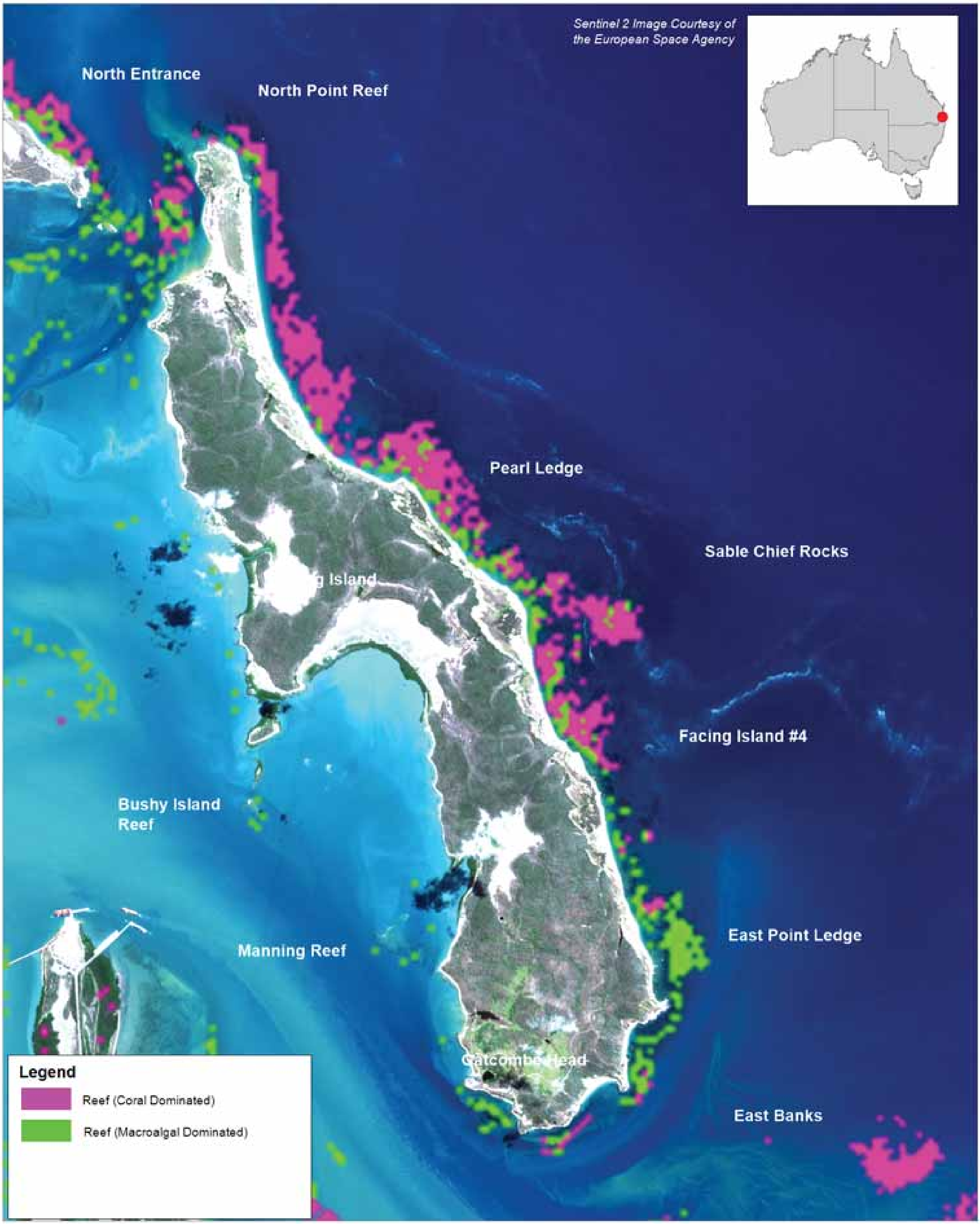
Filepath: I:\B23076.I.CMJ_Facing_Coral\DRG\ECO_005_Facing_Is_DII.wor\



Title:

Facing Island Benthic Reflective Index (Maximum Likelihood Classification)

Figure: 3-2

Rev: A

BMT endeavours to ensure that the information provided in this map is correct at the time of publication. BMT does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

N

0 1.5 3km

Approx. Scale

BMT

www.bmt.org

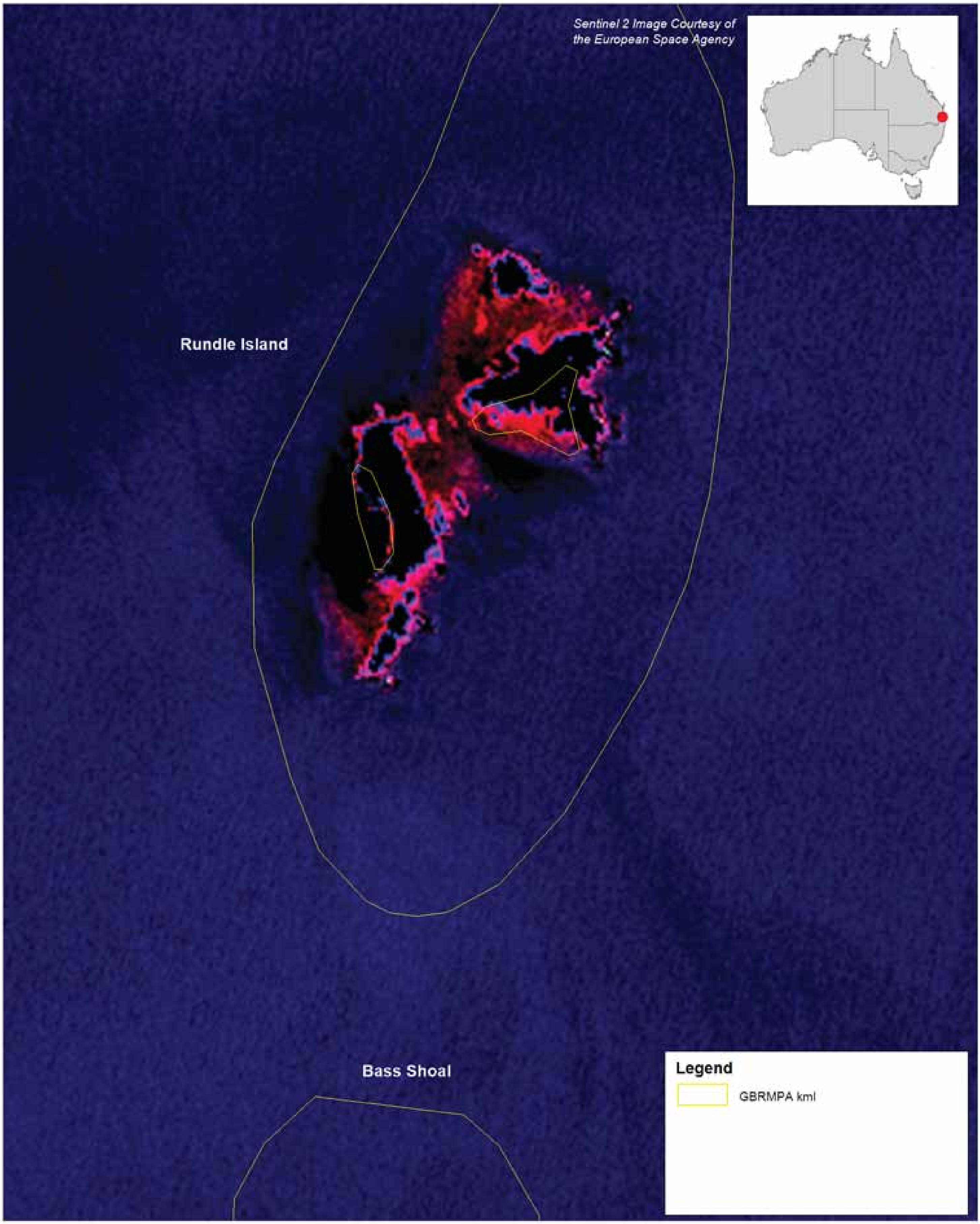
Filepath: I:\B23076.I.CMJ_Facing_Coral\DRG\ECO_005_Facing_Is_DII.wor\

3.1.2 Rundle Island

False-colour imagery of the DII at Rundle Island again shows shallow-water reef communities resolved as bright pink regions (Figure 3-3). This site was not mapped by BMT WBM (2014), but the GBRMPA reef mapping extent is shown as a yellow polygon. Based on ground-truthing, the reef mapping appears consistent with patterns observed on the north-west side of the Island, but has failed to resolve communities deeper than 10 m on the eastern side of the Island. Video transect sites conducted on this side of the Island at RUN 2 do not overlap with the visible area of reef, suggesting that more extensive deep-water communities (>10 m) exist beyond the DII mapping.

The area of Bass Shoals mapped as a large circle to the south of Rundle Island did not show any features consistent with coral at this location.

The maximum likelihood classification of Rundle Island using the BRI has produced a map of coral and macroalgal dominated reefs over some parts of the reef, but mis-classified large sections of reef (Figure 3-4). This map in inconsistent with ground-truthing observations conducted in 2018 and includes only partial classifications of reef habitat and some anomalous classifications of open water.



Title:

Rundle Island Depth Invariant Index

Figure: 3-3

Rev: A

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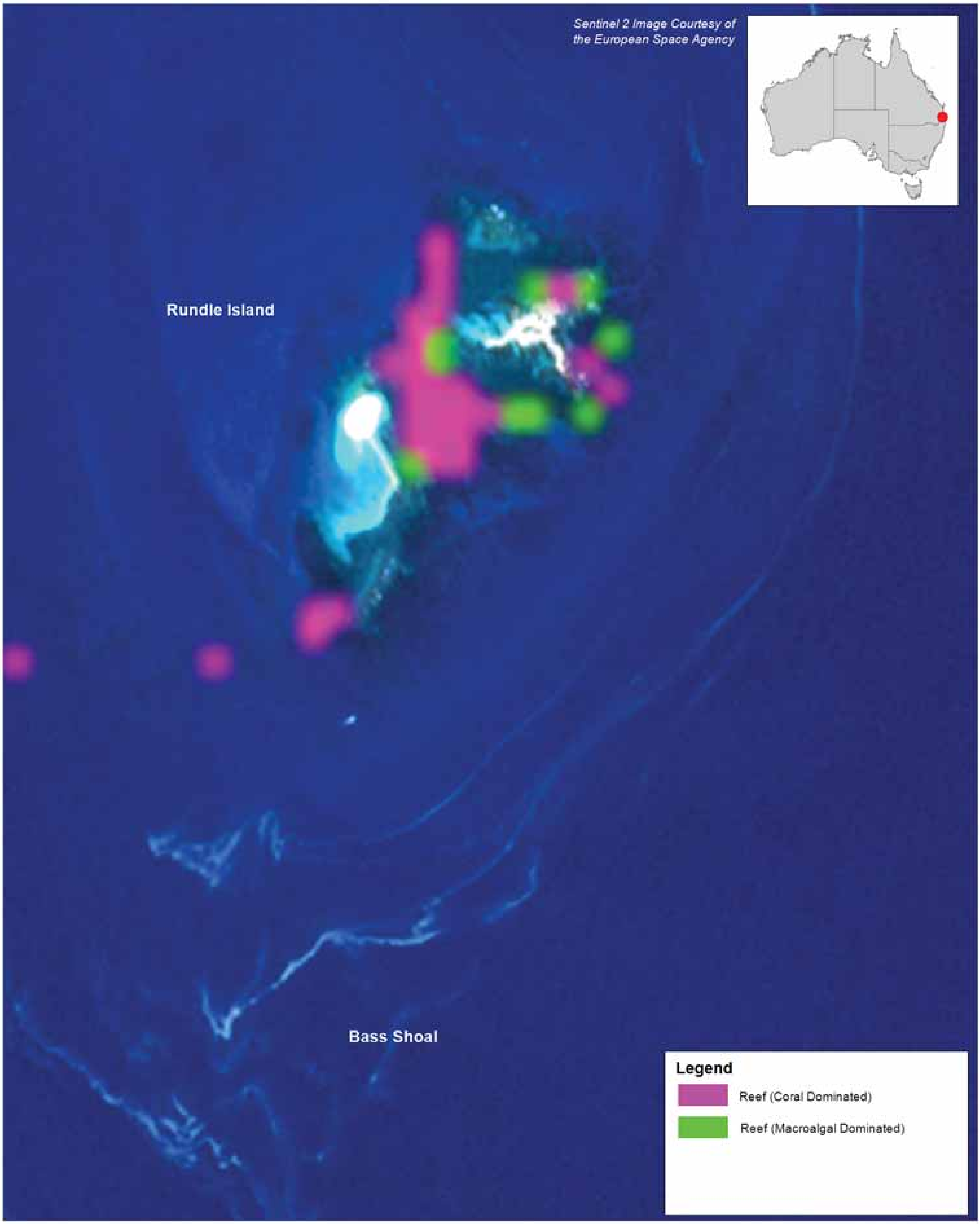
Filepath: I:\B23076.I.CMJ_Facing_Coral\DRG\ECO_007_Rundle_Is_DII.wor



Title:

Rundle Island Benthic Reflective Index (Maximum Likelihood Classification)

Figure: 3-4

Rev: A

N

0 350 700m

Approx. Scale

BMT

www.bmt.org

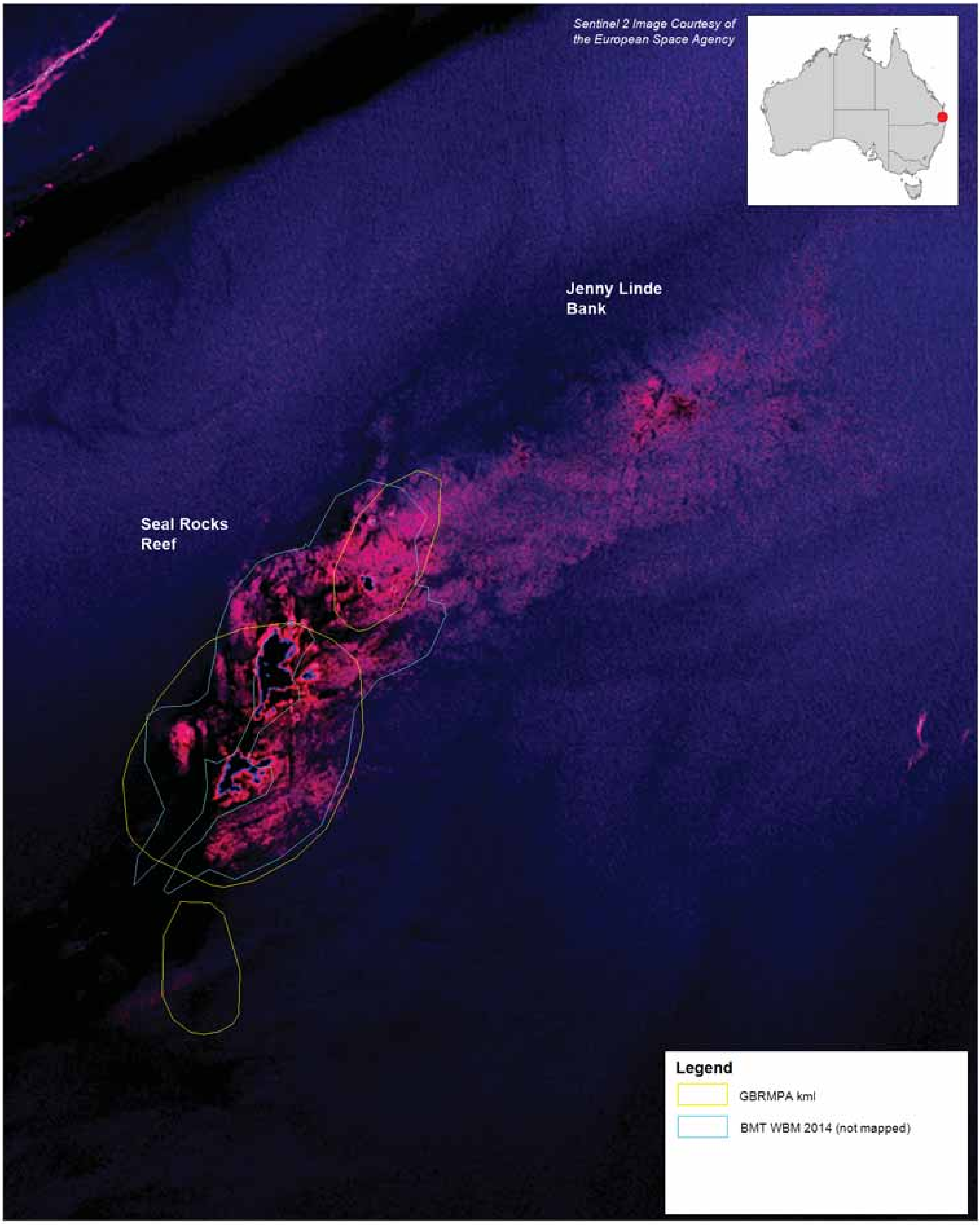
Filepath: I:\B23076.I.CMJ_Facing_Coral\DRG\ECO_008_Rundle_Is_BRI.wor

3.1.3 Seal Rocks

False-colour imagery of the DII at Seal Rocks Reef shows shallow-water reef communities resolved as bright pink regions, running between Seal Rocks and Jenny Lind Bank (Figure 3-5). Darker blue areas probably represent areas of sea floor that are not sand (rubble or shell) or possibly water column artefacts. Previous mapping polygons from BMT WBM (2014) and GBRMPA are shown as blue and yellow polygons, respectively. Unlike previous mapping, the DII shows that reef runs continuously between Seal Rocks Reef and Jenny Lind bank, and the two features should probably be classified and managed as one reef.

The delineation between reef edge and sand (dark pixels) is clear along the northern reef edge. The reef edge becomes more diffuse and patchy along the southern edge, indicating either obstruction of the remotely sensed signal by water clarity, or perhaps that the reef is patchy by nature, consisting of smaller bomboras and outcrops. The DII imagery can greatly improve the accuracy of the BMT WBM (2014) reef extent mapping. In particular, the south-western area previously mapped as reef appears to be sand, the area of seafloor between Seal Rocks and Jenny Lind bank should be included as reef extent. These differences in mapped extent are presumed to be methodological mapping differences rather than an increase in reef extent.

The maximum likelihood classification of Seal Rocks Reef using the BRI produced a map of scattered coral- and macroalgal dominated reef along its length (Figure 3-6). The map suggests that reef in the north-east extremity of the feature (near Jenny Lind Bank) is more coral-dominated, while the reef surrounding Seal Rocks Reef is a mixture of substrates. Extensive ground-truthing of Seal Rocks Reef was not part of the present scope of work, but it appears that some anomalous classifications have been produced, including mis-classifications of reef as sandy substrates along the deeper sections of the reef, and parts of the northern reef edge.



Title:

Seal Rocks Depth Invariant Index

Figure: 3-5

Rev: A

BMT endeavours to ensure that the information provided in this map is correct at the time of publication. BMT does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

N

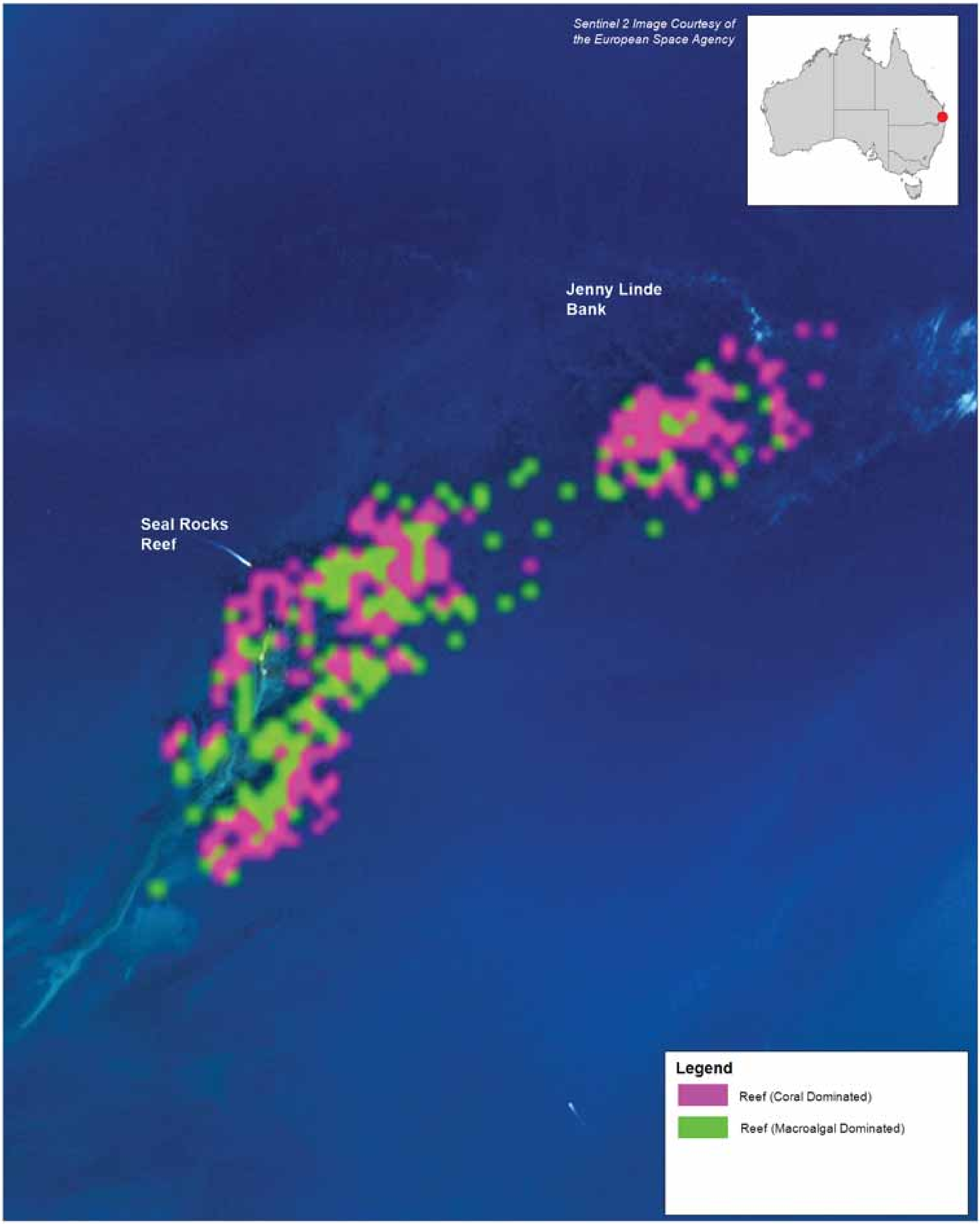
0 350 700m

Approx. Scale

BMT

www.bmt.org

Filepath: I:\B23076.I.CMJ_Facing_Coral\DRG\ECO_009_Seal_Rocks_DII.wor



Title:

Seal Rocks Benthic Reflective Index (Maximum Likelihood Classification)

Figure: **3-6**

Rev: **A**

BMT endeavours to ensure that the information provided in this map is correct at the time of publication. BMT does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

N

0 350 700m

Approx. Scale

BMT

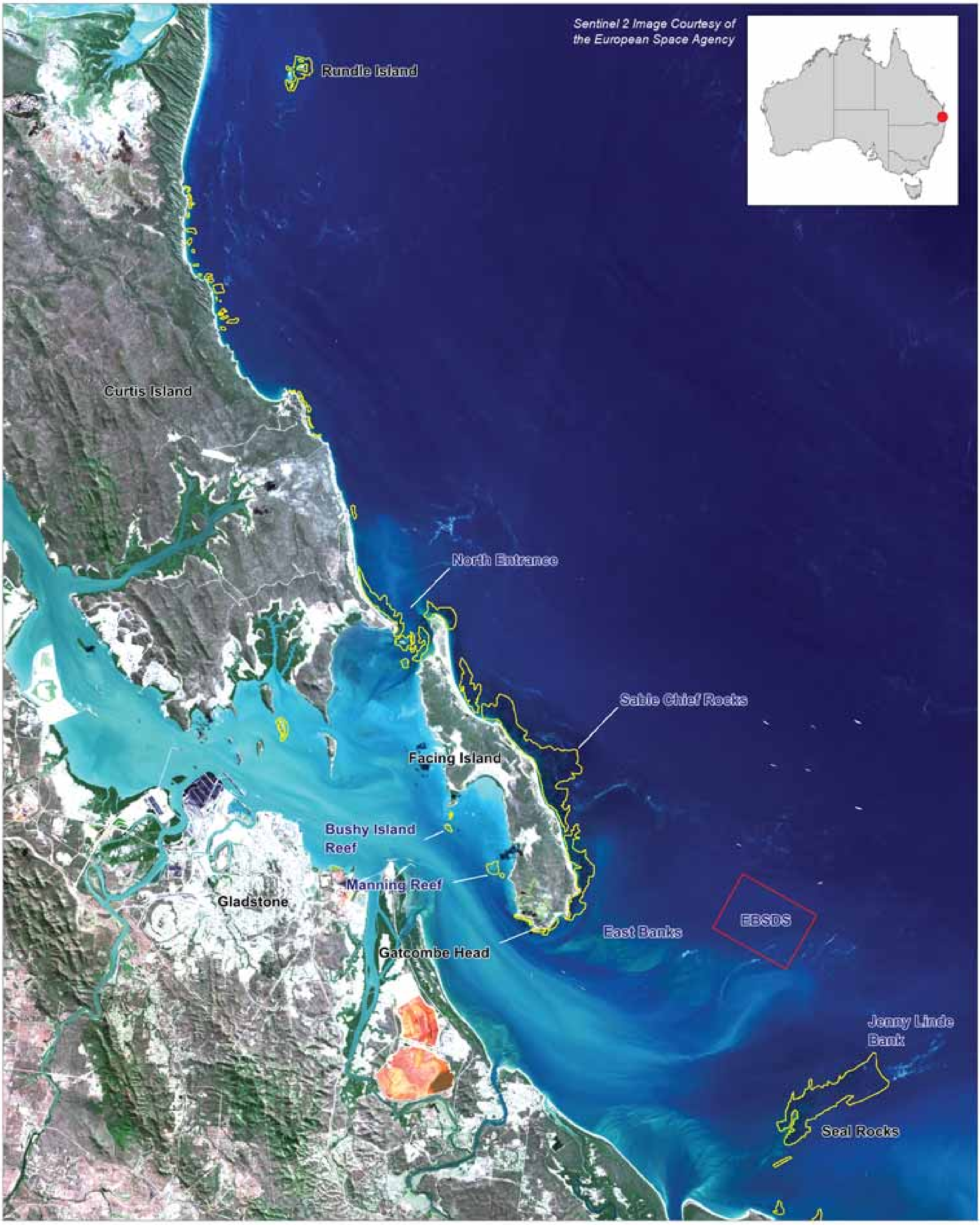
www.bmt.org

Filepath: I:\B23076.I.CMJ_Facing_Coral\DRG\ECO_010_Seal_Rocks_BRI.wor

3.1.4 2018 Revised Reef Layer

The reef layer presented in Figure 3-7 is a revision to the BMT WBM (2014) layer based on interpretation of the DII and BRI indices, and both atmospherically corrected true-colour images. Small reefs along Curtis Island have also been digitised, although not part of the present study. There is no evidence in any of the imagery that the reef situated over East Banks in the GBRMPA layer (Figure 1-1) exists. This area was visited in 2014 and consisted only of sand. The 2018 reef layer represents a total 21.71 Km^2 of reef, compared to 13.90 km^2 mapped in 2014.

Cover types derived using the BRI in this study can be used to map areas of reef dominated by coral or macroalgae. However, this is only considered appropriate at Facing Island; mapping of cover types is considered too anomalous to be of use at Seal Rocks or Rundle Island using Sentinel Imagery, and without dedicated water column removal. For quantitative cover comparisons across the study area, more complicated (and expensive) remote sensing methods involving ultra-high resolution (2 m) imagery and physics-based water column correction should be employed.



Title:

Adjusted Reef Layer 2018

Figure: 3-7

Rev: A

N

0 5 10km

Approx. Scale

BMT

www.bmt.org

Filepath: I:\B23076.I.CMJ_Facing_Coral\DRG\ECO_011_2018_Reef_Layer.wor

3.2 Coral Survey Results

3.2.1 2018 Univariate Cover Analysis

Site-level coral cover data from the 2018 survey followed a Poisson distribution and was analysed using a generalised linear model appropriate to this distribution. There was a significant difference between coral cover at different sites (X^2 residual deviance [7, N = 399) = 6980.5; p<0.001]) and between treatment groups (X^2 residual deviance [2, N = 399) = 10632.4; p<0.001]). Greatest cover of live coral was at sites located at Rundle Island and at outer Facing Island sites FAC3 and SCR (Figure 3-8). At a treatment level the highest coverage of coral was at Rundle Island followed by the outer reefs of Facing Island. Sites at the northern and southern extent of Facing Island (harbour entrance sites) which are exposed to tidal currents and turbidity from Gladstone Harbour had the lowest coral cover.

Soft coral was observed at low levels (<5%) across most sites except RUN2 (Figure 3-9). There were no clear patterns in the distribution of soft coral among treatment groups.

Macroalgae was present at all survey sites in moderate abundance with highest cover seen at harbour entrance sites and lowest at Rundle Island sites (Figure 3-10). Generally, total algae cover followed an inverse distribution to coral cover – i.e. typically where macroalgal cover was higher, cover of corals was lower.

The contribution of macroalgae and turfing algae to total algal cover was examined at each site. At sites where coral cover was highest (Rundle Island sites as well as FAC4 and SCR at outer Facing Island) the algal community was dominated by low lying algal turfs (see Figure 3-8 and Figure 3-10). Algal communities at other sites were comprised of both macroalgae and turfing algae. This relationship is discussed further in Section 3.2.2. Dense macroalgae can form large canopies that shade the substrate, potentially outcompeting corals (McCook *et al.,* 2001); however, both macroalgae and turfing algae can inhibit coral recruitment (Arnold *et al.,* 2010). Phase shifts between coral and algal dominated communities have been well documented in the literature and may be caused by a number of ecological processes or environmental conditions (see McManus and Polsenberg 2004) but regardless of the drivers, cover of hard corals and macroalgae are generally inversely related and this was the pattern observed in the present study.

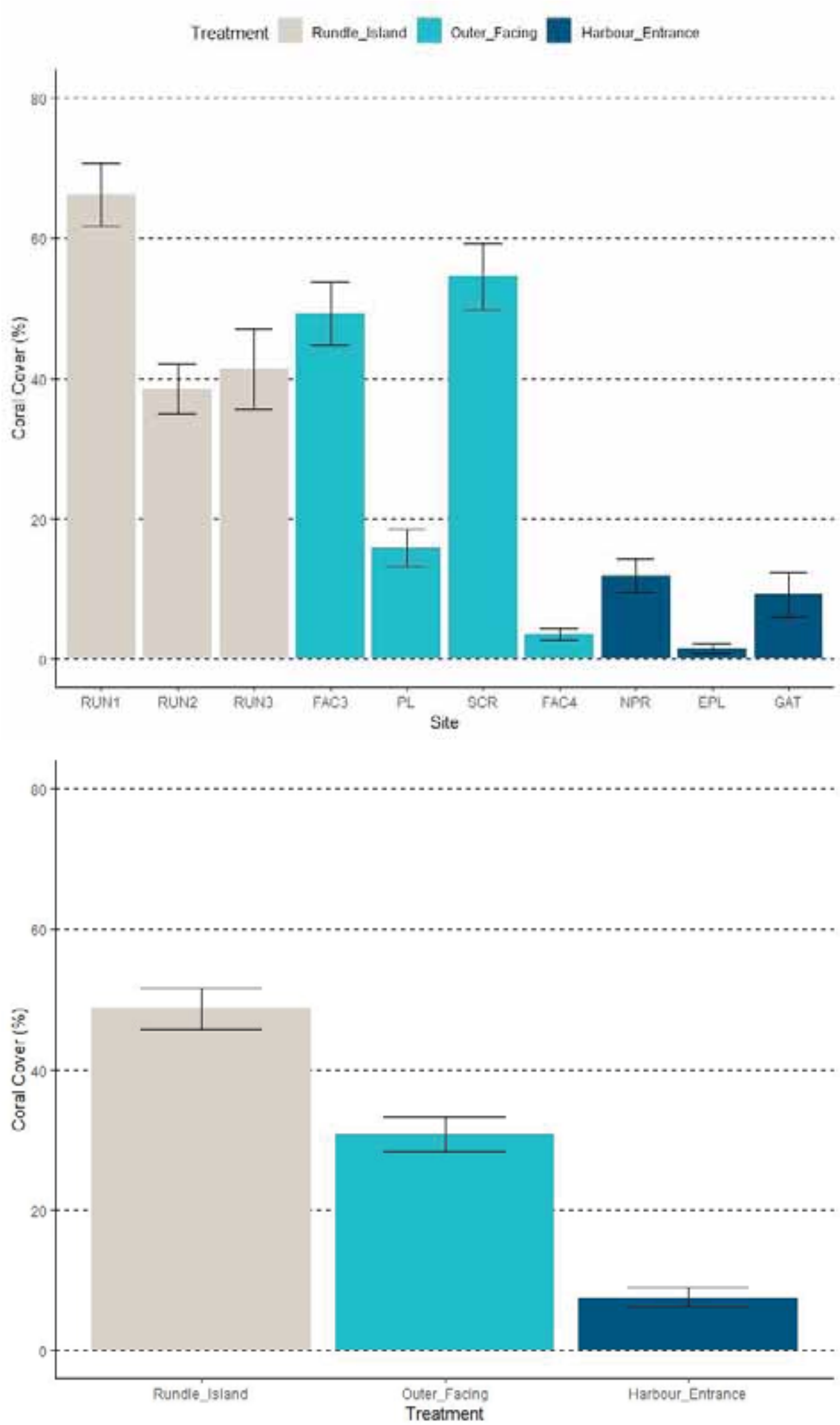


Figure 3-8 Mean coral cover (±SE) by site (upper) and treatment (lower)

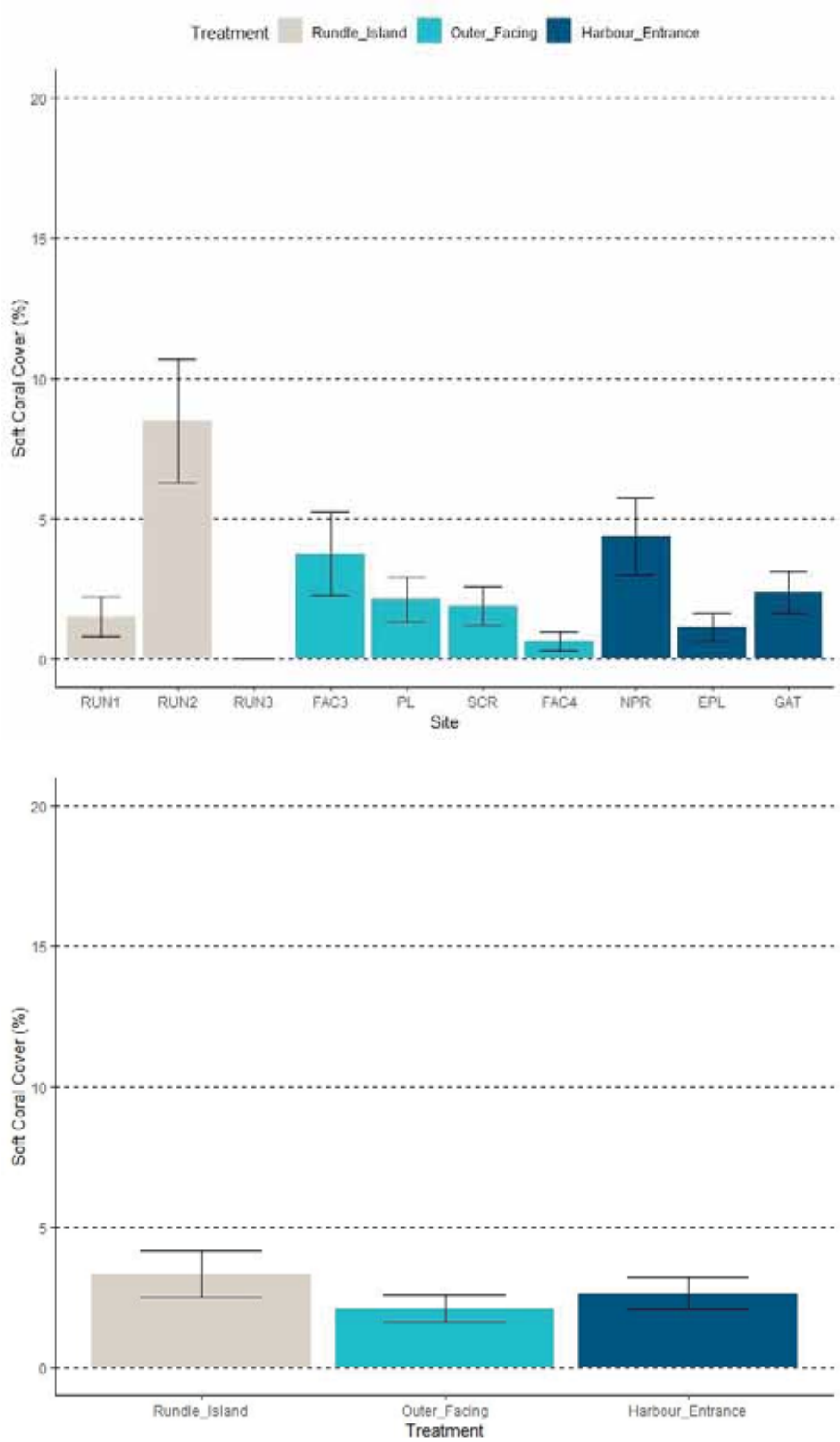


Figure 3-9 Mean soft coral cover (±SE) by site (upper) and treatment (lower)

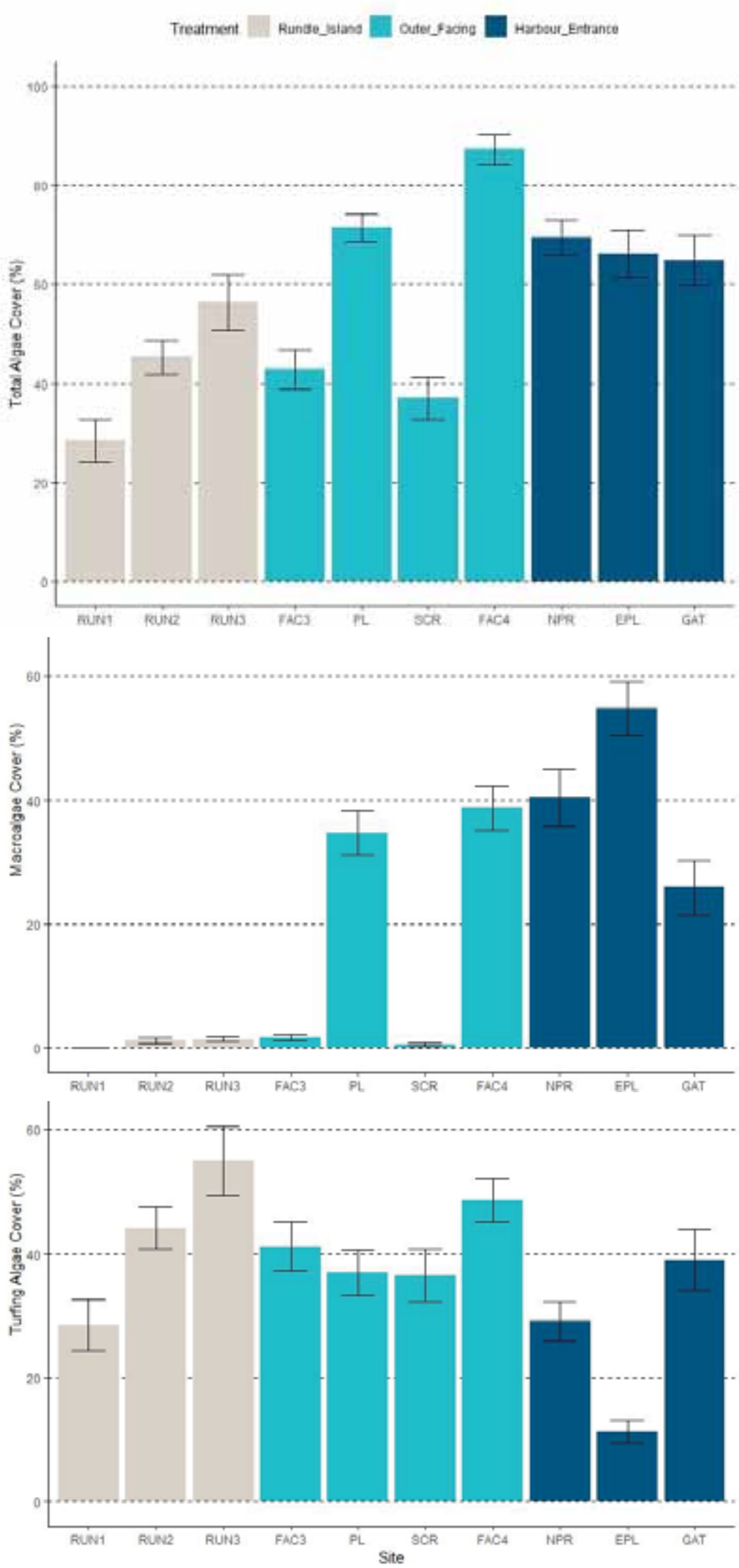


Figure 3-10 mean algae cover (±SE) for total algae (upper) and separated to show cover of macroalgae (middle) and turfing algae (lower)

3.2.2 2018 Multivariate Cover Analysis

Figure 3-11 is an nMDS ordination showing patterns in similarity of benthic communities among sites in two-dimensional space. Samples with similar communities are positioned closer together, while samples with dissimilar communities are positioned further apart. Two communities were distinguished at the 50% Bray Curtis similarity level:

- Rundle Island sites and outer Facing Island sites FAC3 and SCR had similar communities, grouping together at the 50% similarity level on the right side of the ordination. Some sites within this group had a relatively distinct community – most notably sites SCR and RUN1 which were more similar to each other than they were to other sites. Most treatments displayed great within-site variability in communities, often being more similar to other sites than to each other.
- Harbour entrance sites and outer Facing Island sites FAC4 and PL were more similar to one another and were grouped close together on the left-hand site of the plot.

The shade plot in Figure 3-12 provides a graphical representation of the relative abundance of different taxa groups at each site (dark grey = high abundance, white = zero abundance). As discussed above, coral cover was much higher overall at Rundle Island sites, FAC3 and SCR. The shade plot shows that coral cover at these sites was dominated by *Acropora* which was observed in large monospecific stands that were sometimes interspersed with other corals and benthic cover types (Figure 3-13). The corals *Pocillopora* and *Goniastrea* showed similar distributions to *Acropora* while *Porites* and *Montipora* were present more broadly throughout the study sites but were generally more abundant at Rundle Island, FAC3 and SCR. Turfing algae was observed across all sites while bare substrate (Sand/Mud) and the macroalgae *Sargassum* was more common at outer Facing Island sites PL and FAC4 and at harbour entrance sites. The macroalgae *Lobophora* and *Dictoya* showed similar patterns to *Sargassum* in their distribution. These macroalgae species were the most abundant and their distribution is consistent with that for macroalgae discussed above and shown in Figure 3-10. Crustose coralline algae was sparse at all sites but was more common at outer Facing Island and harbour entrance sites and was not widely seen at Rundle Island.

ANOSIM indicated that there were significant differences in communities among sites. Pairwise tests for differences between sites show that most sites were significantly different to each other (see Appendix A for the full test results). Exceptions were sites that did not demonstrate a significant difference (i.e. communities at these sites were very similar) and included sites EPL and GAT ($R=0.375$; $p=0.086$); GAT and NPR ($R=0.302$; $p=0.114$); NPR and PL ($R=0.073$; $p=0.314$) and; RUN1 and SCR ($R=0.26$; $p=0.086$).

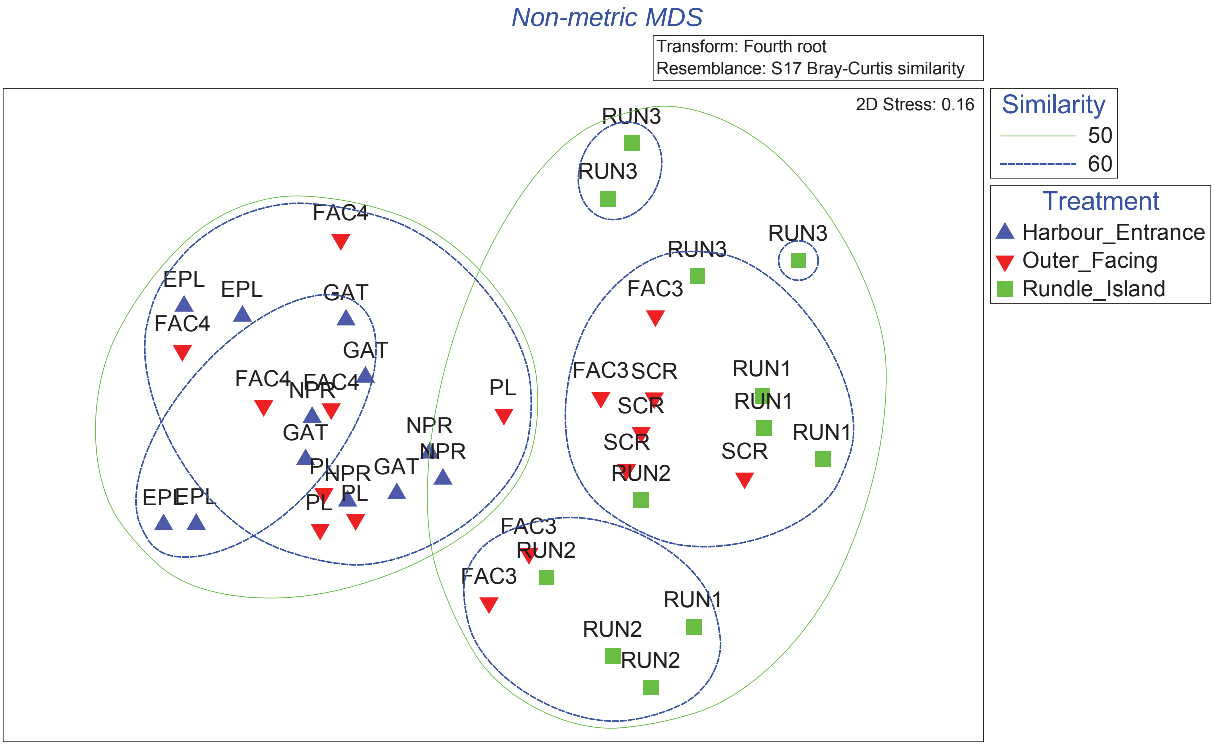


Figure 3-11 nMDS plots showing similarity among benthic communities at different sites, differentiated by treatment groupings

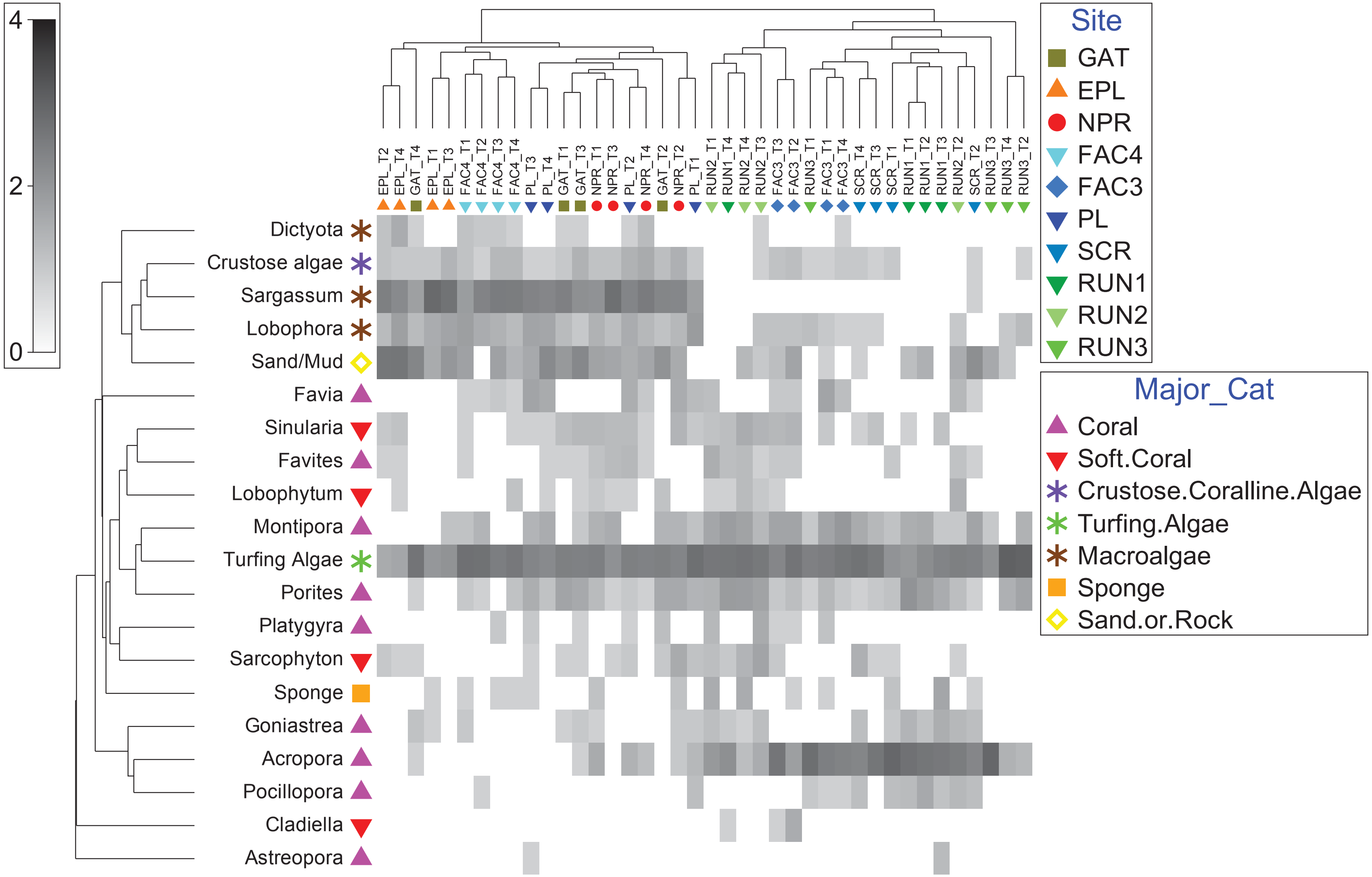


Figure 3-12 Shade plots provide a visual representation of SIMPER results

Figure 3-13 Large stand of *Acropora* at RUN3 and transect tape used to enumerate recruits and incidence of disease

3.2.3 Comparisons Between 2013 and 2018

This section presents qualitative visual comparisons between the data collected in 2013, a subset of sites that were sampled in 2014, and the results of the present survey. Graphs are presented using transect-level data. It should also be noted that whether the algae category includes turfing algae in the 2013 survey is unclear. Sites sampled on all three occasions include:

- Sable Chief Reef (SCR).
- Pearl Ledge (PL).
- Gatcombe (GAT).
- Facing Island Reef # 4 (FAC4).
- East Point Ledge (EPL).

Due to a lack of raw data, no quantitative comparisons have been made between the 2013 and 2018, nor have they been made between 2014 and 2018 due to different levels of transect replication.

Coral cover appeared to have declined between 2013 and 2014 at harbour entrance sites, and has likely remained at similar levels in 2018 to what was observed in 2014 (Figure 3-14). The variability in cover (variability within and between sites) at Rundle Island increased dramatically in the 2018 survey, and this was a reflection of site-level changes that occurred there. Figure 3-14 shows that site RUN1 likely increased in coral cover while site RUN3 likely decreased in coral cover between 2013 and 2018. This divergence in coral cover resulted in increased transect level variability (error) in Figure 3-14. Site RUN3 had recently experienced a large dieback event, and there was active evidence of coral disease (white and brown band disease) at RUN1 and RUN3 (section 3.2.4). Coral cover appeared to remain steady at FAC3 and RUN2 and may have increased at SCR. Recent dieback may have been the result of coral disease and/or thermal bleaching.

Changes in algal cover should be considered cautiously, given the uncertainty regarding the treatment of turfing algae in 2013. However, given the likely reductions in hard coral cover observed outer Facing Island and harbour entrance sites, a commensurate increase in algal cover would be expected, and is consistent with the patterns observed in Figure 3-15. The inclusion of turfing and macroalgae was consistent methodologically between 2014 and 2018, and a slight reduction in algal cover post 2014 would be consistent with some recovery in years after the 2013 floods at harbour entrance sites. Similarly, an increase in macroalgae at Rundle Island would be possible after a significant dieback event. A relatively large increase in algal cover occurred at site RUN3, where numerous incidences of coral disease were encountered.

Looking at site-based data, it is probable that sites PL, FAC4, and FAC3 had increased algal cover between 2013 and 2018, and NPR to a lesser degree. Algal cover was probably similar between 2013 and 2018 at sites RUN1 and RUN2. The site SCR probably had less algae in 2018 than 2013.

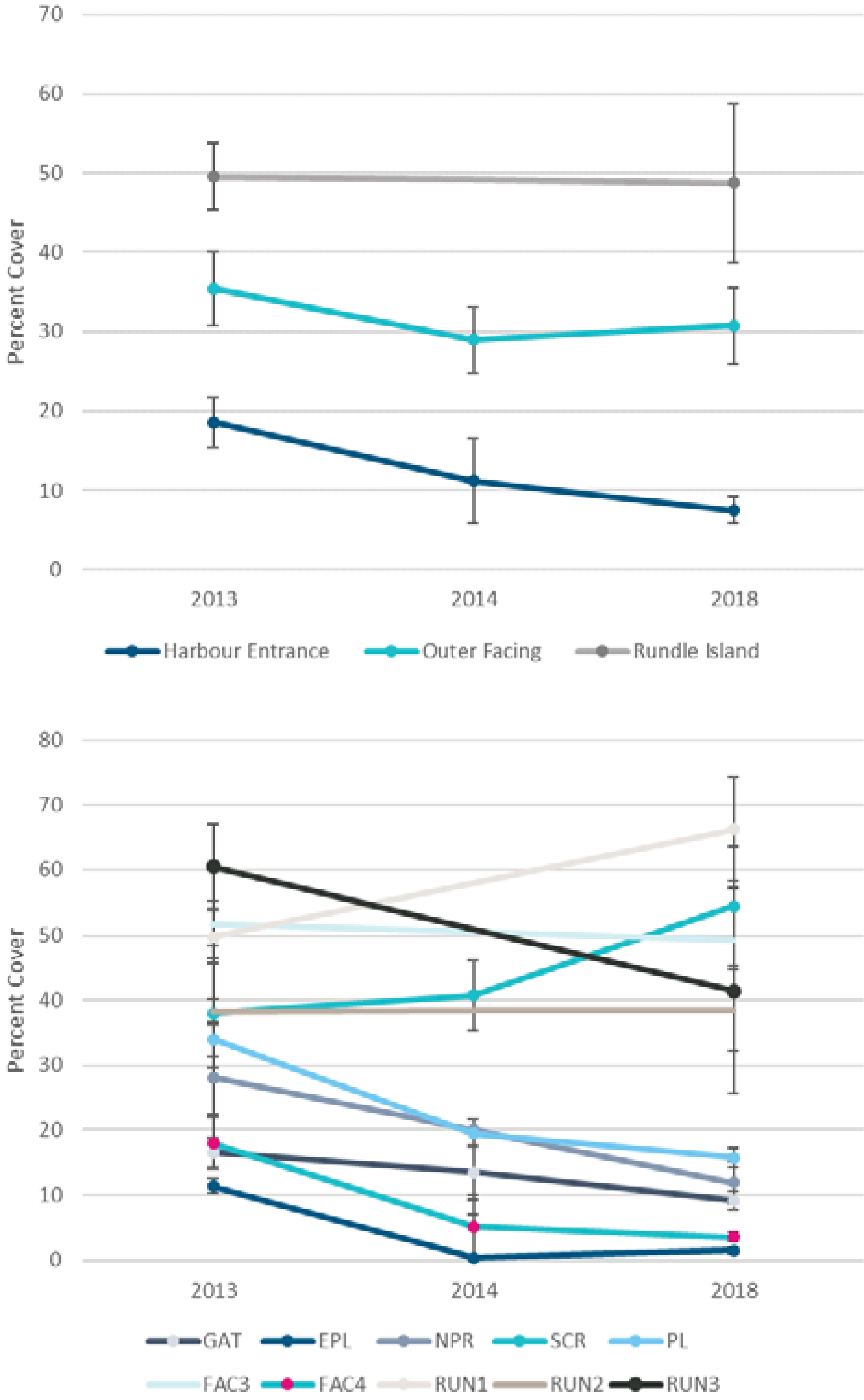
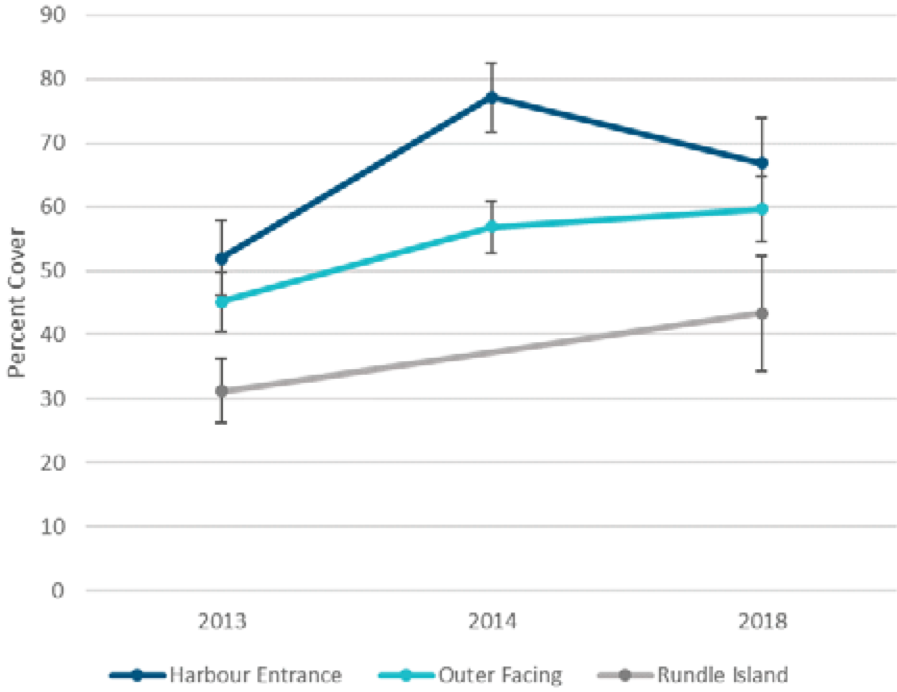


Figure 3-14 Temporal changes in hard coral cover among treatments (above) and sites (below)



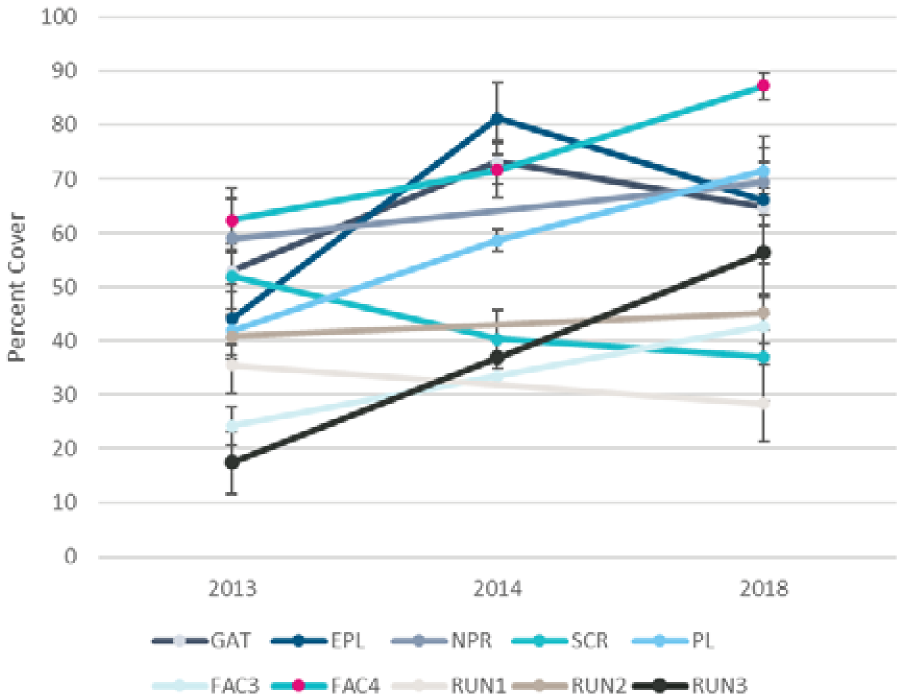


Figure 3-15 Temporal changes in algal cover among treatments (above) and sites (below)

Changes in soft coral cover among sites and treatments were highly variable among sites, treatments and time periods (Figure 3-16). This was attributed to the very low prevalence of this taxon. Differences are unlikely to be significant or meaningful between any of the monitoring periods given the present form of the data.

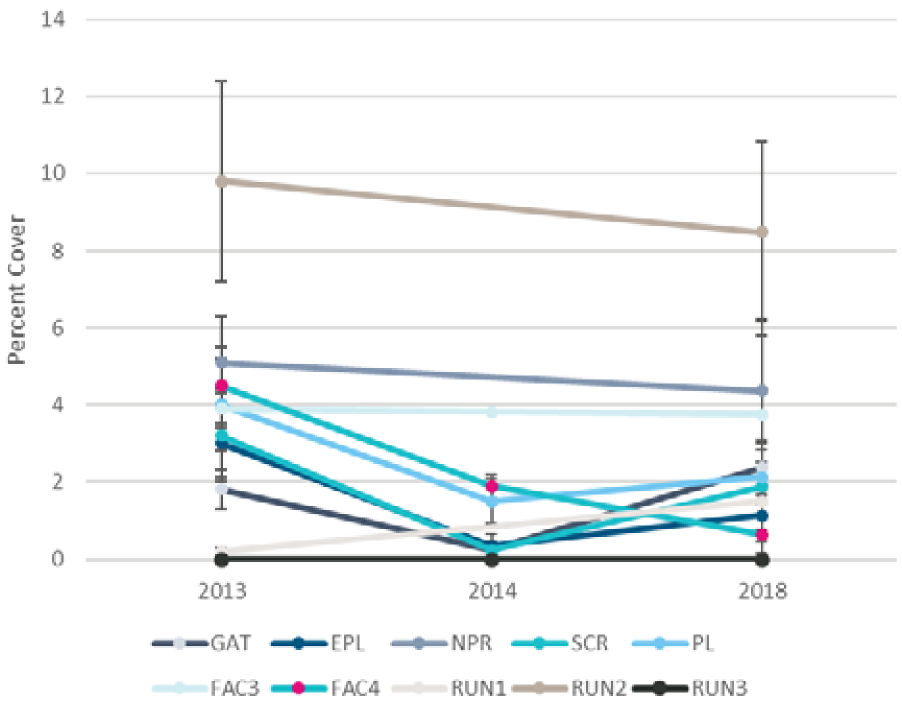


Figure 3-16 Temporal changes in soft coral cover among sites

3.2.4 2018 Coral Disease

Incidence of white and brown band diseases and coral bleaching are shown in Figure 3-17. White and brown band diseases were recorded collectively and show that incidences of coral disease were highest at Rundle Island, particularly at site RUN3, and to a lesser degree at RUN1.

Coral bleaching was observed at more sites than coral disease and again it was observed most frequently at Rundle Island. It was observed at all sites except NPR and GAT (Figure 3-17). Bleaching tended to be on individual colonies or partial colony bleaching, rather than widespread areas of bleaching as is often the case with major thermal bleaching events. In 2017, no severe bleaching was observed on the southern GBR (Swains or Capricorn-Bunker group), with the southernmost severe bleaching restricted to the Mackay Region (GBRMPA unpublished monitoring data).

In many cases, thin algal coatings were on adjacent tissues suggesting that colonies had recently experienced mortality. It is possible that some bleaching counts were actually coral disease, as partial colony bleaching and coral disease can be difficult to distinguish. Sample imagery of this recently deceased coral and white band diseases are shown in Figure 3-18

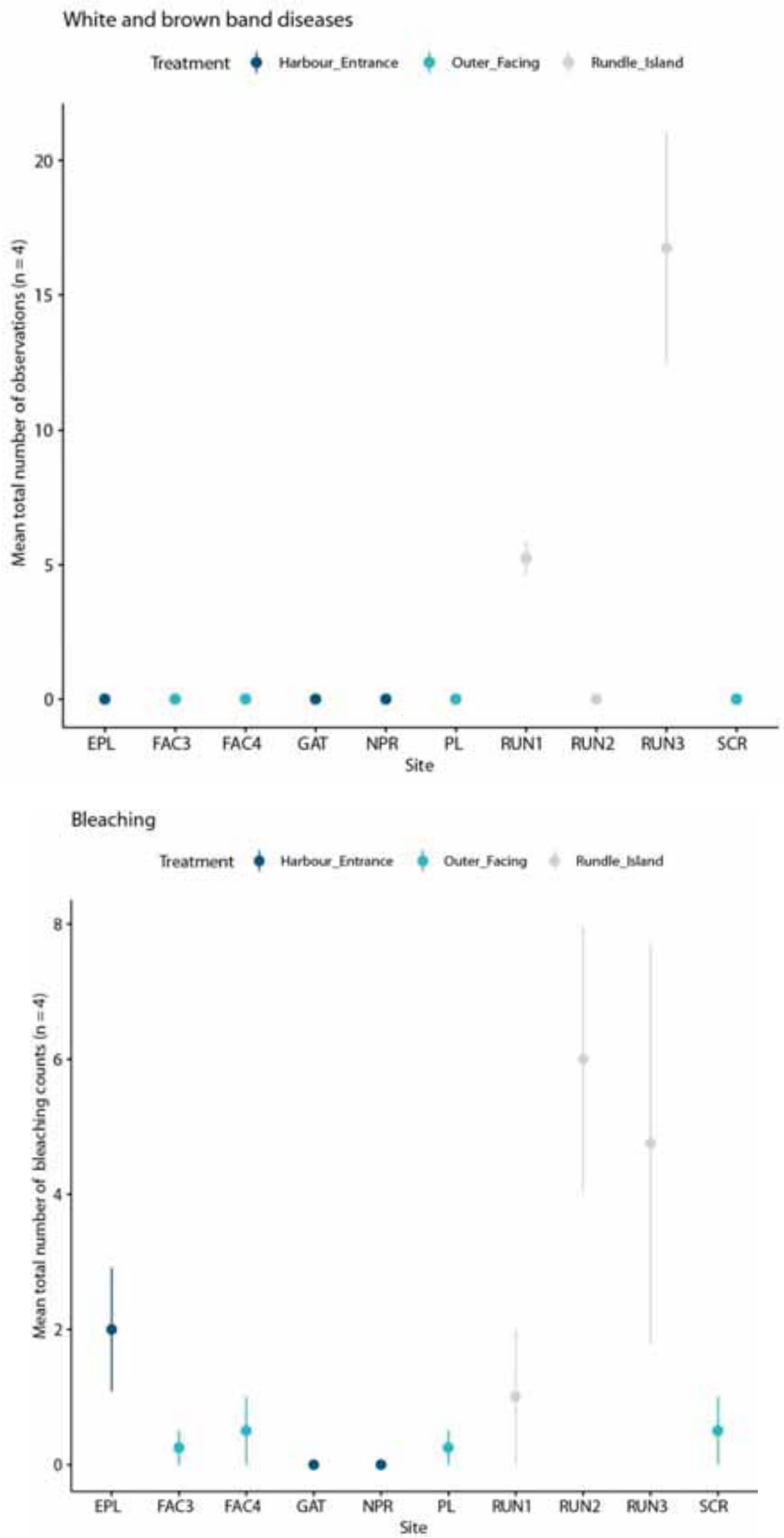


Figure 3-17 Mean (+/- SE) observations of white and brown banding disease (above) and bleaching

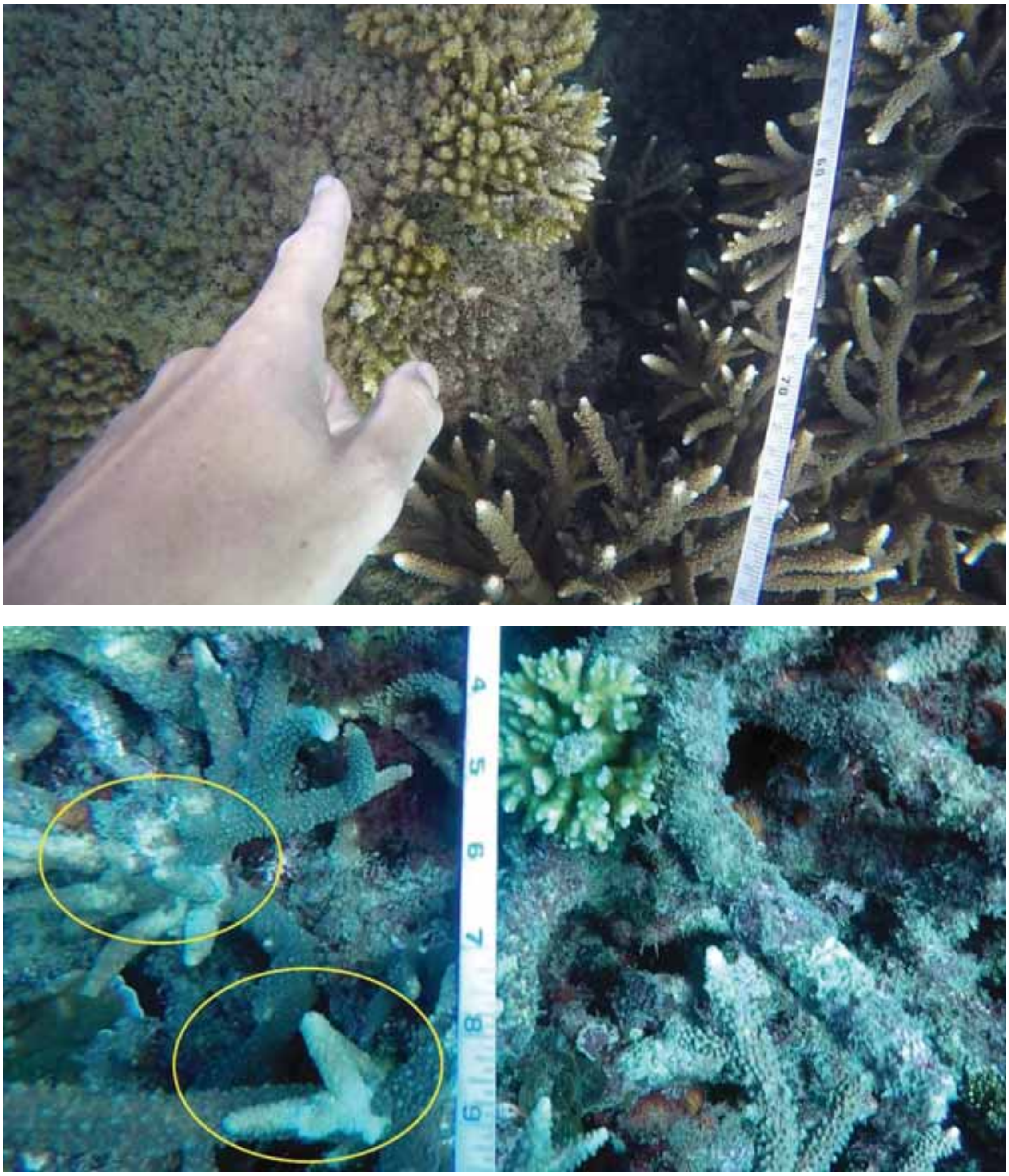


Figure 3-18 Sample imagery of recently dead tissue at Sable Chief Rocks (above) and suspected white band disease at Rundle Island (below)

3.2.5 Coral Recruit Densities 2018

Figure 3-19 shows that the total number of coral recruits was heavily dominated by *Turbinaria*. Recruiting corals were observed at all sites, with the highest levels of recruitment observed at outer Facing Island sites, particularly FAC3 and SCR. Recruit numbers were highly variable at sites where large numbers of recruits were observed, as indicated by large error bars for each site (Figure 3-19).

Rundle Island and harbour entrance sites had similar levels of recruitment, with the lowest numbers of recruits observed at EPL. It should be noted that recruitment counts may be lower than recorded at some harbour entrance sites where *Sargassum* canopies were extensive. At these locations, particularly EPL and GAT, macroalgae often became entangled in the camera array and frequently obstructed the view of the camera and the diver, and counts were made with these limitations.

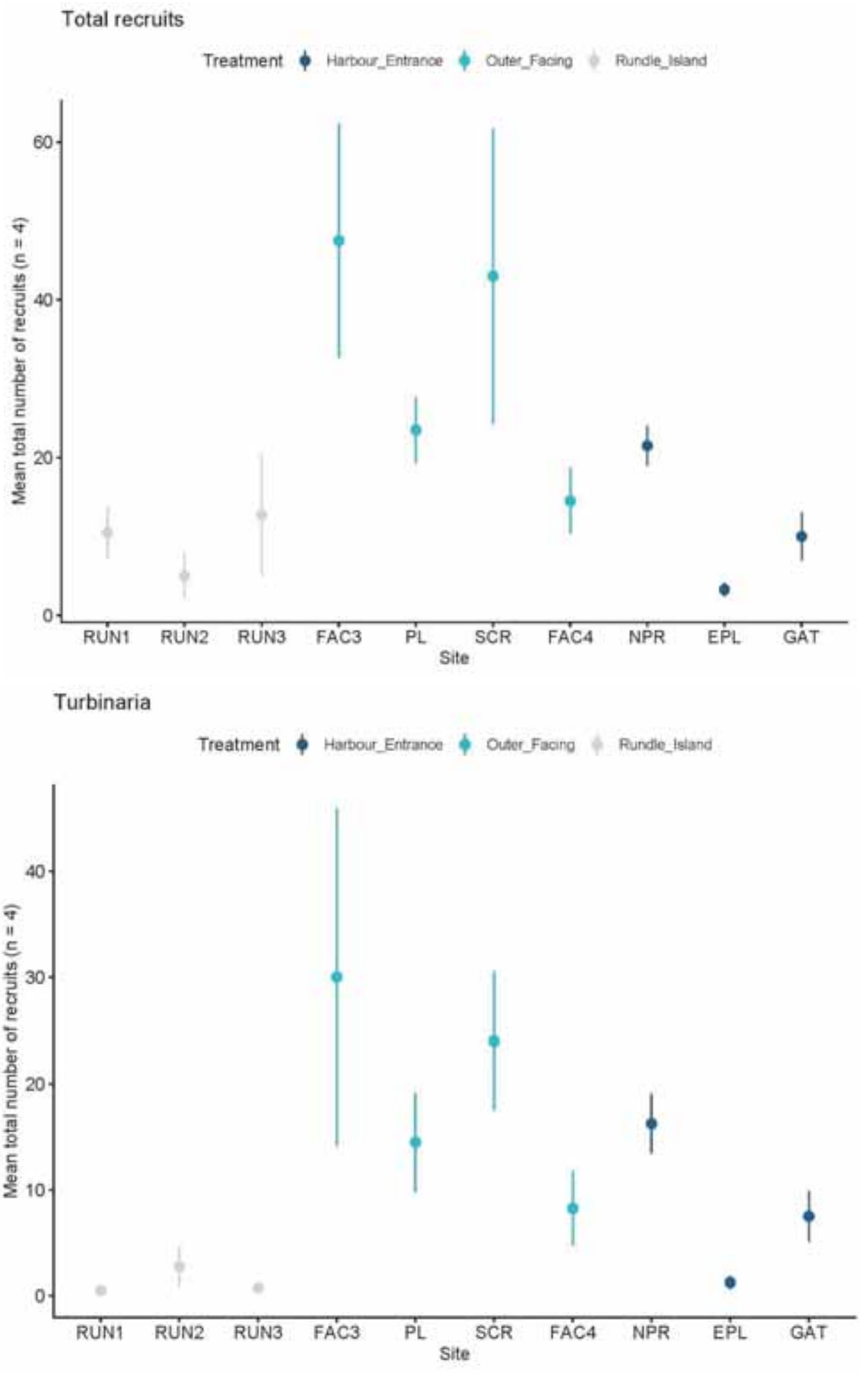


Figure 3-19 Mean (+/- SE) number of total recruits (above) and *Turbinaria* recruits (below)

3.3 3D Models

Four 3D models were produced at a subset of monitoring sites. One model was produced for NPR and SCR, and two models were produced at FAC3. These are shown in Figure 3-20 to Figure 3-23. The bottom image in each figure shows the orthomosaic of the compiled imagery. Colour in all cases appears more red in the shallower parts of the model due to loss of the red spectrum of light at greater depths.

The model at NPR shows reef elevated above the sea floor as a series ridges running north to south and entering the sea floor obliquely (Figure 3-20). A range of faviid and soft corals can be seen atop these ridges. The inter-reefal substrate consists of rubble and sand with bedforms and macroalgae. The macroalgae can be seen sitting mostly on the inter-reefal substrate directly adjacent to the reef ridges.

The first model generated at FAC3 shows a large bombora rising approximately 4 m up from the seafloor (Figure 3-21). Numerous plating acroporid corals and soft corals can be seen on and around the outcrop, including a large bleached coral. Some holes in the image are present along steep surfaces of the model.

The second model generated at FAC3 shows an undulating coral surface including four smaller coral bomboras rising approximately 1 m up from the seafloor (Figure 3-22). Numerous plating acroporid corals and soft corals can be seen throughout the model as it gently slopes away. While the generated surface is intact and free of holes, some of the model is missing from the deepest and shallowest sections of the capture area.

The model generated for SCR shows two large coral outcroppings in the corner of a field of staghorn (A*cropora*) coral (Figure 3-23). The site contains numerous plating acroporid corals amongst dense stands of branching or staghorn coral (*Acropora*). Part of the capture area could not be built into the 3D model due to extremely homogeneous view fields, where 100% *Acropora* was present in many images. Sufficient overlap between distinguishing features could not be achieved due to a combination of substrate homogeneity and water clarity.

A sample shot of the level of detail in the orthomosaic from the top of the outcrop (Figure 3-21) is shown in Figure 3-24.

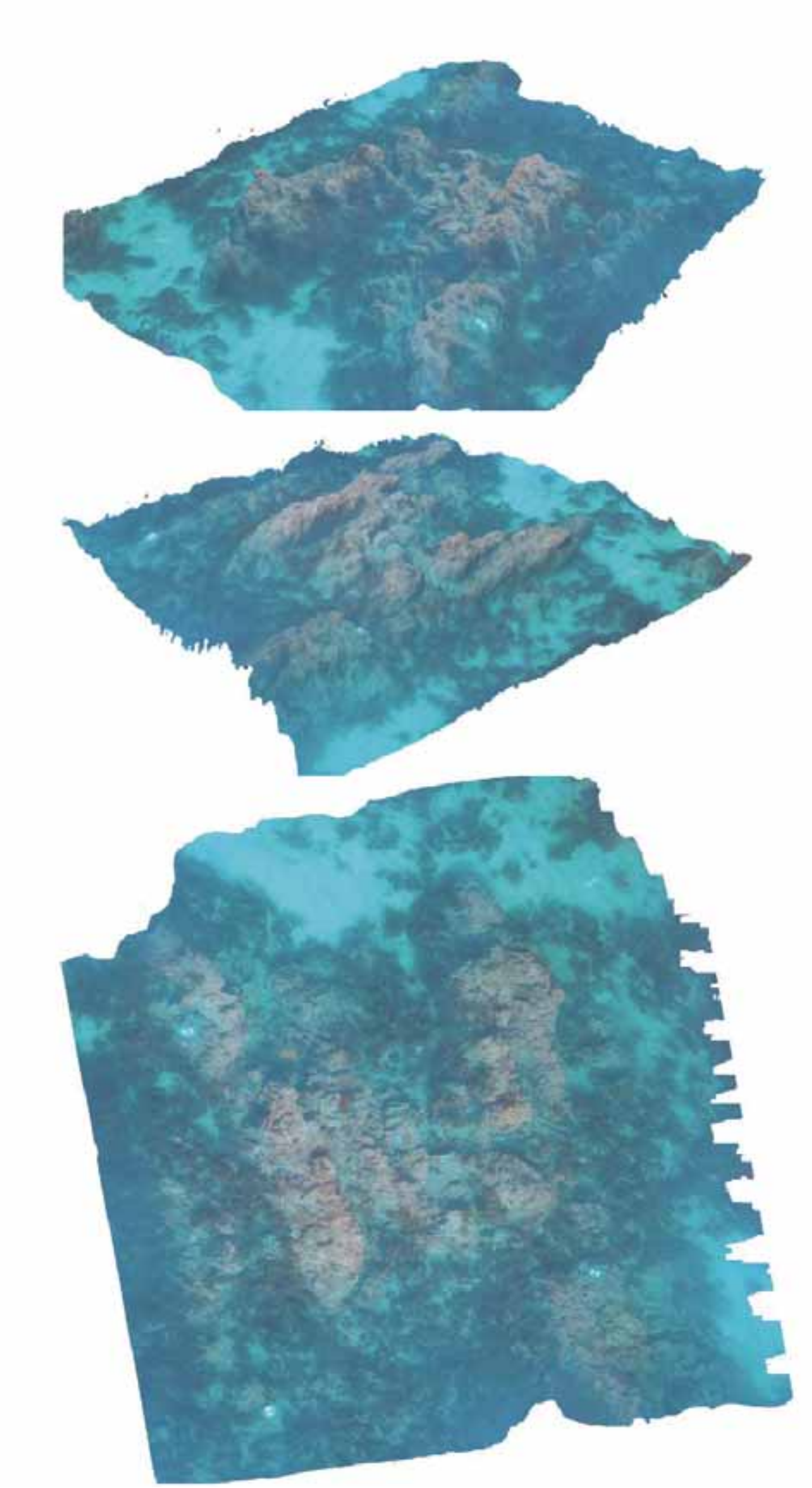


Figure 3-20 Example images of the 3D model from NPR

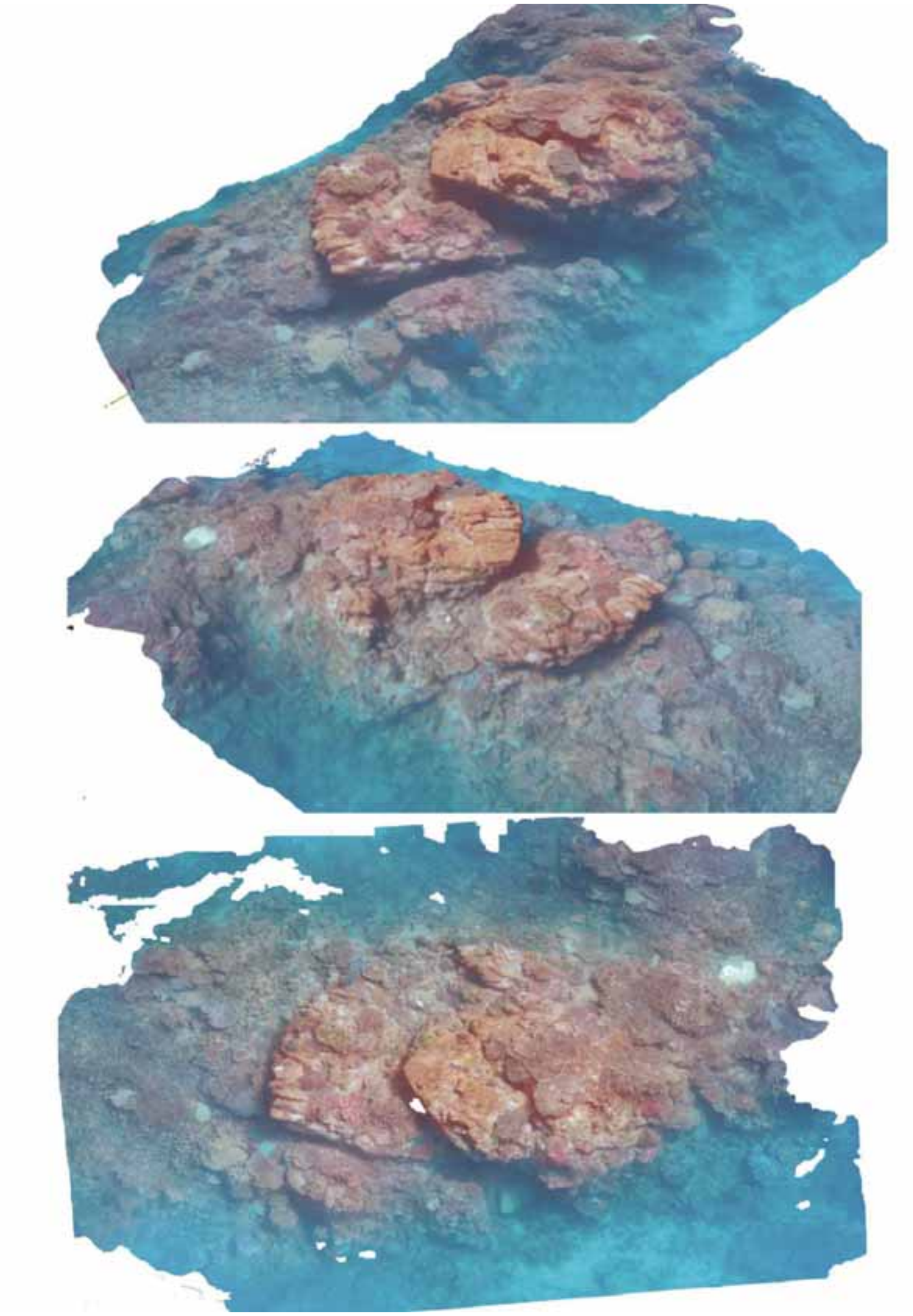


Figure 3-21 Example images of a 3D model from FAC3

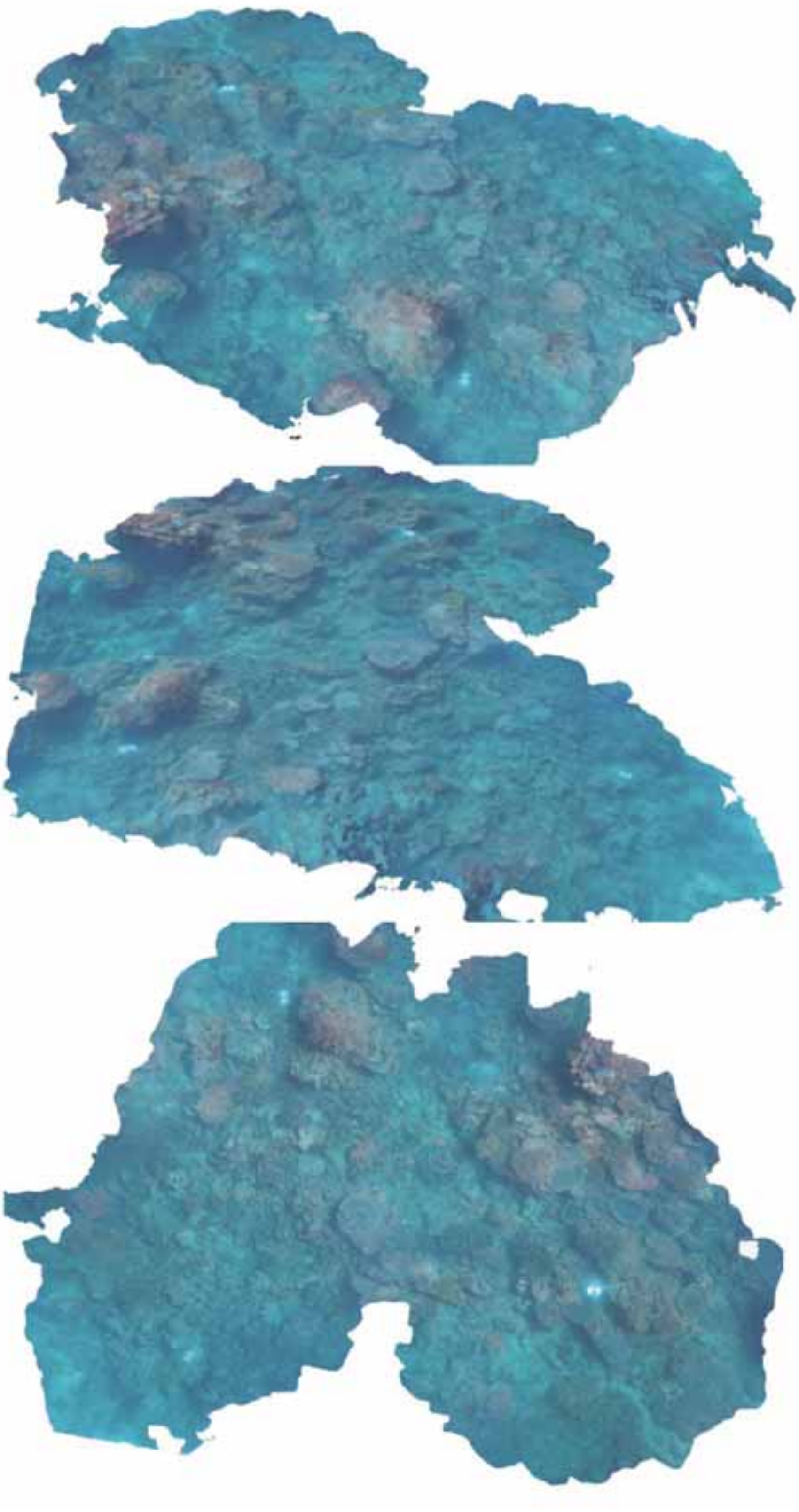


Figure 3-22 Example images of the second model from FAC3

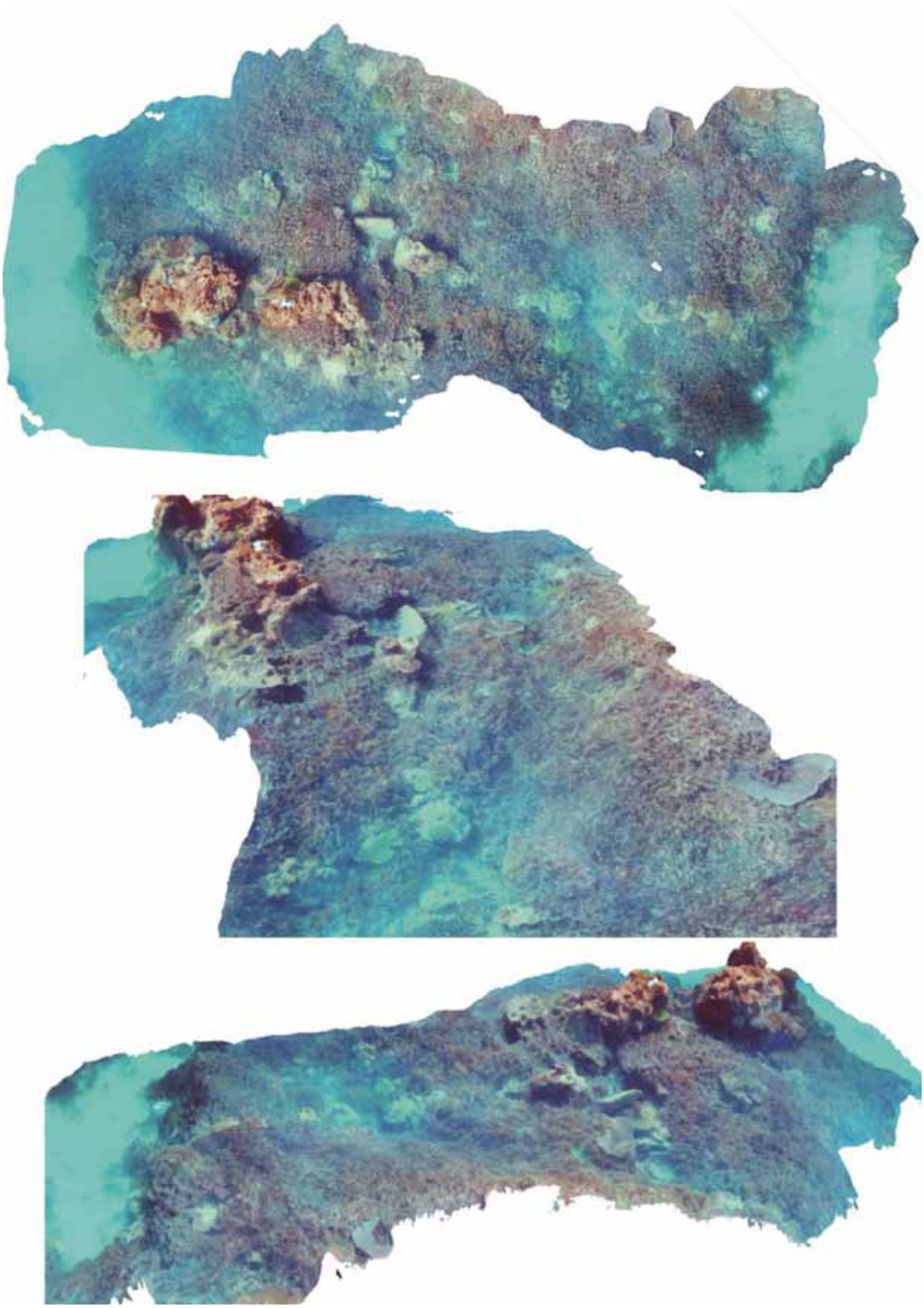


Figure 3-23 Example images of a 3D model from SCR

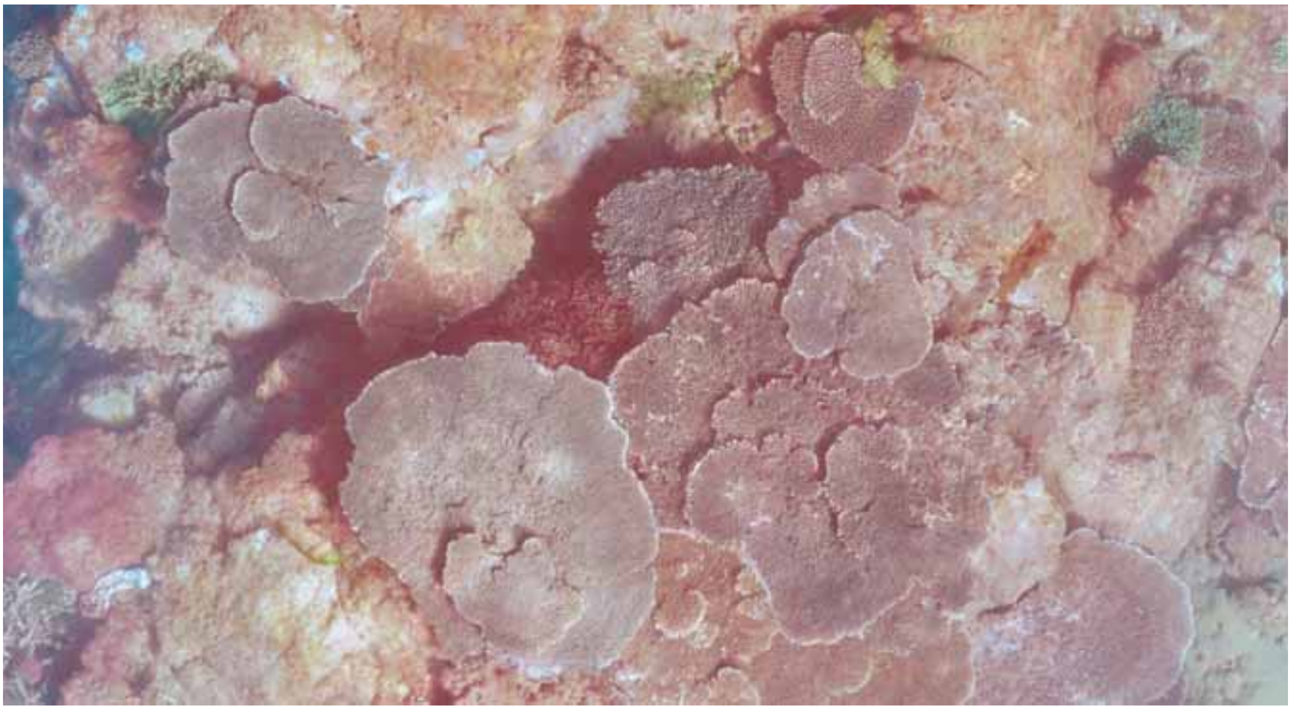


Figure 3-24 Example detail from the orthomosaic generated for top of the bombora shown in in the first FAC3 model (Figure 3-21)

4 Conclusions and Recommendations

4.1 Remote Sensing

The BRI and DII indices when applied to Sentinel-2 scenes, have improved the accuracy of the digitised reef extent performed by BMT WBM (2014). The BRI produced a much better classification of benthic habitats than the DII, which was highly anomalous and not presented. Sagawa *et al.,* (2010) show that their technique is a superior index to the DII in defining seagrass meadows in turbid water conditions (Jerlov water types II and III).

In the present study some anomalous classifications of the BRI required the user to accept or reject classifications, which would hinder the use of this imagery for objective broad-scale monitoring. Training areas were based on known conditions (sand, macroalgal dominated reefs, and coral dominated reefs) in surrounding Facing Island. As such, the classification was most successful east of Facing Island, followed by the Seal Rocks Reef area, and it was least successful at Rundle Island. This is likely due to differences in optical water type, where attenuation of the band signals was based on the water surrounding Facing Island, rather than the typically much clearer water of Rundle Island. Some of the worst classification errors at Rundle Island occurred in the deeper waters east of the island, which were not mapped as coral. Ideally, both indices would be repeated at Rundle Island using ground truthing and attenuation relationships from water in the vicinity. This was not part of the present scope.

While Sentinel-2 represents highly cost-effective imagery at reasonable resolution and high re-visit times, the biggest hurdles to using it for monitoring are the turbidity of the ambient environment, and its resolution. Finer-scale resolution data (1-2 m) would offer more reliable classifications with object-based classification techniques (Roelfsema *et al.,* 2018). However, higher resolution imagery would still be obstructed by ambient turbidity. This can be overcome by using a physics-based water column correction (Ohlendorf *et al.,* 2011), which can be performed at greater cost. This would allow quantitative spatial comparisons in cover types to be made through time. While these methods are costlier to perform than the methods used in this study, the need for more regular monitoring of broad-scale cover data may warrant the additional cost.

While such techniques can show the change in cover types through time over broad areas, such monitoring cannot provide the same level of detail regarding coral health or community change seen in site-based monitoring (divers or remote cameras).

4.2 Coral Monitoring

Coral community data and cover metrics suggest that some of the sites in the monitoring program are fundamentally different based on their living coral cover, health, and composition. The sites differ in their exposure to anthropogenic and catchment disturbance, and the revised design attempts to partition these processes as much as practical. However, some sites will experience inseparable natural and anthropogenic disturbance. Harbour entrance sites GAT and EPL are exposed to plumes generated from maintenance dredging placement on the EBSDS and chronic and acute catchment impacts. Catchment impacts likely exist as a gradient from both harbour entrances to the centre of Facing Island. The site FAC4 could probably sit within either treatment group (outer Facing Island or harbour entrance). The sites SCR, PL, and FAC3 have sufficient community similarity to sites RUN1-3 for meaningful future comparisons.

The SCR and PL sites are very important in the interpretation of potential impacts as they (SCR in particular) experience the most influence from dredged material placement plumes emanating from the EBSDS and are highly protected from catchment impacts.

Cover metrics in 2018 showed that SCR had the second highest living coral cover. While a lack of raw transect data prevented quantitative comparisons between 2013 and 2018, some trends appeared relatively robust and are worthy of mention. Hard coral cover (the primary metric of health) likely increased at SCR, while it may have decreased at PL. Cover appeared relatively unchanged at FAC3. These changes are not consistent with widespread impacts generated by dredge plumes impacting coral communities. If this were the case, reductions in cover would be expected at SCR and FAC3. Communities at Rundle Island, particularly RUN3 were experiencing extensive coral disease and appeared to have recently experienced substantial dieback.

Harbour entrance sites experienced a substantial reduction in living coral cover between 2013 and 2014 (BMT WBM 2014), and do not appear to have recovered between 2014 and 2018. Some coral disease was also present in 2018 at SCR on plate corals, and variable changes in coral cover through time at outer Facing Island sites may be the result of variable recruitment and coral mortality since the last monitoring period. Outer Facing Island sites typically had the highest levels of recruitment.

A large degree of uncertainty exists regarding temporal changes in community mainly to do with low levels of replication and a lack of raw data. Future monitoring should consider the use of photo-quadrat data as the unit of replication, rather than transects to greatly improve the potential to detect changes. Sampling random quadrats from a pool of continuously collected photographs will allow replicate units to be assessed without creating issues of non-independence, provided photos are collected at sufficient intervals to prevent overlap.

4.3 3D Modelling

3D models provide a stakeholder engagement tool to provide a better perspective on the type of communities that exist in each location, particularly for non-specialists, or an audience that is unfamiliar being in the water or reef environments. They are also useful to managers and scientists as visual aids to other numerical data.

As a monitoring tool, they provide the potential to visualise small changes in benthic cover over a reasonably large area that may not be encompassed in point-based or line-intercept monitoring approaches. Observing orthomosaics side by side gives the viewer an opportunity to assess cover without the difficulties of measurement in a highly rugose 3D environment. Benthic cover classifications could be performed over the orthomosaics to determine percent cover of particular groups using image analysis software.

The disadvantages of this form of monitoring are that the ability to build these models is underpinned by the heterogeneity of the substrate. Substrates with a highly repetitive pattern, such as beds of staghorn coral, sands, or seagrasses are difficult to match using pixel matching algorithms. Similarly, moving substrates, such as schools of fish or beds of macroalgae change their orientation through time and create major challenges for photogrammetry. These limitations mean that data collection and model outputs are vulnerable to missing data. The risk of missing data increases with substrate heterogeneity and turbidity, as capture frames become smaller with less overlap, and fewer features for pixel matching algorithms. Other issues include maintaining consistent colour through time with variable turbidity and lighting regimes.

Despite these issues, the models provide visually captivating imagery with the potential to produce high-resolution orthoimagery for subsequent classification and enumeration, in a selection of suitable potential habitats.

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Appendix A ANOSIM Results

Tests for differences between unordered Site groups

Global Test

Sample statistic (R): 0.725

Significance level of sample statistic: 0.1%

Number of permutations: 999 (Random sample from a large number)

Number of permuted statistics greater than or equal to R: 0

Pairwise Tests

Groups	R Statistic	Significance Level (p)	Possible Permutations	Actual Permutations	Number >= Observed
EPL, FAC4	0.417	0.029	35	35	1
EPL, GAT	0.375	0.086	35	35	3
EPL, FAC3	1	0.029	35	35	1
EPL, NPR	0.406	0.029	35	35	1
EPL, PL	0.521	0.029	35	35	1
EPL, RUN1	1	0.029	35	35	1
EPL, RUN2	1	0.029	35	35	1
EPL, RUN3	0.99	0.029	35	35	1
EPL, SCR	1	0.029	35	35	1
FAC4, GAT	0.792	0.029	35	35	1
FAC4, FAC3	0.969	0.029	35	35	1
FAC4, NPR	0.573	0.029	35	35	1
FAC4, PL	0.552	0.029	35	35	1
FAC4, RUN1	1	0.029	35	35	1
FAC4, RUN2	1	0.029	35	35	1
FAC4, RUN3	0.948	0.029	35	35	1
FAC4, SCR	0.99	0.029	35	35	1
GAT, FAC3	0.958	0.029	35	35	1
GAT, NPR	0.302	0.114	35	35	4
GAT, PL	0.542	0.029	35	35	1
GAT, RUN1	1	0.029	35	35	1
GAT, RUN2	0.885	0.029	35	35	1
GAT, RUN3	0.906	0.029	35	35	1

Groups	R Statistic	Significance Level (p)	Possible Permutations	Actual Permutations	Number >= Observed
GAT, SCR	0.948	0.029	35	35	1
FAC3, NPR	0.792	0.029	35	35	1
FAC3, PL	0.667	0.029	35	35	1
FAC3, RUN1	0.729	0.029	35	35	1
FAC3, RUN2	0.646	0.029	35	35	1
FAC3, RUN3	0.615	0.029	35	35	1
FAC3, SCR	0.5	0.029	35	35	1
NPR, PL	0.073	0.314	35	35	11
NPR, RUN1	0.99	0.029	35	35	1
NPR, RUN2	0.896	0.029	35	35	1
NPR, RUN3	0.917	0.029	35	35	1
NPR, SCR	0.917	0.029	35	35	1
PL, RUN1	1	0.029	35	35	1
PL, RUN2	0.885	0.029	35	35	1
PL, RUN3	0.948	0.029	35	35	1
PL, SCR	0.865	0.029	35	35	1
RUN1, RUN2	0.531	0.057	35	35	2
RUN1, RUN3	0.521	0.029	35	35	1
RUN1, SCR	0.26	0.086	35	35	3
RUN2, RUN3	0.875	0.029	35	35	1
RUN2, SCR	0.5	0.057	35	35	2
RUN3, SCR	0.5	0.029	35	35	1

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Brisbane
Level 8, 200 Creek Street
Brisbane Queensland 4000
PO Box 203 Spring Hill QLD 4004
Tel +61 7 3831 6744
Fax +61 7 3832 3627
Email brisbane@bmtglobal.com

Melbourne
Level 5, 99 King Street
Melbourne Victoria 3000
Tel +61 3 8620 6100
Fax +61 3 8620 6105
Email melbourne@bmtglobal.com

Newcastle
126 Belford Street
Broadmeadow New South Wales 2292
PO Box 266 Broadmeadow
New South Wales 2292
Tel +61 2 4940 8882
Fax +61 2 4940 8887
Email newcastle@bmtglobal.com

Adelaide
5 Hackney Road
Hackney Adelaide South Australia 5069
Tel +61 8 8614 3400
Email info@bmtdt.com.au

Northern Rivers
Suite 5
20 Byron Street
Bangalow New South Wales 2479
Tel +61 2 6687 0466
Fax +61 2 6687 0422
Email northernrivers@bmtglobal.com

Sydney
Suite G2, 13-15 Smail Street
Ultimo Sydney New South Wales 2007
Tel +61 2 8960 7755
Fax +61 2 8960 7745
Email sydney@bmtglobal.com

Perth
Level 4
20 Parkland Road
Osborne Park WA 6017
PO Box 2305 Churchlands WA 6918
Tel +61 8 6163 4900
Email perth@bmtglobal.com

London
1st Floor, International House
St Katharine's Way
London
E1W 1UN
Tel +44 (0) 20 8090 1566
Email london@bmtglobal.com

Aberdeen
Broadfold House
Broadfold Road, Bridge of Don
Aberdeen
AB23 8EE
UK
Tel: +44 (0) 1224 414 200
Fax: +44 (0) 1224 414 250
Email enquiries@bmtcordah.com

Asia Pacific
Indonesia Office
Perkantoran Hijau Arkadia
Tower C, P Floor
Jl: T.B. Simatupang Kav.88
Jakarta, 12520
Indonesia
Tel: +62 21 782 7639
Fax: +62 21 782 7636
Email asiapacific@bmtglobal.com

Alexandria
4401 Ford Avenue, Suite 1000
Alexandria
VA 22302
USA
Tel: +1 703 920 7070
Fax: +1 703 920 7177
Email inquiries@dandp.com