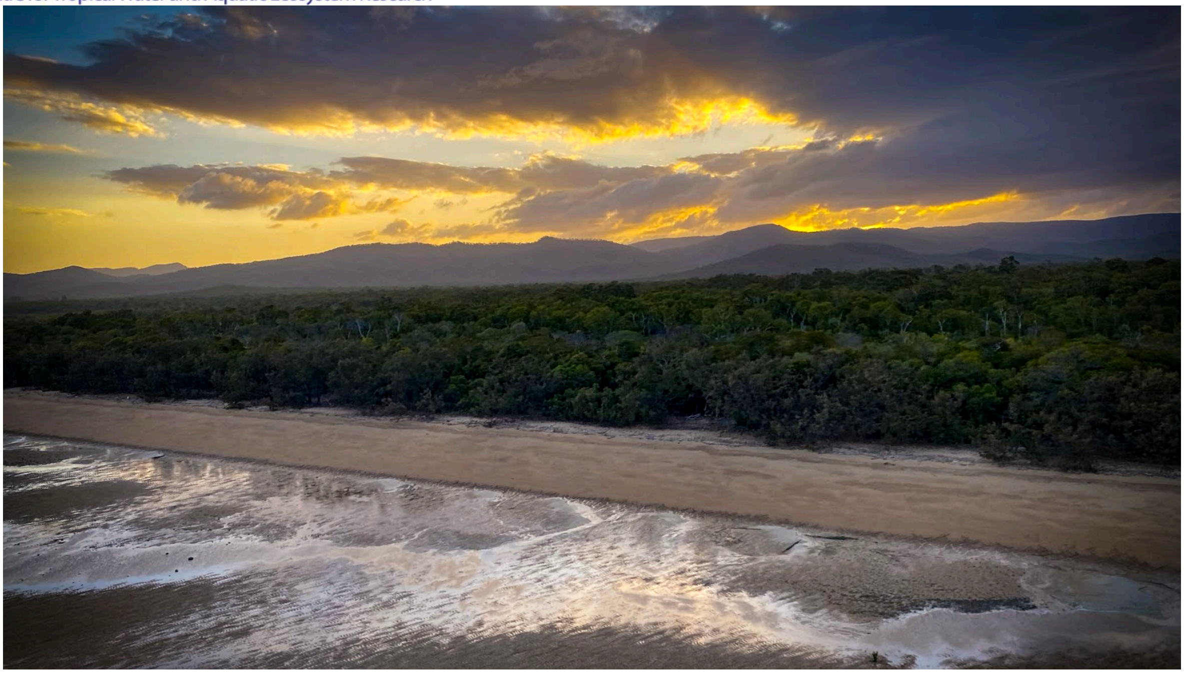

Mackay-Whitsunday-Isaac Seagrass Monitoring

2017-2020:

Marine Inshore South Zone

van de Wetering C, Carter AB, Rasheed MA

Report No. 21/06

Mackay-Whitsunday-Isaac Seagrass Monitoring 2017- 2020:

Marine Inshore South Zone

Report No. 21/06

May 2021

Chris van de Wetering, Alex Carter and Michael Rasheed

Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER)
James Cook University
PO Box 6811
Cairns Qld 4870
Phone : (07) 4781 4262
Email: seagrass@jcu.edu.au
Web: www.jcu.edu.au/tropwater/

Information should be cited as:
Van de Wetering C, Carter AB, and Rasheed MA (2021) 'Mackay-Whitsunday-Isaac Seagrass Monitoring 2017-2020: Marine Inshore South Zone', Centre for Tropical Water & Aquatic Ecosystem Research Publication 21/06. James Cook University, Cairns, 30 pp.

For further information contact:
Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER)
James Cook University
seagrass@jcu.edu.au
PO Box 6811
Cairns QLD 4870

This publication has been compiled by the Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook University.

Acknowledgments:
This project was funded by the Mackay-Whitsunday-Isaac Healthy Rivers to Reef Partnership. We thank Gabrielle Breen from Dalrymple Bay Coal Terminal (pictured) for assistance with field work.

KEY FINDINGS

1. This is the fourth consecutive year of annual seagrass monitoring for the southern marine zone in Mackay-Whitsunday-Isaac Healthy Rivers to Reef Partnership (HR2RP).

2. There were favourable conditions for seagrass growth leading up to the 2020 survey, with no noteworthy natural or anthropogenic impacts in the region since the previous survey.

3. The two large seagrass meadows along the mainland coast were in a similar condition to 2019 when they had shown a general improvement in meadow area and biomass from the initial seagrass monitoring conducted in 2017 following Cyclone Debbie.

4. The smaller offshore meadow adjacent to Flock Pidgeon Island had a substantial decline in area from previous surveys. At this stage it is unclear if this is part of a normal range of change for this meadow.

5. Despite the relatively low above-ground biomass and extremely thin leaf morphology of seagrasses throughout the region, there has been a continued presence of dugong feeding trails recorded across the initial 4 years of the monitoring program.

6. These surveys are providing the baseline conditions to establish scores for future reporting in the HR2RP report card which will be available from 2021 after 5 years of baseline data has been collected.

TABLE OF CONTENTS

Key Findings ..... **i**

1 INTRODUCTION **1**

2 METHODS **4**

2.1 Survey Approach 4
2.2 Field Surveys 4
2.3 Biomass and Species Composition 4
2.4 Seagrass Meadow Mapping and Geographic Information System (GIS) 5
2.5 Seagrass Meadow Condition Index 6

3 RESULTS **8**

4 DISCUSSION **15**

5 REFERENCES **17**

6 APPENDICES **22**

Appendix 1. Seagrass Condition Calculations 22
A1.1 Baseline Calculations **22**
A1.2 Meadow Classification **22**
A1.3 Threshold Definition **22**
A1.4 Grade and Score Calculations **23**
A1.5 Score Aggregation **25**
Appendix 2. Biomass score calculation example 26

1 INTRODUCTION

Seagrass habitats are immensely productive and provide a range of ecosystem services with substantial economic value (Costanza et al. 2014, Scott et al. 2018). These services include coastal protection, support of fisheries production, nutrient cycling, particle trapping, removal of bacterial pathogens, and acting as a carbon sink (Hemminga and Duarte 2000, Fourqurean et al. 2012, Lamb et al. 2017). Seagrasses provide food for herbivores like dugongs (*Dugong dugon*) and green turtles (*Chelonia mydas*) (Heck et al. 2008, Unsworth and Cullen 2010, Scott et al. 2018, Scott et al. 2020).

Natural and anthropogenic factors have contributed to global declines in seagrass (Waycott et al. 2009). Natural disturbances include tropical cyclones, floods, disease, and overgrazing by herbivores (Robblee et al. 1991, Fourqurean et al. 2010, McKenna et al. 2015). Anthropogenic activities that threaten seagrass habitat in the tropical Indo-Pacific region include industrial and urban run-off, port and coastal development, and dredging (Grech et al. 2012, York et al. 2015a).

The sensitivity of seagrass to disturbance and environmental change make it an excellent indicator of marine environmental health (Dennison et al. 1993, Abal and Dennison 1996, Orth et al. 2006). Seagrass condition assessments require adequate baseline information on seagrass presence/absence, biomass, species composition, and meadow area, plus ongoing monitoring to understand and detect change. Long-term monitoring and condition reporting on Queensland's seagrass is largely undertaken by the Queensland Ports Seagrass Monitoring Program (QPSMP) that occurs in the majority of commercial ports (www.jcu.edu.au/portseagrassqld), and the Marine Monitoring Program (MMP) that focusses on the inshore Great Barrier Reef (GBR) (http://www.gbrmpa.gov.au/managing-the-reef/how-the-reefs-managed/reef-2050-marine-monitoring-program) and reports seagrass condition as part of the Reef Water Quality Protection Plan (https://www.reefplan.qld.gov.au/measuring-success/report-cards/).

The QPSMP and MMP contribute their seagrass condition assessments to a variety of regional report cards. These include the Mackay-Whitsunday-Isaac Healthy Rivers to Reef Partnership (HR2RP; http://healthyriverstoreef.org.au/), the Wet Tropics Healthy Waterways Partnership (WTHWP; http://wettropicswaterways.org.au/report-card/), the Dry Tropics Partnership for Healthy Waters (DTPHW; https://drytropicshealthywaters.org/report-cards-1), and the Gladstone Healthy Harbour Partnership (GHHP; http://ghhp.org.au/report-cards/2020) Regional report cards at the Natural Resource Management (NRM) scale are divided into zones defined largely by habitat and latitude (Figure 1a). Attempts to report zone-scale seagrass condition revealed a number of gaps with no long-term monitoring data available to inform report card scores. For the HR2RP report card, the southern inshore marine zone was identified as a major data and knowledge gap for seagrass condition (http://healthyriverstoreef.org.au/report-card-results/).

TropWATER were contracted in 2017 by the HR2RP to address the knowledge gaps in environmental condition, including seagrass, for the southern inshore marine zone. The longer-term (5 years) objective is to provide report card scores for seagrass in this zone that will be incorporated into the regional report card. TropWATER have conducted seagrass surveys previously in this zone: (1) in 1987, as part of large-scale seagrass assessments along the Queensland coast (Coles et al. 1987); (2) in 1997, during GBR-wide deep water surveys (Coles et al. 2009); (3) in 1999, during assessments for Dugong Protection Areas (Coles et al. 2002); and (4) in 2003-2004, during GBR-wide seabed biodiversity surveys led by CSIRO (Pitcher et al. 2007). These surveys revealed substantial intertidal seagrass meadows along the coast, but sparse and patchy subtidal seagrass. The largest intertidal meadows were located in the Clairview Dugong Protection Area (DPA) between Carmila and Clairview Bluff (Figure 1b). These meadows were mapped in 1987 (Coles et al. 1987), and revisited in 1999 (Roder et al. 2002), and were the focus for TropWATER's seagrass baseline survey in 2017.

The 2017 survey was an important first step in addressing seagrass knowledge gaps in the southern inshore zone of the HR2RP report card (Carter and Rasheed 2018). The 2017 and 1999 surveys revealed similar seagrass distribution, biomass, and species composition to the original 1987 survey, indicating these seagrass areas are likely to be relatively permanent features and ideal for monitoring. Three meadows were selected for long-term monitoring: two large intertidal meadows between Clairview and Clairview Bluff (Meadows 6 and 7), and the intertidal meadow at Flock Pigeon Island (Meadow 2).

This report presents findings from the 2020 seagrass monitoring survey of the HR2RP southern inshore marine zone. Our objectives were to:

- Map seagrass distribution, density and community composition in monitoring meadows;
- Compare results with previous seagrass monitoring results of these meadows;
- Incorporate results into a Geographic Information System (GIS) database for the zone.

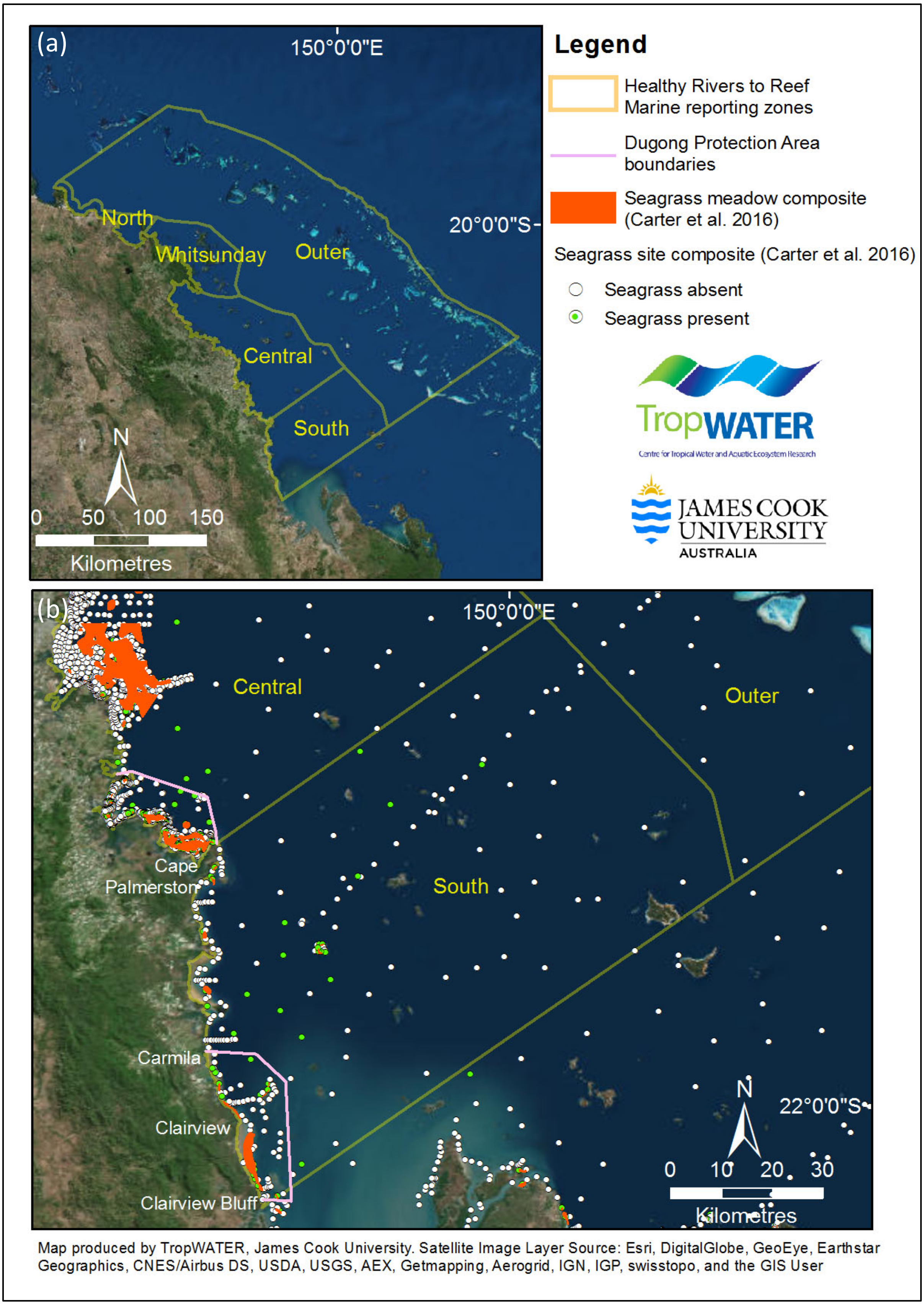

Figure 1. (a) Mackay-Whitsunday-Isaac Healthy Rivers to Reef Partnership reporting zones for inshore marine (North, Whitsunday, Central, South) and offshore marine (outer); and (b) historical seagrass survey data collected 1987 – 2004 in the southern inshore marine zone.

2 METHODS

2.1 Survey Approach

The survey was conducted in October 2020 to coincide with the peak seagrass growing season, when meadows are likely to contain maximum biomass and area. Survey methods and the seagrass metrics recorded followed the established methods for Queensland seagrass monitoring which also occur at Townsville (Mckenna et al. 2021b), Gladstone (Smith et al. 2021b), Cairns (Reason and Smith 2021), Mourilyan (Reason et al. 2021) , Mackay-Hay Point (York and Rasheed 2021), Abbot Point (McKenna et al. 2021a), Thursday Island (Wells et al. 2019), Weipa (Smith et al. 2021a), and Karumba (Scott and Rasheed 2021). Using standardised methods ensures seagrass data is comparable with that used to report seagrass condition for other marine inshore zones in the HR2RP report card, and in the WTHWP, DTPHW, GHHP, and QPSMP report cards. Standardisation also allows for comparisons with historical data sets collected previously in the same area.

2.2 Field Surveys

Intertidal meadows were sampled at low tide using a helicopter. Monitoring meadows are all intertidal because: (1) the large tidal range (up to 8.5m) means that intertidal seagrasses are exposed during spring low tides so helicopter surveys are likely to capture the majority of seagrasses in the region; and (2) subtidal meadows form a relatively minor component of seagrass area and are restricted to very shallow subtidal water, with the same species composition as the much larger adjacent/adjoining intertidal meadows (Carter and Rasheed 2018).

At each site the helicopter came to a low hover (within a metre of the ground). Within a $10m^2$ circular area seagrass biomass was ranked, and the percent contribution of each species to that biomass was estimated, from three 0.25 m^2 randomly placed quadrats. Within the larger $10m^2$ circular area the percent cover of seagrass, algae, and other benthic macro-invertebrates (BMI) were recorded. GPS was used to record the position of each site, and also intertidal meadow boundaries when visible.

2.3 Biomass and Species Composition

Seagrass above-ground biomass was determined using a "visual estimates of biomass" technique (Kirkman 1978, Mellors 1991). For each 0.25 m^2 quadrat an observer assigned a biomass rank, made in reference to a series of 12 quadrat photographs of similar seagrass habitats for which the above-ground biomass had previously been measured. At the completion of ranking, the observer also ranked a series of at least five photographs of calibration quadrats that represented the range of seagrass observed during the survey. These calibration quadrats had previously been harvested and the actual biomass determined in the laboratory. A separate regression of ranks and biomass from the calibration quadrats were generated for each observer and applied to the biomass ranks given in the field. Field biomass ranks were converted into above-ground biomass estimates in grams dry weight per square metre (g DWm^{-2}; total and for each species).

During analysis of the 2020 biomass data an error within some of the previous 2017-2019 biomass calibrations was identified. This has now been corrected and updated for this report and the GIS for previous years layers has been updated with the correct information and additional QAQC steps added to prevent similar errors occurring. The errors impacted some of the biomass and species composition values reported in the past reports.

2.4 Seagrass Meadow Mapping and Geographic Information System (GIS)

All survey data were entered into a Geographic Information System (GIS) developed for the HR2RP southern inshore zone using ArcGIS 10.8. Three GIS layers were created to describe seagrass features in the region: a seagrass site layer, seagrass meadow layer, and seagrass biomass interpolation layer.

Site layer
The site layer contains data collected at each site, including:

- Temporal details – survey date.
- Spatial details – latitude and longitude.
- Habitat information – sediment type; seagrass information including presence/absence, above-ground biomass (total and for each species) and biomass standard error (SE); percent cover of seagrass, algae, and open substrate; presence/absence of dugong feeding trails (DFTs).
- Sampling method and any relevant comments.

Interpolation layer
The interpolation layer describes spatial variation in seagrass biomass across each meadow and was created using an inverse distance weighted (IDW) interpolation of seagrass site data within each meadow using ArcGIS®.

Meadow layer
The meadow (polygon) layer provides summary information for all sites within each of the three monitoring meadows, including:

- Temporal details – survey date.
- Habitat information – mean meadow biomass ± standard error (SE), meadow area (hectares) ± reliability estimate (R), number of sites within each meadow, seagrass species present, meadow density and community type, meadow landscape category (Figure 2).
- Meadow identification number – A unique number assigned to each monitoring meadow to allow comparisons over time.
- Sampling method and any relevant comments.

Meadow boundaries were constructed using seagrass presence/absence site data, field notes, GPS marked meadow boundaries, colour satellite imagery of the survey region (Source: ESRI, HERE, Garmin © Open Street Map contributors, and the GIS user community), and aerial photographs taken during helicopter surveys.

Meadow area was determined using the calculate geometry function in ArcGIS®. Meadows were also assigned a mapping precision estimate (in metres) based on mapping methods used for that meadow. The mapping precision for coastal seagrass meadows ranged from ±20 m for intertidal seagrass meadows with boundaries mapped by helicopter, to ±50 m for boundaries mapped by distance between sites with and without seagrass. The mapping precision estimate was used to calculate a buffer around each meadow representing error; the area of this buffer is expressed as a meadow reliability estimate (R) in hectares.

Meadows were described using a standard nomenclature system. Seagrass community type is defined using the dominant species' percent contribution to mean meadow biomass (for all sites within a meadow) (Table 1). Meadow density is based on mean biomass and the dominant species within the meadow (Table 2).

<u>Isolated seagrass patches</u>
The majority of area within the meadow consists of unvegetated sediment interspersed with isolated patches of seagrass.

<u>Aggregated seagrass patches</u>
The meadow consists of numerous seagrass patches but still features substantial gaps of unvegetated sediment within the boundary.

<u>Continuous seagrass cover</u>
The majority of meadow area consists of continuous seagrass cover with a few gaps of unvegetated sediment.

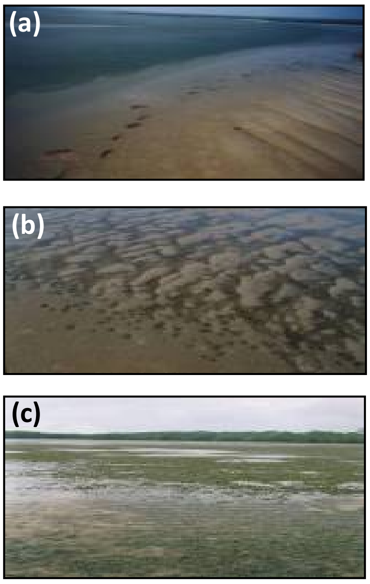

Figure 2. Seagrass meadow landscape categories: (a) Isolated seagrass patches, (b) aggregated seagrass patches, (c) continuous seagrass cover.

Table 1. Seagrass meadow community types.

Community type	Species composition
Species A	Species A is 90-100% of composition
Species A with Species B	Species A is 60-90% of composition
Species A with Species B/Species C	Species A is 50% of composition
Species A/Species B	Species A is 40-60% of composition

Table 2. Seagrass meadow density categories.

	Mean above-ground biomass (g DW m^{-2})	
Density	*H. uninervis* (thin) / *Z. muelleri* subsp. *capricorni* (thin)	*H. ovalis / H. decipiens*
Light	< 1	< 1
Moderate	1 - 4	1 - 5
Dense	> 4	> 5

2.5 Seagrass Meadow Condition Index

A condition index is being developed for seagrass monitoring meadows in the HR2RP southern inshore marine zone based on changes in mean above-ground biomass, meadow area, and species composition relative to a baseline. This is the second year that monitoring meadows in the southern inshore zone have been given preliminary grades for each of the three indicators. Seagrass condition for each indicator in each meadow is scored from 0 to 1 and assigned one of five grades: A (very good), B (good), C (satisfactory), D (poor) and E (very poor). A seagrass condition score for the southern inshore zone will be presented for the HR2RP 2021 report card when 5 years of baseline data will be available for each monitoring meadow. From 2021,overall meadow condition index will be calculated as the lowest indicator score where this is driven by biomass or area. Where species composition is the lowest score, it will contribute 50% of the overall meadow score, and the next lowest indicator (area or biomass) will contribute the remaining 50%. The flow chart in Figure 3 summarises the methods used to calculate seagrass condition. See Appendix 1 and 2 for full details of score and grade calculations.

Figure 3. Process used to determine seagrass monitoring meadow condition grades and scores each year in the HR2RP southern inshore marine zone. Score aggregations will be applied and incorporated into the HR2RP regional waterway health report card when 5 years of monitoring data is available.

3 RESULTS

Four seagrass species were recorded during the 2020 survey: *Zostera muelleri* subsp. *capricorni* (abbreviated to *Z. capricorni* throughout this report), *Halodule uninervis*, *Halophila decipiens* and *Halophila ovalis* (Figure 4). Only thin leaf morphologies of *Z. capricorni* and *H. uninervis* are found in the survey area. These variants of the two species have very similar above ground characteristics and are difficult to differentiate as part of rapid visual surveys.

Extensive seagrass habitat was recorded, with seagrass present at 75% of the 160 intertidal survey sites (Figure 5). The mainland coastal Meadows 6 and 7 were characterised by a continuous cover of seagrass, while Meadow 2 at Flock Pigeon Island had isolated patches of seagrass cover (Figure 6).

Biomass in Meadow 2 was 0.84 ± 0.49 g DWm^{-2} in 2020, the lowest level in four years (Figure 7). There was a substantial reduction in area of this small meadow, from 101 ± 11 ha in 2019 to 37 ± 7 ha in 2020, which likely represents a very poor condition for area based on the preliminary 4 year data set (Figure 7). Meadow 2 is dominated by *Z. capricorni*, however, the proportion of *H. uninervis* has been increasing gradually since 2017 resulting in a satisfactory score in our preliminary species composition condition grade (Figure 7).

Meadow 6 is the largest monitoring meadow in the southern inshore zone. Since the program began in 2017 the biomass has been relatively low and variable from year to year, with the second highest recording to date in the 2020 survey (2.06 ± 0.18 g DWm^{-2}), a good condition score based on interim 4 year analysis. Meadow area has been fairly stable over the last three years, ranging from 1369 ± 47 ha in 2020 to 1421 ± 45 ha in 2019 (Figure 8). This meadow is dominated by *H. uninervis*, with an increasing presence of *Z. capricorni* since surveys began (Figure 9).

Meadow 7 had the greatest biomass (3.5 ± 0.6 g DWm^{-2}), area (239 ± 23 ha) and highest proportion of more stable species recorded since monitoring began in 2017, with all condition indicators rated very good (Figure 9). The mean species composition of Meadow 7 is 90% *Z. capricorni*, with less stable species *H. uninervis* and *H. decipiens* making up the remainder of seagrass biomass.

Within each meadow seagrass biomass varied substantially ranging from 0 to 8.73 g DWm^{-2} (Figures 7-9). Biomass was greatest throughout Meadow 7 and in the southern end of Meadow 6. These areas of high biomass coincide with where the majority of dugong feeding trails were recorded (Figure 10). No dugong feeding was recorded in Meadow 2 for the second year in a row (Figure 10).

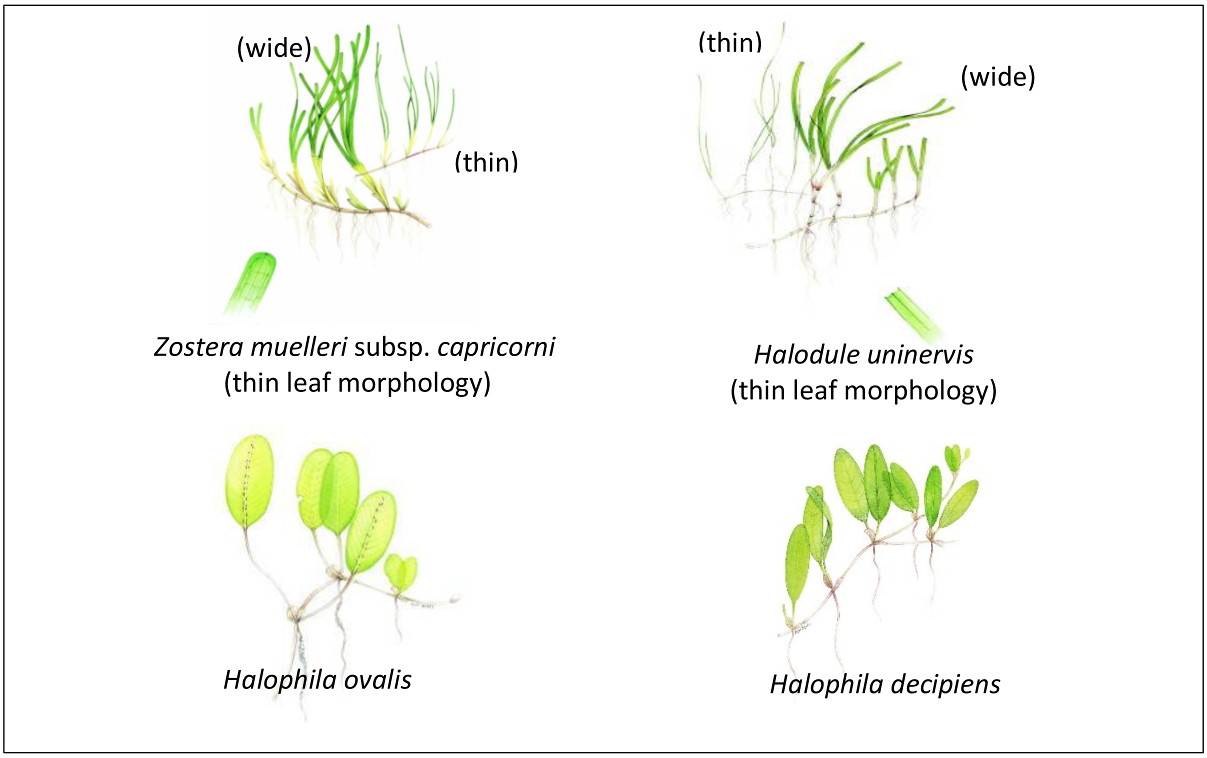

Figure 4. Seagrass species present in the HR2RP southern inshore marine zone during the October 2020 survey.

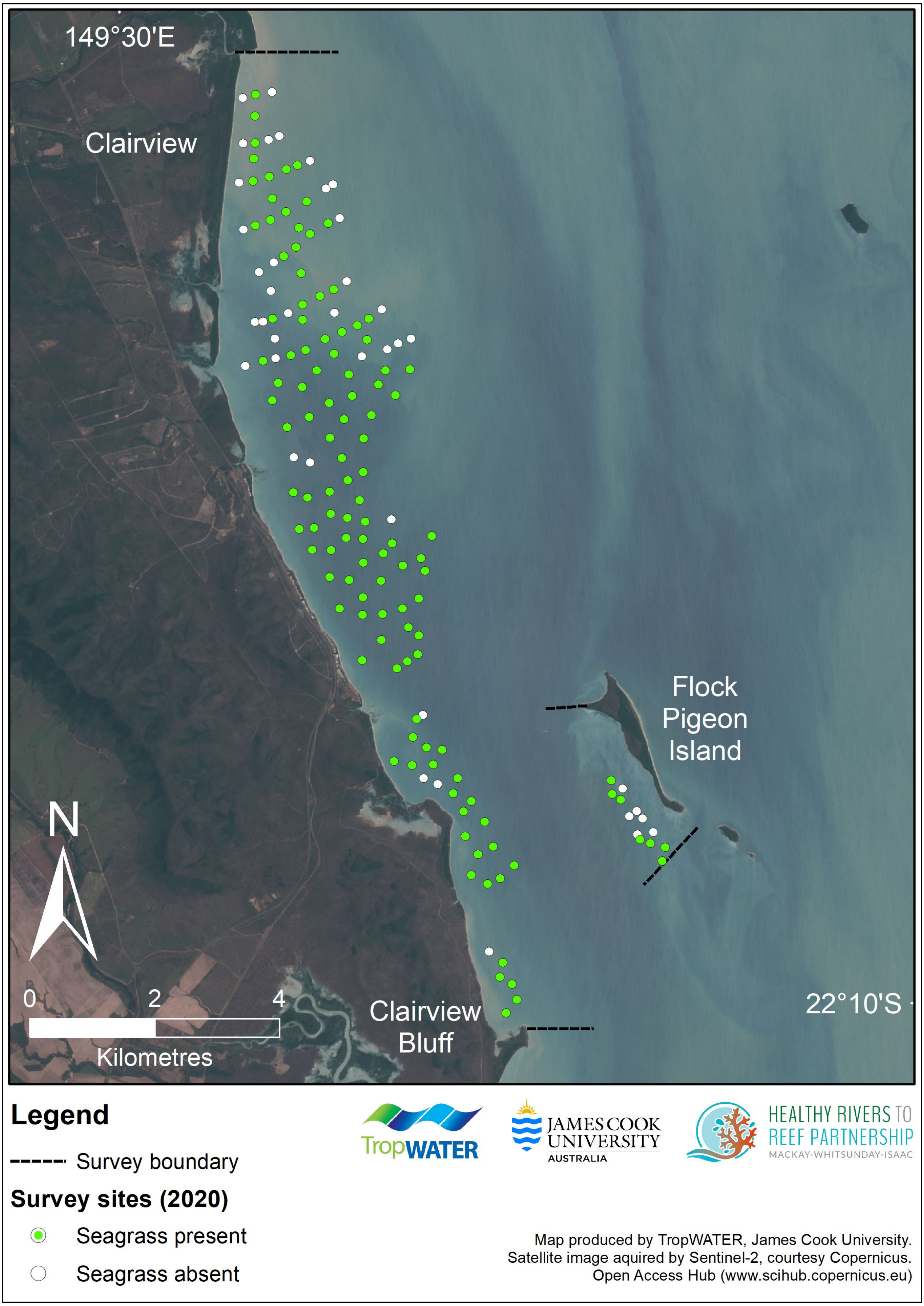

Figure 5. Location of intertidal survey sites in the southern inshore marine zone with seagrass presence/absence in 2020.

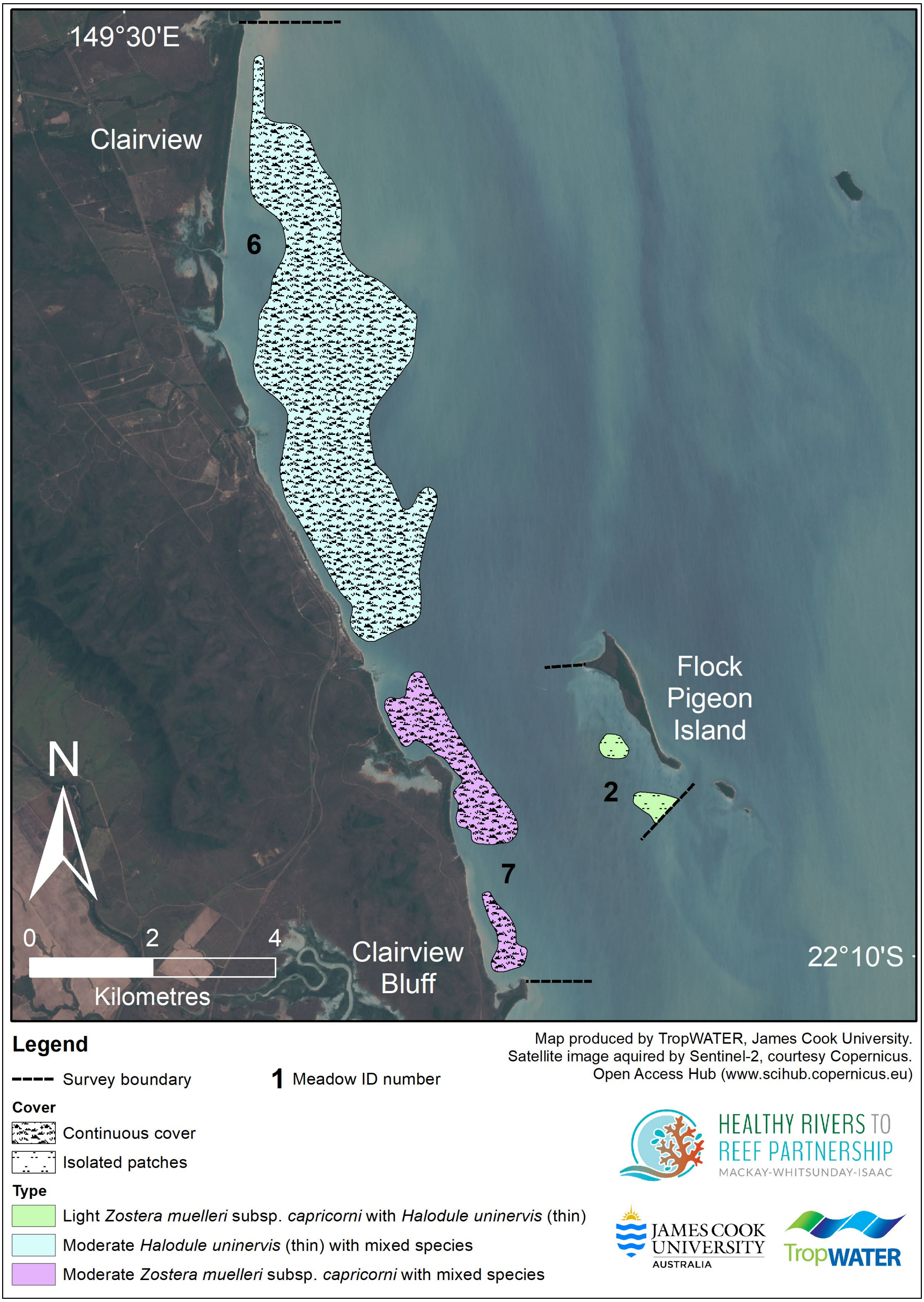

Figure 6. Seagrass monitoring meadow landscape categories and community types in 2020.

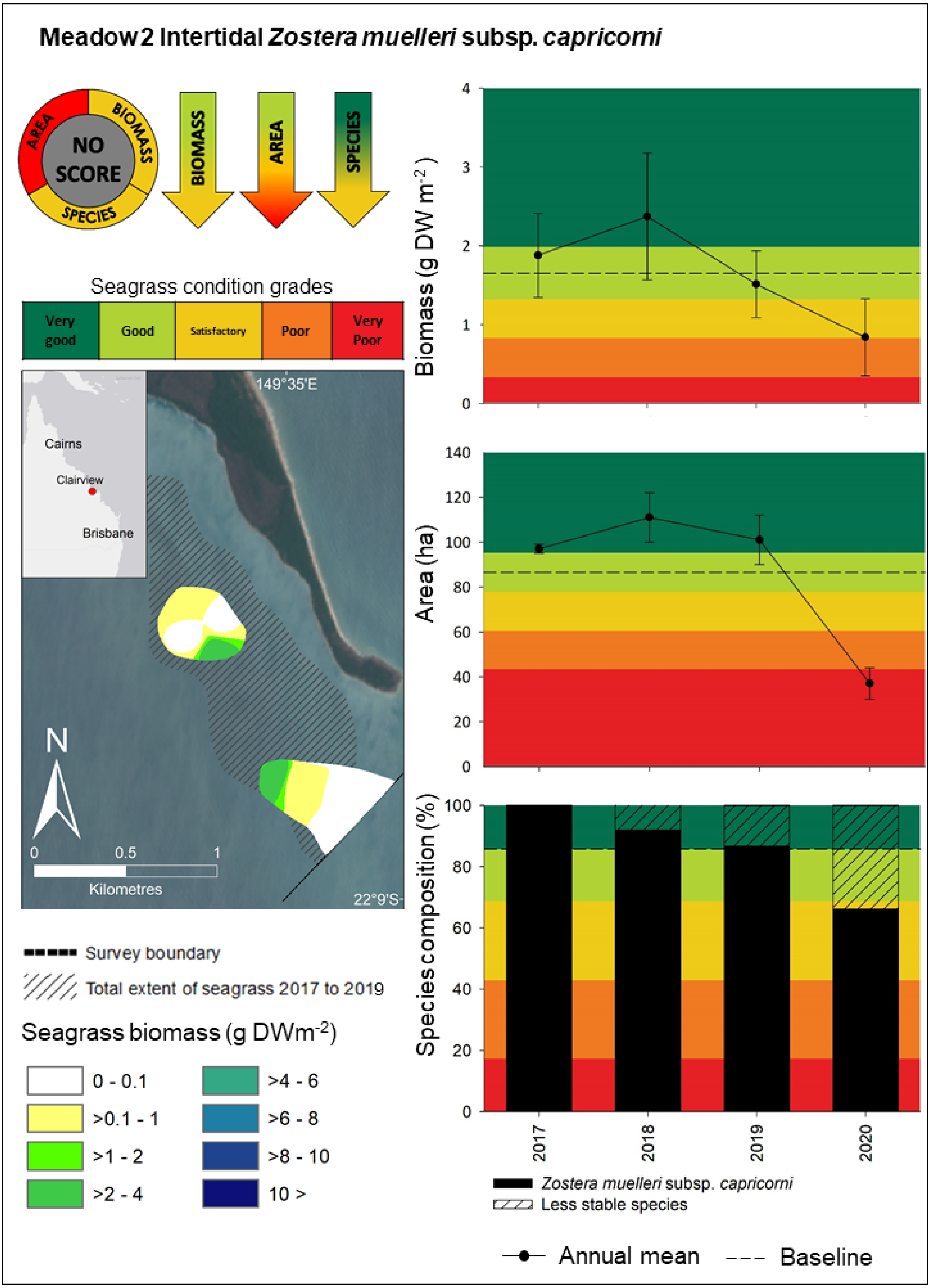

Figure 7. Changes in biomass, area and species composition for Meadow 2, 2017 - 2020 (biomass error bars = SE; area error bars = "R" reliability estimate).

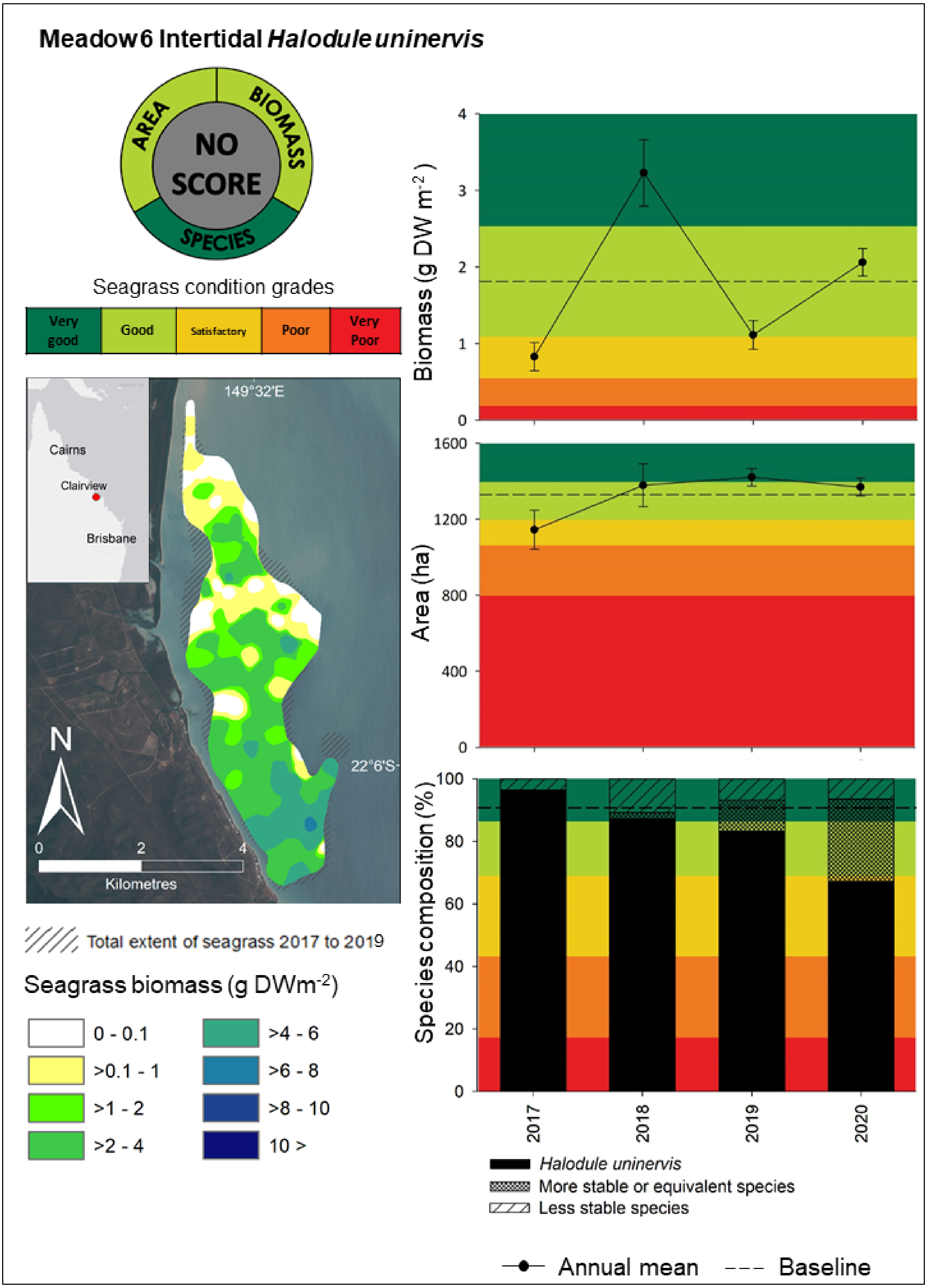

Figure 8. Changes in biomass, area and species composition for Meadow 6, 2017 - 2020 (biomass error bars = SE; area error bars = "R" reliability estimate).

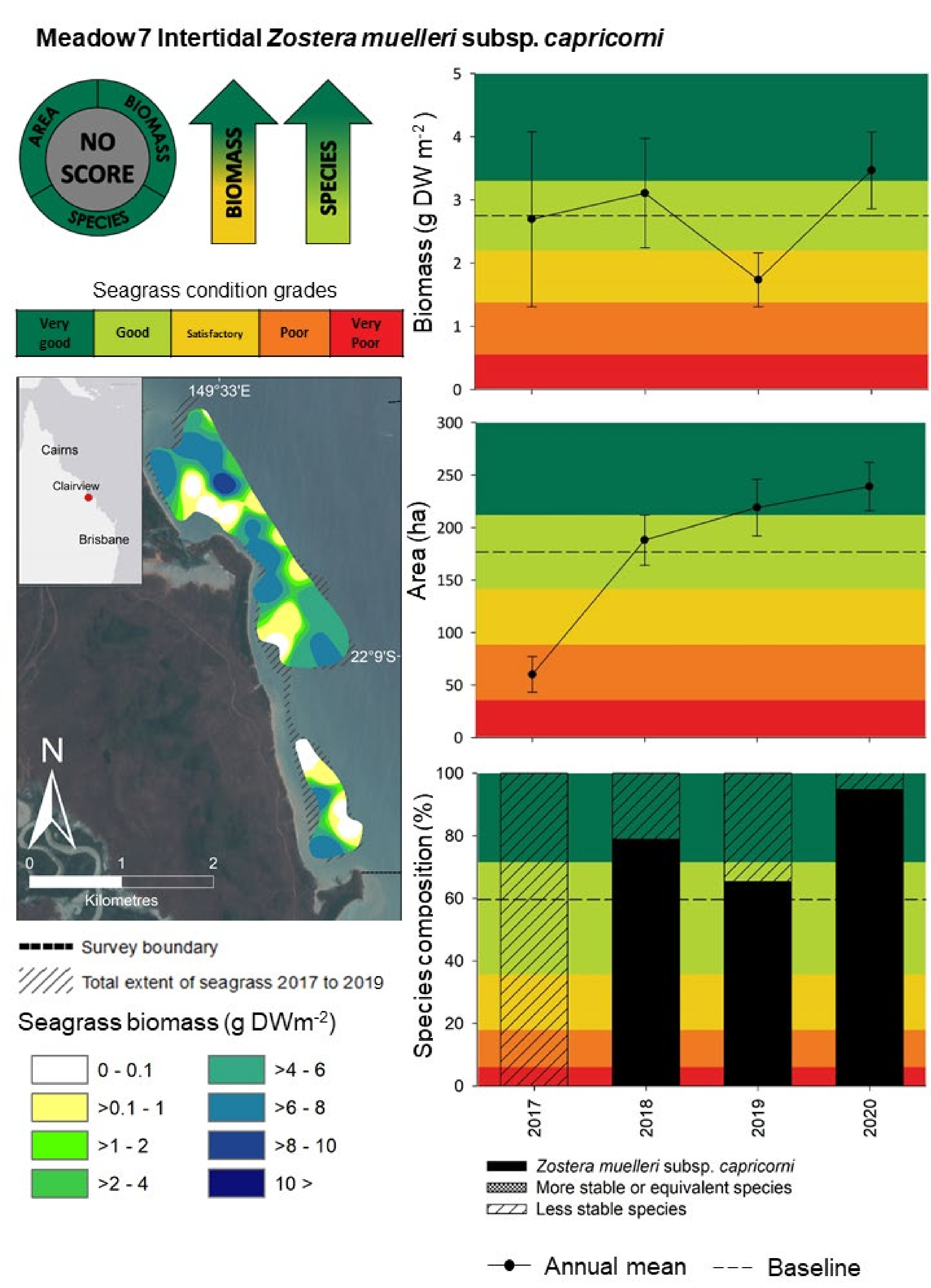

Figure 9. Changes in biomass, area and species composition for Meadow 7, 2017 - 2020 (biomass error bars = SE; area error bars = "R" reliability estimate).

4 DISCUSSION

This is the fourth year of seagrass monitoring in the southern inshore marine zone for the Mackay-Whitsunday-Isaac HR2RP. Overall results were positive with the large coastal meadows either similar too, or improving in condition from the previous year. However the smaller meadow adjacent to Flock Pigeon Island decreased in area and has also declined in biomass and species composition. Dugong feeding trails were abundant in the inshore meadows and correlated with higher biomass areas, similar to observations between 2017 and 2019 (Figure 10). This is a positive indicator that despite the seemingly low biomass these seagrasses are important for the local dugong population (Figure 10).

Climate patterns associated with the El Niño portion of the El Niño Southern Oscillation (ENSO) weather system are generally favourable for seagrass growth (Lin et al. 2018). The improvements recorded at the inshore meadows are likely due to a combination of favourable climate related to El Niño along with the absence of other major climatic or anthropogenic impacts in the region leading up to the survey. While the higher biomass of seagrasses was a positive result it's important to note that the relative change over the 4 years isn't substantial, with changes from 0.8 to 2.1 and 1.7 to 3.5 g DWm^{-2} for meadows 6 and 7, respectively (Figures 8 and 9). While these are relatively small meadow biomasses they are typical for coastal seagrasses in the Mackay-Whitsunday-Isaac region (Van De Wetering et al. 2020, York and Rasheed 2020).

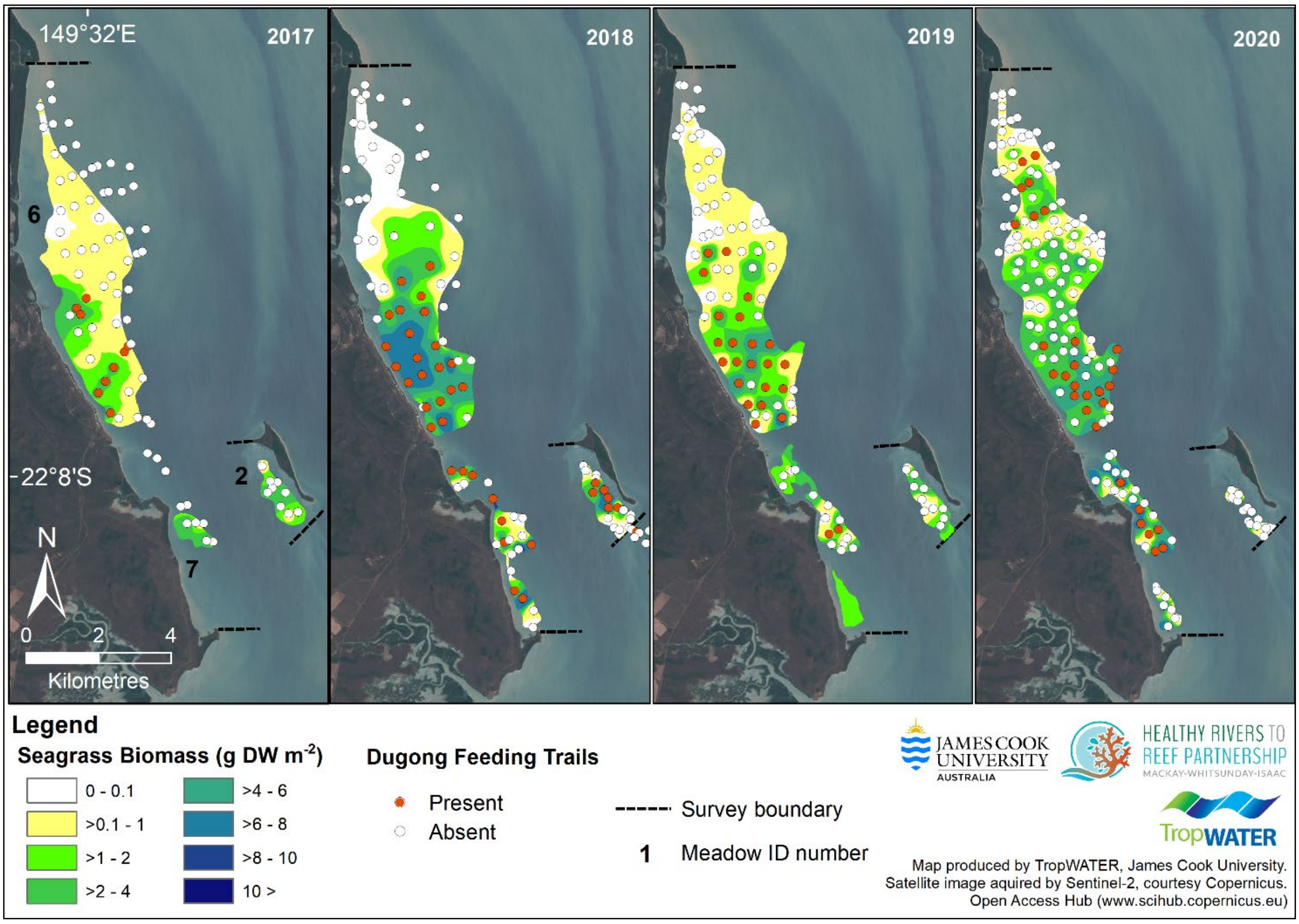

Figure 10. Variation in intertidal seagrass biomass within monitoring meadows, and presence of dugong feeding trails, 2017-2020.

Tropical seagrass meadows can be highly dynamic at small spatial scales, with spatial and temporal variability even in the absence of major natural or anthropogenic impacts (Saunders et al. 2015, York et al. 2015b, Alonso Aller et al. 2019).

While seagrasses were similar or improved for the large mainland coastal meadows, the smaller offshore meadow adjacent to Flock Pidgeon Island had a substantial decline in area from the previous three surveys. At this stage it is unclear if this is part of a normal range of change for this meadow. Similar low biomass meadows in the region can have substantial variability; as more data is collected we will have a clearer understanding of this meadow and whether such changes are outside of normal expectations.

Throughout the monitoring program only the thin leaf morphology for *Z. capricorni* and *H. uninervis* has been recorded. (Figure 4). Morphoplasticity of seagrasses is well documented (Bujang et al. 2008, Hedge et al. 2009, Hughes et al. 2009). Multiple studies have found that *Z. capricorni* has a thinner and shorter leaf morphology under increasing daily irradiance (Abal et al. 1994, Conacher et al. 1994, Bintz and Nixon 2001). However, York et al. (2013) found that thinner leaf morphology was associated with low light treatments, as well as prolonged exposure to temperatures near the maximum threshold of 30°C. These discrepancies outline the complex relationship between environmental conditions and seagrass morphology. McMillan (1983) found that *H. uninervis* with thin leaf morphology was associated with highly unstable salinity, sandy sediments and exposure to air. Persistent herbivory from megaherbivores such as sea turtles has also been shown to decrease seagrass leaf width (Kuiper-Linley et al. 2007, Fourqurean et al. 2010). The southern inshore zone is subject to a mixture of sandy sediments, extended open-air exposure, and considerable herbivory pressure. These likely all contribute towards the thin morphology present for *Z. capricorni* and *H. uninervis* observed in this region. The similar thin leaf morphology of the two species in the region means they are likely providing similar ecological roles compared with other locations where larger leaf variants of the species occur. This may mean that an adjustment to the “successional” hierarchy of species for species composition scores (Appendix 1 - Figure A1.1) may be warranted, where the thin leaf variant of *Z. capricorni* is considered on an equal footing with *H. uninervis.* This would also solve the issue of the difficulty in reliably differentiating the two species as part of rapid visual assessments of above ground structures.

The Mackay-Whitsunday-Isaac HR2RP provides a valuable opportunity to understand seagrass communities within the southern inshore zone, filling an important information gap for the HR2RP report card. The importance of this resource for megaherbivores (such as dugongs and green sea turtles) is outlined both by the presence of dugong feeding trails as well as being within a declared Dugong Protection Area. After 4 years of annual surveys, we’ve provided our second preliminary assessment of seagrass condition for this zone. These scores include indicators for key seagrass health metrics (area, biomass and species composition) using the methods outlined for score development by Carter et al. (2015). Bryant et al. (2014) determined that 10 years of monitoring is required for seagrasses throughout north Queensland to accurately define their base condition. This allows sufficient time to encompass the wide range of environmental conditions that could typically influence seagrass condition, such as ENSO cycles and extreme weather events. As a result we recommend waiting 5 years before providing a reportable score, with the baseline continuing to be refined until 10 years of data is collected. For this reason, the preliminary scores we have provided for individual meadow indicators in this report should be considered with caution as they are subject to change as baselines are adjusted. In 2021 we will have 5 years of baseline data and will be able to provide seagrass scores for the region that can be incorporated in the Mackay-Whitsunday-Isaac HR2R report card.

5 REFERENCES

Abal, E., and W. Dennison. 1996. Seagrass depth range and water quality in southern Moreton Bay, Queensland, Australia. Marine and Freshwater Research **47**:763-771.

Abal, E., N. Loneragan, P. Bowen, C. Perry, J. W. Udy, and W. C. Dennison. 1994. Physiological and morphological responses of the seagrass *Zostera capricorni* Aschers. to light intensity. Journal of Experimental Marine Biology and Ecology **178**:113-129.

Alonso Aller, E., J. S. Eklöf, M. Gullström, U. Kloiber, H. W. Linderholm, and L. M. Nordlund. 2019. Temporal variability of a protected multispecific tropical seagrass meadow in response to environmental change. Environmental Monitoring and Assessment **191**:774.

Bintz, J. C., and S. W. Nixon. 2001. Responses of eelgrass Zostera marina seedlings to reduced light. Marine Ecology Progress Series **223**:133-141.

Bryant, C., J. C. Jarvis, P. York, and M. Rasheed. 2014. Gladstone Healthy Harbour Partnership Pilot Report Card; ISP011: Seagrass., Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 14/53, James Cook University, Cairns.

Bujang, J. S., N. A. Nazri, M. H. Zakaria, A. Arshad, and H. Ogawa. 2008. Morphological plasticity of Halodule species in response to different environments. Marine Research in Indonesia **33**:11-16.

Carter, A., and M. Rasheed. 2018. Mackay-Whitsunday 2017 Baseline Seagrass Survey: Marine Inshore South Zone. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 18/08, James Cook University, Cairns.

Carter, A. B., J. C. Jarvis, C. V. Bryant, and M. A. Rasheed. 2015. Development of seagrass indicators for the Gladstone Healthy Harbour Partnership Report Card, ISP011: Seagrass. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 15/29, James Cook University, Cairns.

Coles, R., L. McKenzie, G. De'ath, A. Roelofs, and W. L. Long. 2009. Spatial distribution of deepwater seagrass in the inter-reef lagoon of the Great Barrier Reef World Heritage Area. Marine Ecology Progress Series **392**:57-68.

Coles, R. G., W. J. Lee Long, L. J. McKenzie, and C. A. Roder. 2002. Seagrass and Marine Resources in the Dugong Protection Areas of Upstart Bay, Newry Region, Sand Bay, Llewellyn Bay, Ince Bay and the Clairview Region: April/May 1999 and October 1999. Great Barrier Reef Marine Park Authority, Townsville.

Coles, R. G., J. Mellors, J. M. Biddy, K. J. Derbyshire, B. A. Squire, L. C. Squire, and W. J. Lee Long. 1987. Distribution of seagrasses and associated juvenile commercial prawns and fish between Bowen and Water Park Point. A report to the Great Barrier Reef Marine Park Authority. Queensland Department of Primary Industries, Brisbane.

Collier, C. J., K. Chartrand, C. Honchin, A. Fletcher, and M. Rasheed. 2016. Light thresholds for seagrasses of the GBR: a synthesis and guiding document. Including knowledge gaps and future priorities. Report to the National Environmental Science Programme, Cairns.

Conacher, C. A., I. R. Poiner, and M. O'Donohue. 1994. Morphology, flowering and seed production of *Zostera capricorni* Aschers. in subtropical Australia. Aquatic Botany **49**:33-46.

Costanza, R., R. de Groot, P. Sutton, S. van der Ploeg, S. J. Anderson, I. Kubiszewski, S. Farber, and R. K. Turner. 2014. Changes in the global value of ecosystem services. Global Environmental Change **26**:152-158.

Dennison, W. C., R. J. Orth, K. A. Moore, J. C. Stevenson, V. Carter, S. Kollar, P. W. Bergstrom, and R. A. Batiuk. 1993. Assessing water quality with submersed aquatic vegetation: Habitat requirements as barometers of Chesapeake Bay health. BioScience **43**:86-94.

Fourqurean, J. W., C. M. Duarte, H. Kennedy, N. Marbà, M. Holmer, M. A. Mateo, E. T. Apostolaki, G. A. Kendrick, D. Krause-Jensen, and K. J. McGlathery. 2012. Seagrass ecosystems as a globally significant carbon stock. Nature Geoscience **5**:505-509.

Fourqurean, J. W., S. Manuel, K. A. Coates, W. J. Kenworthy, and S. R. Smith. 2010. Effects of excluding sea turtle herbivores from a seagrass bed: Overgrazing may have led to loss of seagrass meadows in Bermuda. Marine Ecology Progress Series **419**:223-232.

Grech, A., K. Chartrand-Miller, P. Erftemeijer, M. Fonseca, L. McKenzie, M. Rasheed, H. Taylor, and R. Coles. 2012. A comparison of threats, vulnerabilities and management approaches in global seagrass bioregions. Environmental Research Letters **7**:024006.

Heck, K. L., T. J. B. Carruthers, C. M. Duarte, A. R. Hughes, G. Kendrick, R. J. Orth, and S. W. Williams. 2008. Trophic Transfers from Seagrass Meadows Subsidize Diverse Marine and Terrestrial Consumers. Ecosystems **11**:1198-1210.

Hedge, S., N. Smith, and R. Unsworth. 2009. Temporal and spatial morphological variability of the seagrasses Halophila ovalis and Halodule uninervis throughout the Great Barrier Reef region: Preliminary analysis. Report to the Marine and Tropical Sciences Research Facility:15.

Hemminga, M. A., and C. M. Duarte. 2000. Seagrass Ecology. Cambridge University Press, Cambridge, United Kingdom.

Hughes, A., J. Stachowicz, and S. Williams. 2009. Morphological and physiological variation among seagrass (*Zostera marina*) genotypes. Oecologia **159**:725-733.

Kilminster, K., K. McMahon, M. Waycott, G. A. Kendrick, P. Scanes, L. McKenzie, K. R. O'Brien, M. Lyons, A. Ferguson, P. Maxwell, T. Glasby, and J. Udy. 2015. Unravelling complexity in seagrass systems for management: Australia as a microcosm. Science of The Total Environment **534**:97-109.

Kirkman, H. 1978. Decline of seagrass in northern areas of Moreton Bay, Queensland. Aquatic Botany **5**:63-76.

Kuiper-Linley, M., C. R. Johnson, and J. M. Lanyon. 2007. Effects of simulated green turtle regrazing on seagrass abundance, growth and nutritional status in Moreton Bay, south-east Queensland, Australia. Marine and Freshwater Research **58**:492-503.

Lamb, J. B., J. A. J. M. van de Water, D. G. Bourne, C. Altier, M. Y. Hein, E. A. Fiorenza, N. Abu, J. Jompa, and C. D. Harvell. 2017. Seagrass ecosystems reduce exposure to bacterial pathogens of humans, fishes, and invertebrates. Science **355**:731-733.

Lin, H.-J., C.-L. Lee, S.-E. Peng, M.-C. Hung, P.-J. Liu, and A. B. Mayfield. 2018. The effects of El Niño-Southern Oscillation events on intertidal seagrass beds over a long-term timescale. Global Change Biology **24**:4566-4580.

McKenna, S., J. Jarvis, T. Sankey, C. Reason, R. Coles, and M. Rasheed. 2015. Declines of seagrasses in a tropical harbour, North Queensland, Australia, are not the result of a single event. Journal of Biosciences **40**:389-398.

McKenna, S., C. Van De Wetering, J. Wilkinson, and M. Rasheed. 2021a. Port of Abbot Point Long-Term Seagrass Monitoring Program - 2020. James Cook University, Cairns.

Mckenna, S., J. Wilkinson, K. Chartrand, C. Van De Wetering, A. Carter, and M. Rasheed. 2021b. Port of Townsville Seagrass Monitoring Program: 2020. James Cook University Publication, Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), Cairns.

McMillan, C. 1983. Morphological diversity under controlled conditions for the Halophila ovalis-H. minor complex and the Halodule uninervis complex from Shark Bay, Western Australia. Aquatic Botany **17**:29-42.

Mellors, J. E. 1991. An evaluation of a rapid visual technique for estimating seagrass biomass. Aquatic Botany **42**:67-73.

Orth, R. J., T. J. B. Carruthers, W. C. Dennison, C. M. Duarte, J. W. Fourqurean, K. L. Heck, A. R. Hughes, G. A. Kendrick, W. J. Kenworthy, S. Olyarnik, F. T. Short, M. Waycott, and S. L. Williams. 2006. A global crisis for seagrass ecosystems. BioScience **56**:987-996.

Pitcher, C. R., P. Doherty, P. Arnold, J. Hooper, N. Gribble, C. Bartlett, M. Browne, N. Campbell, T. Cannard, M. Cappo, G. Carini, S. Chalmers, S. Cheers, D. Chetwynd, A. Colefax, R. Coles, S. Cook, P. Davie, G. De'ath, D. Devereux, B. Done, T. Donovan, B. Ehrke, N. Ellis, G. Ericson, I. Fellegara, K. Forcey, M. Furey, D. Gledhill, N. Good, S. Gordon, M. Haywood, P. Hendriks, I. Jacobsen, J. Johnson, M. Jones, S. Kinninmoth, S. Kistle, P. Last, A. Leite, S. Marks, I. McLeod, S. Oczkowicz, M. Robinson, C. Rose, D. Seabright, J. Sheils, M. Sherlock, P. Skelton, D. Smith, G. Smith, P. Speare, M. Stowar, C. Strickland, C. Van der Geest, W. Venables, C. Walsh, T. Wassenberg, A. Welna, and G. Yearsley. 2007. Seabed Biodiversity on the Continental Shelf of the Great Barrier Reef World Heritage Area. AIMS/CSIRO/QM/QDPI CRC Reef Research Task Final Report.

Reason, C., and T. R. Smith, M. 2021. Seagrass habitat of Cairns Harbour and Trinity Inlet: Cairns Shipping Development Program and Annual Monitoring Report 2020. JCU Publication, Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), Cairns.

Reason, C., P. York, and M. Rasheed. 2021. Seagrass habitat of Mourilyan Harbour: Annual Monitoring Report – 2020. James Cook University, Cairns.

Robblee, M. B., T. R. Barber, P. R. Carlson, Jr., M. J. Durako, J. W. Fourqurean, L. K. Muehlstein, D. Porter, L. A. Yarbro, R. T. Zieman, and J. C. Zieman. 1991. Mass mortality of the tropical seagrass *Thalassia testudinum* in Florida Bay (USA). Marine Ecology Progress Series **71**:297-299.

Roder, C. A., R. G. Coles, L. J. McKenzie, and W. J. Lee Long. 2002. Seagrass Resources of the Clairview Region Dugong Protection Area - Reconaissance 1999. Pages 85-115 *in* R. G. Coles, W. J. Lee Long, L. J. McKenzie, and C. A. Roder, editors. Seagrass and Marine Resources in the Dugong Protection Areas of Upstart Bay, Newry Region, Sand Bay, Ince Bay, Llewellyn Bay and Clairview Region, April/May 1999 and October 1999. Final report to Great Barrier Reef Marine Park Authority, research publication no.72, Cairns.

Saunders, M. I., E. Bayraktarov, C. M. Roelfsema, J. X. Leon, J. Samper-Villarreal, S. R. Phinn, C. E. Lovelock, and P. J. Mumby. 2015. Spatial and temporal variability of seagrass at Lizard Island, Great Barrier Reef. Botanica Marina **58**:35-49.

Scott, A. L., and M. Rasheed. 2021. Port of Karumba Long-term Annual Seagrass Monitoring 2020. Centre for Tropical Water & Aquatic Ecosystem Research Publication Number 21/05, James Cook University, Cairns.

Scott, A. L., P. H. York, C. Duncan, P. I. Macreadie, R. M. Connolly, M. T. Ellis, J. C. Jarvis, K. I. Jinks, H. Marsh, and M. A. Rasheed. 2018. The Role of Herbivory in Structuring Tropical Seagrass Ecosystem Service Delivery. Frontiers in Plant Science **9**.

Scott, A. L., P. H. York, and M. A. Rasheed. 2020. Green turtle (*Chelonia mydas*) grazing plot formation creates structural changes in a multi-species Great Barrier Reef seagrass meadow. Marine environmental research **162**:105183.

Smith, T., C. Reason, and M. Rasheed. 2021a. Port of Weipa long-term seagrass monitoring program, 2000 - 2020. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 20/58, James Cook University Cairns.

Smith, T., C. Reason, and M. Rasheed. 2021b. Seagrasses in Port Curtis and Rodds Bay 2020 Annual long-term monitoring. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook University, Cairns.

Unsworth, R. K. F., and L. C. Cullen. 2010. Recognising the necessity for Indo-Pacific seagrass conservation. Conservation Letters **3**:63-73.

Van De Wetering, C., P. York, C. Reason, J. Wilkinson, and M. A. Rasheed. 2020. Port of Abbot Point Long-Term Seagrass Monitoring Program - 2019. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER). Publication 20/12., Cairns.

Waycott, M., C. M. Duarte, T. J. B. Carruthers, R. J. Orth, W. C. Dennison, S. Olyarnik, A. Calladine, J. W. Fourqurean, K. L. Heck, A. R. Hughes, G. A. Kendrick, W. J. Kenworthy, F. T. Short, and S. L. Williams. 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proceedings of the National Academy of Sciences of the United States of America **106**:12377-12381.

Wells, J., M. Rasheed, and R. Coles. 2019. Seagrass Habitat in the Port of Thursday Island: Annual Monitoring Report 2019. James Cook University, Cairns.

York, P., A. Carter, K. Chartrand, T. Sankey, L. Wells, and M. Rasheed. 2015a. Dynamics of a deep-water seagrass population on the Great Barrier Reef: Annual occurrence and response to a major dredging program. Scientific Reports **5**:13167.

York, P., and M. Rasheed. 2020. Annual Seagrass Monitoring in the Mackay-Hay Point Region – 2019. James Cook University, Cairns.

York, P., and M. Rasheed. 2021. Annual Seagrass Monitoring in the Mackay-Hay Point Region – 2020. JCU Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), Cairns.

York, P. H., A. B. Carter, K. Chartrand, T. Sankey, L. Wells, and M. A. Rasheed. 2015b. Dynamics of a deep-water seagrass population on the Great Barrier Reef: annual occurrence and response to a major dredging program. Scientific Reports **5**:13167.

York, P. H., R. K. Gruber, R. Hill, P. J. Ralph, D. J. Booth, and P. I. Macreadie. 2013. Physiological and Morphological Responses of the Temperate Seagrass <italic>Zostera muelleri</italic> to Multiple Stressors: Investigating the Interactive Effects of Light and Temperature. PLoS ONE **8**:e76377.

6 APPENDICES

Appendix 1. Seagrass Condition Calculations

A1.1 Baseline Calculations

Baseline conditions for seagrass biomass, meadow area and species composition will be established from annual means calculated over the first 10 years of monitoring, following the methods of Carter et al. (2015) and Bryant et al. (2014).

Baseline conditions for species composition are based on the annual percent contribution of each species to mean meadow biomass of the baseline years. Meadows are classified as either single species dominated (one species comprising ≥80% of baseline species), or mixed species (all species comprise <80% of baseline species composition). Where a meadow baseline contains an approximately equal split in two dominant species (i.e. both species accounted for 40–60% of the baseline), the baseline is set according to the percent composition of the more persistent/stable species of the two (see A1.4 Grade and Score Calculations and Figure A1.1).

A1.2 Meadow Classification

A meadow classification system was developed for the three condition indicators (biomass, area, species composition) in recognition that for some seagrass meadows these measures are historically stable, while in other meadows they are relatively variable. The coefficient of variation (CV) for each baseline for each meadow is used to determine historical variability. Meadow biomass and species composition are classified as either stable or variable (Table A1.1). Meadow area is classified as either highly stable, stable, variable, or highly variable (Table A1.1). The CV is calculated by dividing the standard deviation of the baseline years by the baseline for each condition indicator.

Table A1.1 Coefficient of variation (CV; %) thresholds used to classify stability or variability of meadow biomass, area and species composition.

Indicator	Class			
	Highly stable	Stable	Variable	Highly variable
Biomass	-	< 40%	≥ 40%	-
Area	< 10%	≥ 10, < 40%	≥ 40, <80%	≥ 80%
Species composition	-	< 40%	≥ 40%	-

A1.3 Threshold Definition

Seagrass condition for each indicator is assigned one of five grades (very good (A), good (B), satisfactory (C), poor (D), and very poor (E)). Threshold levels for each grade are set relative to the baseline and based on meadow class. This approach accounts for historical variability within the monitoring meadows and expert knowledge of the different meadow types and assemblages in the region (Table A1.2).

Table A1.2. Threshold levels for grading seagrass indicators for various meadow classes relative to the baseline. Upwards/ downwards arrows are included where a change in condition has occurred in any of the three condition indicators (biomass, area, species composition) from the previous year.

Seagrass condition indicators/ Meadow class		Seagrass grade				
		A Very good	B Good	C Satisfactory	D Poor	E Very Poor
Biomass	Stable	>20% above	20% above - 20% below	20-50% below	50-80% below	>80% below
	Variable	>40% above	40% above - 40% below	40-70% below	70-90% below	>90% below
Area	Highly stable	>5% above	5% above - 10% below	10-20% below	20-40% below	>40% below
	Stable	>10% above	10% above - 10% below	10-30% below	30-50% below	>50% below
	Variable	>20% above	20% above - 20% below	20-50% below	50-80% below	>80% below
	Highly variable	> 40% above	40% above - 40% below	40-70% below	70-90% below	>90% below
Species composition	Stable and variable; Single species dominated	>0% above	0-20% below	20-50% below	50-80% below	>80% below
	Stable; Mixed species	>20% above	20% above - 20% below	20-50% below	50-80% below	>80% below
	Variable; Mixed species	>20% above	20% above- 40% below	40-70% below	70-90% below	>90% below
	Increase above threshold from previous year			Decrease below threshold from previous year		

A1.4 Grade and Score Calculations

A score system (0–1) and score range is applied to each grade to allow numerical comparisons of seagrass condition (see Carter *et al.* 2015 for a detailed description, and Table A1.3). Score calculations for each meadow's condition require calculating the biomass, area and species composition for that year (see A1.1 Baseline Calculations, above), allocating a grade for each indicator by comparing the current year's values against meadow-specific thresholds for each grade, then scaling biomass, area and species composition values against the prescribed score range for that grade. Scaling was required because the score range in each grade was not equal (Table A1.3). Within each meadow, the upper limit for the very good grade (score = 1) for species composition is set as 100% (as a species could never account for >100% of species composition). For biomass and area, the upper limit is set as the maximum mean plus standard error (SE; i.e. the top of the error bar) value for a given year, compared among years during the baseline period.

An example of calculating a meadow score for biomass in good condition is provided in Appendix 2.

Table A1.3. Score range and grading colours used in the seagrass report card.

Grade	Description	Score Range	
		Lower bound	Upper bound
A	Very good	≥0.85	1.00
B	Good	≥0.65	<0.85
C	Satisfactory	≥0.50	<0.65
D	Poor	≥0.25	<0.50
E	Very poor	0.00	<0.25

Where species composition is determined to be anything less than in "perfect" condition (i.e. a score <1), a decision tree is used to determine whether equivalent and/or more persistent species are driving this grade/score (Figure A1.1). If this is the case then the species composition score and grade for that year is recalculated including those species. Concern regarding any decline in the stable state species should be reserved for those meadows where the directional change from the stable state species is of concern (Figure A1.1). This would occur when the stable state species is replaced by species considered to be earlier colonisers. Such a shift indicates a decline in meadow stability (e.g. a shift from *H. uninervis* to *H. ovalis*). An alternate scenario can occur where the stable state species is replaced by what is considered an equivalent species (e.g. shifts between *C. rotundata* and *C. serrulata*), or replaced by a species indicative of an improvement in meadow stability (e.g. a shift from *H. decipiens* to *H. uninervis* or any other species).

The directional change assessment is based largely on dominant traits of colonising, opportunistic and persistent seagrass genera described by Kilminster et al. (2015). Adjustments to the Kilminster model included: (1) positioning *S. isoetifolium* further towards the colonising species end of the list, as successional studies following disturbance demonstrate this is an early coloniser in Queensland seagrass meadows (Rasheed 2004); and (2) separating and ordering the *Halophila* genera by species. Shifts between *Halophila* species are ecologically relevant; for example, a shift from *H. ovalis* to *H. decipiens* may indicate declines in water quality and available light for seagrass growth as *H. decipiens* has a lower light requirement (Collier et al. 2016) (Figure A1.1).

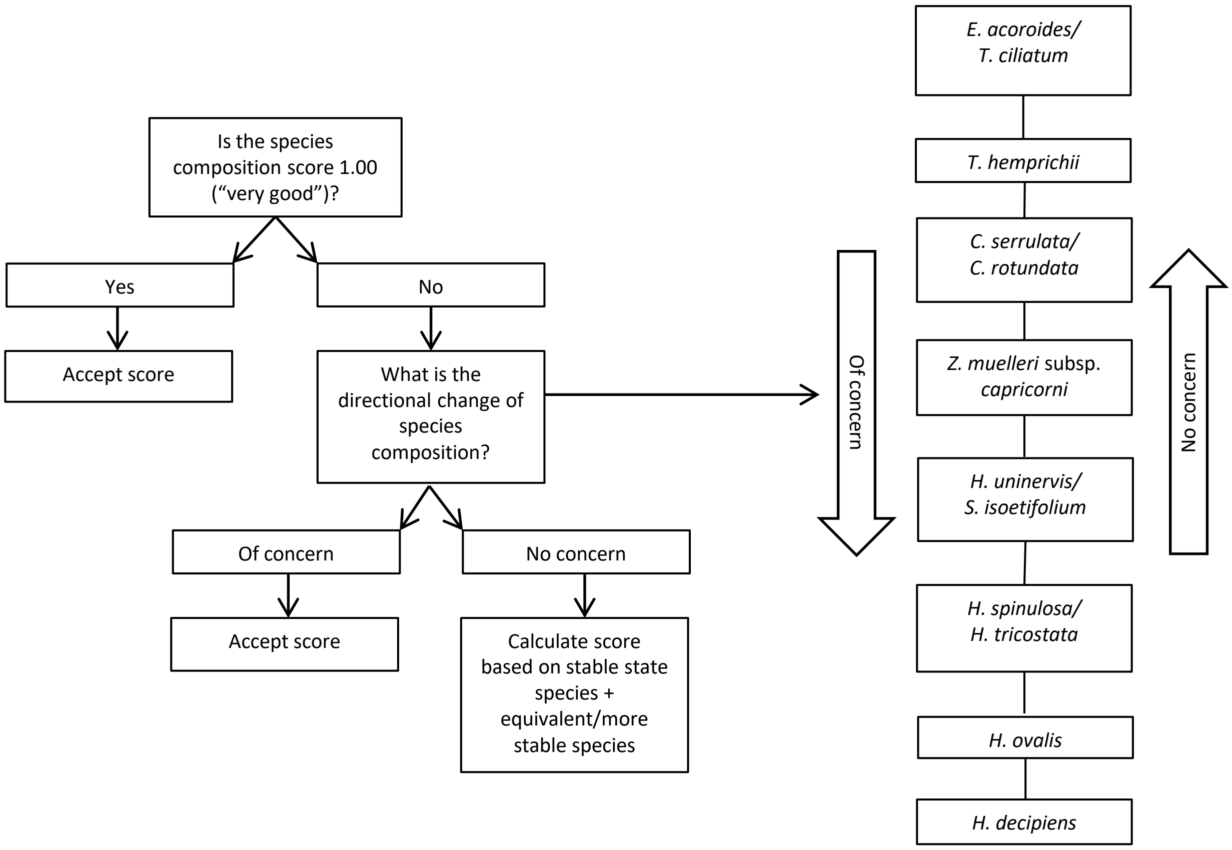

Figure A1.1. (a) Decision tree and (b) directional change assessment for grading and scoring seagrass species composition.

A1.5 Score Aggregation

Each overall meadow grade/score is defined as the lowest grade/score of the three condition indicators within that meadow. The lowest score, rather than the mean of the three indicator scores, is applied in recognition that a poor grade for any one of the three described a seagrass meadow in poor condition. Maintenance of each of these three fundamental characteristics of a seagrass meadow is required to describe a healthy meadow. This method allows the most conservative estimate of meadow condition to be made (Bryant et al. 2014). In cases where species composition is the lowest score, an average of both the species composition score and the next lowest score is used to determine the overall meadow score. This is to prevent a case where a meadow may have a spatial footprint and seagrass biomass but a score of zero due to changes in species composition.

Appendix 2. Biomass score calculation example

1. Determine the grade for the 2019 (current) biomass value (i.e. good).

2. Calculate the difference in biomass (B_{diff}) between the 2019 biomass value (B_{2019}) and the biomass value of the lower threshold boundary for the “good” grade (B_{good}):

$$B_{diff} = B_{2019} - B_{good}$$

Where B_{good} or any other threshold boundary will differ for each condition indicator depending on the baseline value, meadow class (stable, variable, highly variable [area only]), and whether the meadow is dominated by a single species or mixed species (species composition calculations only).

3. Calculate the range for biomass values (B_{range}) in that grade:

$$B_{range} = B_{very\ good} - B_{good}$$

Where B_{good} is the upper threshold boundary for the good grade.
Note: For species composition, the upper limit for the very good grade is set as 100%. For area and biomass, the upper limit for the very good grade is set as the mean plus the standard error (i.e. the top of the error bar) for the maximum recorded mean annual value for that indicator and meadow.

4. Calculate the proportion of the good grade (B_{prop}) that B_{2019} takes up:

$$B_{prop} = \frac{B_{diff}}{B_{range}}$$

5. Determine the biomass score for 2019 ($Score_{2019}$) by scaling B_{prop} against the score range (SR) for the good grade (SR_{good}), i.e. 0.20 units (see Table A1.3):

$$Score_{2019} = LB_{good} + (B_{prop} \times SR_{good})$$

Where LB_{good} is the defined lower bound (LB) score threshold for the good grade, i.e. 0.65 units.