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JAMES COOK UNIVERSITY
AUSTRALIA

Seagrasses in Port Curtis and Rodds Bay 2021
Annual long-term monitoring

Smith TM, Reason C, McKenna S
& Rasheed MA

Report No. 22/14

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Annual long-term monitoring survey

A Report for Gladstone Ports Corporation

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March 2022

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KEY FINDINGS

Seagrass Condition 2021

Good

1. Seagrasses in Port Curtis and Rodds Bay were surveyed from the 3rd – 15th November 2021 as part of a long-term annual monitoring program.

2. Overall, seagrass condition was good for the third consecutive year after an extended period of poor or satisfactory seagrass condition prior to 2019.

3. Nine of the fourteen annual monitoring meadows were in a good to very good condition and a further four in satisfactory condition.

4. All meadows in the Western Basin were in good or very good condition except for one ephemeral deep-water meadow that was in satisfactory condition.

5. The large Pelican Banks meadow adjacent to Curtis Island increased in biomass and the proportion of *Zostera muelleri* to be in satisfactory condition after six years of being in poor condition.

6. Favourable seagrass growing conditions due to a lack of major rainfall events and low river flows over the last three years has led to successive years of good seagrass condition in Port Curtis and Rodds Bay.

7. A small monitoring meadow in Rodds Bay underwent declines in meadow area, biomass and species composition to be in very poor condition but the two larger Rodds Bay meadows were in good and satisfactory condition.

8. Seagrass remained in good condition in 2021 and meadows in the Western Basin had some of the highest biomass recorded with meadows likely to have high levels of resilience against major weather events and anthropogenic factors.

IN BRIEF

Seagrass monitoring in Port Curtis and Rodds Bay commenced in 2002 and has been conducted annually since 2004. Fourteen monitoring meadows are assessed annually and the condition of the meadows evaluated based on variations in three key seagrass metrics - biomass, area and species composition. Monitoring meadows represent the range of different seagrass community types in Port Curtis and Rodds Bay (Figure 1) and every 5 years all seagrasses within the greater port limits are reassessed (last done in 2019).

Overall seagrass condition in 2021 was good. This is the third consecutive year that seagrass was in good condition following improvements in 2019 when seagrass was in the best condition for a decade. In 2021 nine of the 14 individual monitoring meadows were rated as being in good or very good condition (Figures 2, 3 and section 3 for more details). There was however a decline from good to very poor in a small monitoring meadow outside the port in Rodds Bay (meadow 94) due to decreases in all meadow metrics from 2020. These losses were not reflected in the other two Rodds Bay monitoring meadows where seagrass condition was good and satisfactory. Seagrass in Port Curtis and Rodds Bay was in poor condition from 2010 until 2017 following widespread seagrass losses in 2009-10 resulting from high rainfall and flooding events associated with extended La Niña weather conditions. Seagrass recovery over the last four years is likely related to low rainfall and local river flows leading to favourable growing conditions that have allowed seagrass to expand and maintain good overall condition.

The seagrass meadow at Pelican Banks is historically the largest and highest biomass meadow in the Port Curtis and Rodds Bay region. In 2021 the meadow recorded increases in biomass and species composition to be in satisfactory condition after 6 years of poor condition. An increase in the proportion of the larger species *Z. muelleri* in the meadow led to an overall increase in biomass which should continue to increase if the proportion of *Z. muelleri* remains high. This meadow had undergone large declines in seagrass biomass and loss of the foundation species *Z. muelleri* over the six years prior to 2021, potentially due to grazing by megaherbivores (green turtles and dugongs). Megaherbivore grazers may potentially have focused grazing effort in other meadows as seagrass condition declined at Pelican Banks, releasing the meadow from grazing pressure and allowing the biomass to increase in 2021. Direct measures of herbivory pressure during 2021 were not carried out as part of this study though.

Changes in the benthic light environment associated with dredge plumes can impact seagrass condition leading to losses in biomass and cover (Chartrand et al. 2018). However, the amount and period of light reduction required to create impacts means that dredging activity can generally be managed in a way that protects seagrasses from light related loss (Chartrand et al 2018) particularly for shorter duration maintenance programs. Annual maintenance dredging occurs within the Port of Gladstone each year in channels and facilities adjacent to seagrass meadows. Modelling and impact assessment of maintenance dredging plumes as well as plume field studies have been carried out in the Port of Gladstone (BTM 2017, 2019). These studies have shown dredging plumes can increase turbidity leading to reduced benthic light but these conditions are short lived relative to ambient conditions (BTM 2017, 2019). Results of this monitoring program show that in 2021 seagrass meadows closest to maintenance dredge activity were in good condition and in similar condition to meadows in the out of port reference area in Rodds Bay. Continued high biomass and meadow area in 2021 will help seagrass meadows in Port Curtis and Rodds Bay remain resilient to natural and anthropogenic stressors in 2022.

Continuing good condition of seagrass in Port Curtis and Rodds Bay over the last four years is in line with trends in other regions where seagrass is monitored as part of the network of seagrass monitoring in Queensland. In ports such as Cairns, and Mackay/Hay Point where local environmental and weather conditions have been favourable and seagrasses have recovered at similar rates to Port Curtis and Rodds Bay. In contrast, localised floods at Townsville and Karumba in 2019 led to seagrass declines. For full details of the Queensland ports seagrass monitoring program see: www.tropwater.com/project/management-of-ports-and-coastal-facilities/

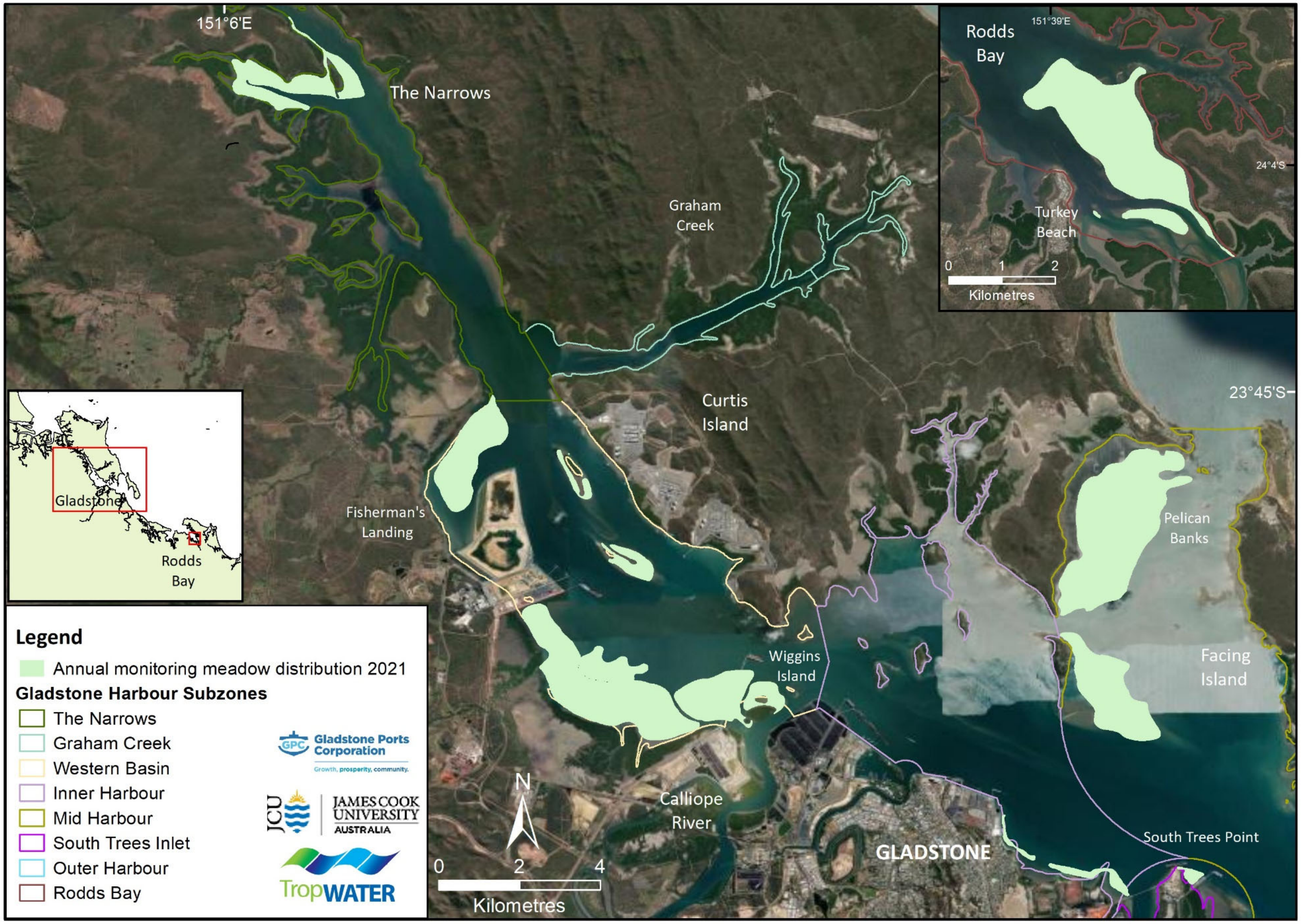

Figure 1. Seagrass distribution of Port Curtis and Rodds Bay monitoring meadows in November 2021.

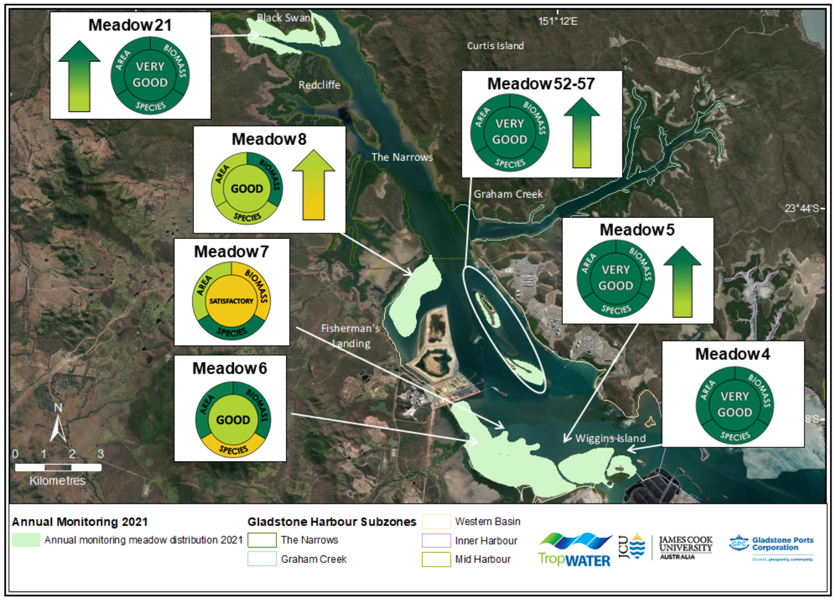

Figure 2. Seagrass distribution and meadow condition in The Narrows and Western Basin Zones (Port Curtis), November 2021. Arrows indicate overall grade change from 2020.

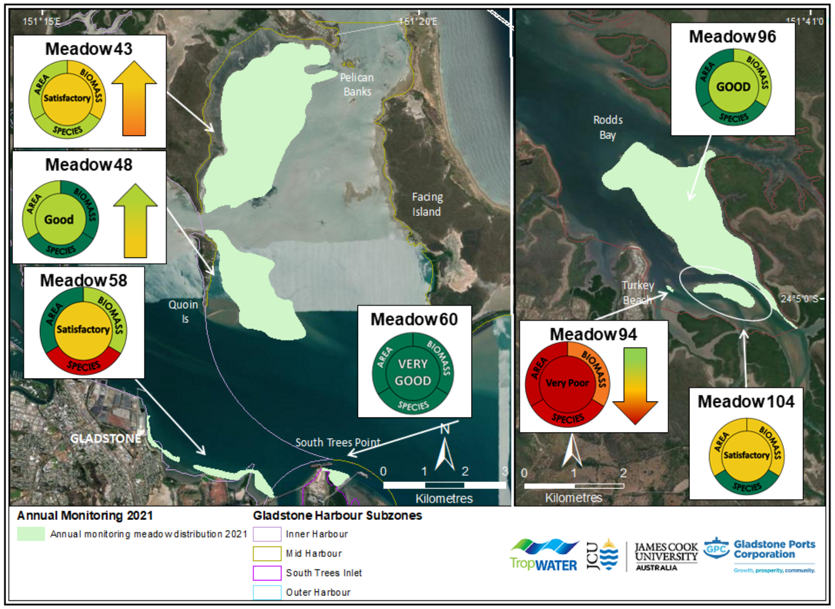

Figure 3. Seagrass distribution and meadow condition in the Inner Harbour, Mid Harbour, and South Trees Inlet Zones (Port Curtis), and Rodds Bay, November 2021. Arrows indicate an overall grade change from 2020.

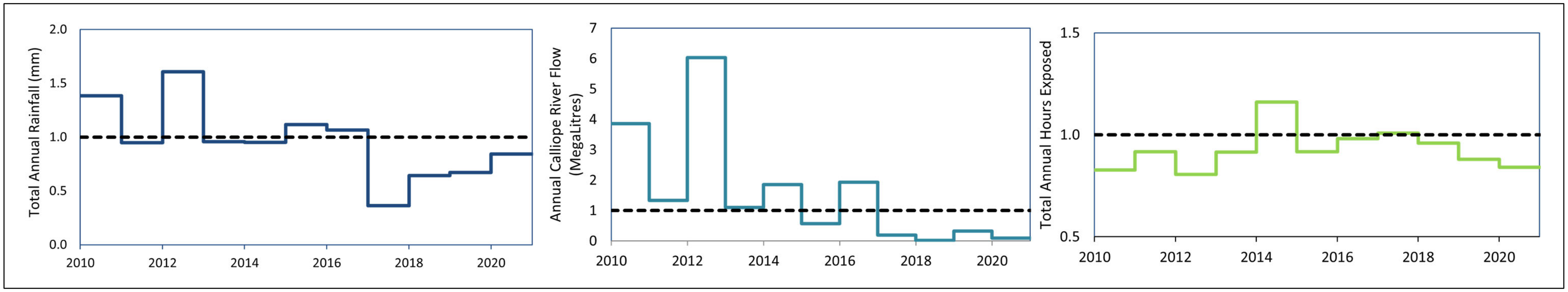

Figure 4. Climate trends in Port Curtis, 2010 to 2021. Change in climate variables as a proportion of the long-term average. See section 3.3 for detailed climate data for the Gladstone region

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ACRONYMS AND ABBREVIATIONS

dbMSL	Depth below Mean Sea Level
DFT	Dugong Feeding Trail
DPA	Dugong Protection Area
DW	Dry Weight
GIS	Geographic Information System
GPC	Gladstone Ports Corporation
GPS	Global Positioning System
IDW	Inverse Distance Weighted
JCU	James Cook University
MSQ	Maritime Safety Queensland
PCIMP	Port Curtis Integrated Management Program
R	Reliability estimator of seagrass meadow area
SE	Standard Error
TropWATER	Centre for Tropical Water & Aquatic Ecosystem Research
WBDDP	Western Basin Dredging and Disposal Project

1 INTRODUCTION

Seagrasses provide a range of critically important and economically valuable ecosystem services including coastal protection, support of fisheries production, nutrient cycling, and particle trapping (Costanza et al. 2014; Hemminga and Duarte 2000). Seagrass meadows show measurable responses to changes in water quality, making them ideal indicators to monitor the health of marine environments (Orth et al. 2006; Abal and Dennison 1996; Dennison et al. 1993).

1.1 Queensland ports seagrass monitoring program

A long-term seagrass monitoring and assessment program was established in the majority of Queensland's commercial ports. The program was developed by the Seagrass Ecology Group at James Cook University's (JCU) Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) in partnership with the various Queensland port authorities. The aim of the program was to achieve a common method and rationale that established a network of seagrass monitoring locations comparable across the State (Figure 5).

A strategic long-term assessment and monitoring program for seagrass provides port managers and regulators with key information for effective management of seagrass habitat. This information is central to planning and implementing port development and maintenance programs to ensure minimal impact on seagrass.

The program provides an ongoing assessment of many of the most vulnerable seagrass communities in Queensland, and feeds into regional assessments of the status of seagrass. The program provides significant advances in the science and knowledge of tropical seagrass ecology. This includes the development of tools, indicators, and thresholds for the protection and management of seagrass, and an understanding of the reasons for seagrass change.

Figure 5. Location of Queensland ports where seagrass monitoring occurs. Red dots: long-term monitoring; blue dots: baseline mapping only.

For more information on the program and reports from other monitoring locations see www.tropwater.com/project/management-of-ports-and-coastal-facilities/

1.2 Port Curtis and Rodds Bay seagrass monitoring program

Diverse and productive seagrass meadows and benthic macro- and mega-fauna flourish in Port Curtis and Rodds Bay (McKenna et al. 2014; Rasheed et al. 2003; Lee Long et al. 1992). Gladstone Ports Corporation (GPC) first commissioned a baseline survey of seagrass resources in Port Curtis, Rodds Bay, and the adjacent offshore area in the Great Barrier Reef Marine Park in 2002 (Rasheed et al. 2003). Over 7000 ha of coastal seagrass was mapped, including an extensive area within the port limits. The majority of Port Curtis and Rodds Bay lies within a Dugong Protection Area (DPA; declared in 1996), an indication of the region's importance as a dugong foraging ground. Port Curtis seagrasses also contribute to the Outstanding Universal Values of the Great Barrier Reef World Heritage Area rated as providing a moderate contribution locally (GPC 2019).

Annual seagrass monitoring commenced in Port Curtis and Rodds Bay in 2004 in response to a whole of port review (SKM 2004) and following recommendations from the Port Curtis Integrated Monitoring Program (PCIMP). Ten meadows representative of the range of seagrass communities within Port Curtis were initially selected for monitoring. These included meadows most likely to be impacted by port activities, intertidal and subtidal meadows, meadows preferred by herbivores such as dugong and turtle, and those likely to support high fisheries productivity. Three monitoring meadows in Rodds Bay were selected as reference sites, i.e. outside port limits, to determine port-related versus regional causes of seagrass change.

The annual monitoring program has been adapted over the years in response to infrastructure developments within the port area including the Western Basin Dredging and Disposal Project (WBDDP). Adaptations and additions included:

1. Survey expansion to include all intertidal and shallow subtidal seagrass in the Port Curtis monitoring area from 2009-2018.
2. Two monitoring meadows (Meadows 21 and 52-57) added to the program in 2009 due to port developments in the Curtis Island area.
3. One meadow (Meadow 9) removed from the monitoring program in 2011 due to the Western Basin reclamation area's expansion at Fisherman's Landing.
4. All seagrass from The Narrows to Rodds Bay periodically remapped, extending into deep water and to offshore Port Curtis limits, in 2002, 2009, 2013, 2014 and 2019 (Smith et al. 2021; Carter et al. 2015a; Bryant et al. 2014b; Thomas et al. 2010).
5. Monitoring of seagrass reproduction and seed banks at Pelican Banks, Rodds Bay and Wiggins Island between 2009 and 2016 (Reason et al. 2017a).

The current program has been developed to meet GPC's obligations pertaining to the Long-Term Maintenance Dredging Management Plan and includes annual mapping and monitoring of 14 coastal seagrass monitoring meadows and five-yearly mapping of all coastal and deep water seagrass in Port Curtis and Rodds Bay. Additional research and monitoring programs have complemented annual monitoring.
These have included:

- Biannual surveys of Port Curtis and Rodds Bay monitoring areas from 2010-2014 (Carter et al. 2015a; Bryant et al. 2014b; Davies et al. 2013; Rasheed et al. 2012; Chartrand et al. 2011; Thomas et al. 2010);
- The establishment of sensitive receptor sites where information on seagrass change was collected monthly to quarterly and linked to water quality monitoring (Bryant et al. 2016; Davies et al. 2015; Bryant et al. 2014a; McCormack et al. 2013);
- Establishment of seagrass light requirements and investigations of sub-lethal indicators of seagrass stress (Schliep et al. 2015; Chartrand et al. 2012; 2016).
- Assessing the importance of herbivores including turtles and dugongs in structuring seagrass meadows (Scott et al. 2021a, 2021b).

Annual monitoring and the additional programs have demonstrated inter- and intra-annual variability in seagrass meadow biomass, area and species composition in the region. Seagrass condition varies according to regional and local climate and weather conditions (Chartrand et al. 2009). Climate induced inter-annual variability is common throughout tropical seagrass meadows of the Indo-Pacific (Agawin et al. 2001). Seagrasses are also highly seasonal. Gladstone seagrass has two broad seasons; the growing season (July – January) when meadows typically increase in biomass and area in response to favourable conditions for growth; and the senescent season (February – June) when meadows typically retract and rely on carbohydrate stores or seeds to persist following wet season conditions such as flooding, poor water quality and light reductions (Chartrand et al. 2016). Annual monitoring is scheduled to coincide with the growing season when seagrass meadows are generally at their peak.

High rainfall, river outflow and tropical cyclones from the 2009/2010 and 2010/2011 La Niña led to significant seagrass losses in Port Curtis and Rodds Bay and more broadly across North East Queensland (Chartrand et al. 2019; McKenna et al. 2015; Rasheed et al. 2014). In extreme cases, such as in Rodds Bay, meadows were temporally lost (Rasheed et al. 2012; Carter et al. 2015a). Recovery has been slow in many regions and many meadows in Port Curtis and Rodds Bay were in poor or very poor condition from 2011-2014 (Chartrand et al. 2019). Favourable climate conditions such as low rainfall and river outflow saw an improvement in meadow condition over the last 3-5 years culminating in most meadows returning to near or above long-term average for condition indicators since 2019 (Smith et al. 2021). In this report we update seagrass condition for the 14 established monitoring meadows in 2021.

2 METHODS

2.1 Field surveys

Survey and monitoring methods followed the established techniques for TropWATER's Queensland-wide seagrass monitoring programs. Detailed methods used in Gladstone are in previous reports (Rasheed et al. 2005; Rasheed et al. 2003). Seagrass was surveyed 3rd – 15th November 2021 during the peak seagrass growth period. Standardising surveys to every October-December allows for appropriate comparisons of seagrass condition among years. This survey involved mapping and assessing the 14 long-term monitoring meadows within Port Curtis and Rodds Bay.

Intertidal meadows were surveyed at low tide using a helicopter. GPS was used to map the position of meadow boundaries and sites were scattered haphazardly within each meadow. Sites were surveyed as the helicopter hovered within one metre above the substrate (Figure 6a). Shallow subtidal meadows were sampled by boat using camera drops and a Van Veen grab (16.5 cm x 17.5 cm, depth 8 cm, Figure 6b, c). Subtidal sites were positioned at ~50 - 500 m intervals running perpendicular from the shoreline, or where major changes in bottom topography occurred, and extended offshore beyond the edge of each meadow. The appropriate number of sites required to detect seagrass change for each monitoring meadow was informed by power analysis (Rasheed et al. 2003). Where underwater visibility was poor additional sites using the van Veen grab were used to assist in determining the presence of seagrass for mapping meadow boundaries. The details recorded at each site are listed in Section 2.3.

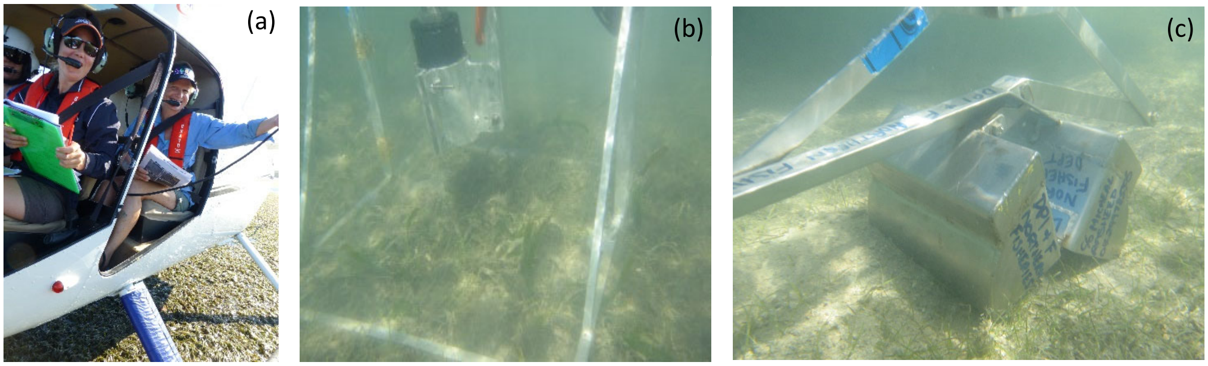


Figure 6. Seagrass monitoring methods in 2021. (a) helicopter survey of intertidal seagrass, (b, c) boat-based camera drops and van Veen grab for subtidal seagrass.

2.2 Seagrass biomass

Seagrass above-ground biomass was determined using a "visual estimates of biomass" technique (Mellors 1991; Kirkman 1978). At each coastal site a 0.25 m^2 quadrat was placed haphazardly three times. An observer assigned a biomass rank to each quadrat while referencing a series of quadrat photographs of similar seagrass habitats where the above-ground biomass had previously been measured. Two separate ranges were used - low biomass and high biomass. The percentage contribution of each species to each quadrat's biomass also was recorded.

At the survey's completion, the observer ranked a series of calibration quadrat photographs representative of the range of seagrass biomass and species composition observed during the survey. These calibration quadrats had previously been harvested and the above-ground biomass weighed in the laboratory. A separate regression of ranks and biomass from the calibration quadrats was generated for each observer and applied to the biomass ranks recorded in the field. Field biomass ranks were converted into above-ground biomass estimates in grams dry weight per square metre (g DW m^{-2}) for each of the replicate quadrats at a site. Site biomass, and the biomass of each species, is the mean of the replicates.

2.3 Geographic Information System

All survey data were entered into a Geographic Information System (GIS) using ArcGIS 10.8®. Three GIS layers were created to describe seagrass in the survey area: a site layer, biomass interpolation layer and meadow layer.

2.3.1 Site layer

The site (point) layer contains data collected at each site, including:

- Site number.
- Temporal details – Survey date and time.
- Spatial details – Latitude, longitude, depth below mean sea level (metres) for subtidal sites.
- Habitat information – Sediment type; seagrass information including presence/absence, above-ground biomass (total and for each species) and biomass standard error (SE); site benthic cover (percent cover of algae, seagrass, benthic macro-invertebrates, open substrate); dugong feeding trail presence/absence.
- Sampling method and any relevant comments.

2.3.2 Interpolation layer

The interpolation (raster) 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.

2.3.3 Meadow layer

The meadow (polygon) layer provides summary information for all sites within each meadow, including:

- Meadow ID number – A unique number assigned to each meadow to allow comparisons among surveys.
- Temporal details – Survey date.
- Habitat information – Mean meadow biomass ± (SE), meadow area (hectares) ± reliability estimate (R) (Table 1), number of sites within the meadow, seagrass species present, meadow density and community type (Tables 2, 3), meadow landscape category (Figure 7).
- Sampling method and any relevant comments.

Meadow boundaries were constructed using GPS marked meadow boundaries where possible, seagrass presence/absence site data, field notes, colour satellite imagery of the survey region (Source: ESRI), and aerial photographs taken during helicopter surveys. Meadow area was determined using the calculate geometry function in ArcGIS® 10.8. Meadows were assigned a mapping precision estimate (in metres) based on mapping methods used for that meadow (Table 1). Mapping precision ranged from <5 m for intertidal seagrass meadows with boundaries mapped by helicopter to ±50 m for subtidal meadows with 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 developed for Queensland's seagrass meadows. Seagrass community type was determined using the dominant and other species' percent contribution to mean meadow biomass (for all sites within a meadow) (Table 2). Community density was based on mean biomass of the dominant species within the meadow (Table 3).

Table 1. Methods used to determine mapping precision estimates for each seagrass meadow.

Mapping precision	Mapping method
<5 m	Meadow boundaries mapped by GPS from helicopter, Intertidal meadows completely exposed or visible at low tide, Relatively high density of mapping and survey sites, Recent aerial photography aided in mapping.
10-20 m	Meadow boundaries determined from helicopter and boat surveys, Intertidal boundaries interpreted from helicopter mapping and survey sites, Recent aerial photography aided in mapping, Subtidal boundaries interpreted from survey sites, Moderately high density of mapping and survey sites.
20-50 m	Meadow boundaries determined from helicopter and boat surveys, Intertidal boundaries interpreted from helicopter mapping and survey sites, Subtidal boundaries interpreted from boat survey sites, Lower density of survey sites for some sections of boundary.
50–200 m	Meadow boundaries determined from boat surveys, Subtidal meadows interpreted from survey sites, Lower density of survey sites for meadow boundary.

Table 2. Nomenclature for seagrass community types in Gladstone.

Community type	Species composition
Species A	Species A is >90-100% of composition
Species A with Species B (2 species present) Species A with mixed species (>2 species)	Species A is >60-90% of composition
Species A/Species B	Species A is 40-60% of composition

Table 3. Seagrass meadow density categories based on mean above-ground biomass ranges for the dominant species.

Density	**Mean above-ground biomass (g DW m^{-2})**				
	Halodule uninervis (thin)	*Halophila ovalis; Halophila decipiens*	*Halodule uninervis* (wide)	*Halophila spinulosa*	*Zostera muelleri*
Light	<1	<1	<5	<15	<20
Moderate	1-4	1-5	5-25	15-35	20–60
Dense	>4	>5	>25	>35	>60

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

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

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

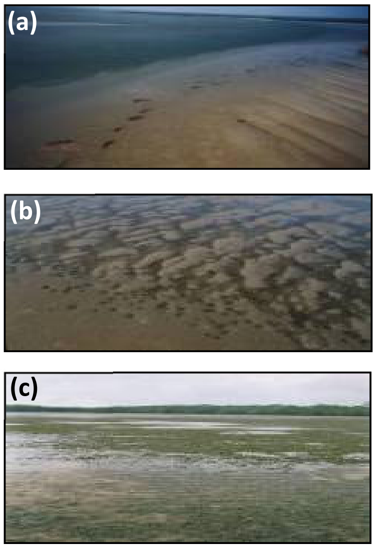


Figure 7. Seagrass meadow landscape categories: (a) Isolated seagrass patches, (b) aggregated seagrass patches, (c) continuous seagrass cover.

2.4 Environmental data

Environmental data were collated for the 12 months preceding each of the monitoring surveys. Tidal data was provided by Maritime Safety Queensland (© The State of Queensland (Department of Transport and Main Roads) 2020/21, Tidal Data) for Gladstone at Auckland Point (MSQ station #052027A; www.msq.qld.gov.au). Total daily rainfall (mm) was obtained for the nearest weather station from the Australian Bureau of Meteorology (Gladstone Radar station #039123; http://www.bom.gov.au/climate/data/). Calliope River water flow data (total monthly megalitres) was obtained from the Department of Regional Development, Manufacturing and Water (station #132001A; https://water-monitoring.information.qld.gov.au/).

2.5 Seagrass condition index

A condition index was developed for seagrass monitoring meadows based on changes in mean above-ground biomass, total meadow area and species composition relative to a 10 year baseline. Seagrass condition for each indicator in each meadow was scored from 0 to 1 and assigned one of five grades: A (very good), B (good), C (satisfactory), D (poor) and E (very poor). Overall meadow condition is the lowest indicator score where this is biomass or area. Where species composition is the lowest score, it contributes 50% of the overall meadow score, and the next lowest indicator (area or biomass) contributes the remaining 50%. The flow chart in Figure 8 summarises the methods used to calculate seagrass condition. See Appendix 1 and 2 for full details of score calculation.

Figure 8. Flow chart used to determine monitoring meadow condition.

3 RESULTS

3.1 Seagrass presence and species in Port Curtis and Rodds Bay

A total of 791 coastal sites were assessed across the 14 seagrass monitoring meadows in 2021 (Figure 9). Five seagrass species from three families were observed during the survey (Figure 10). Total seagrass area was 2,565 ± 86 ha across the 14 monitoring meadows in Port Curtis and Rodds Bay. In the Western Basin, seagrass covered 1015 ± 43 ha, slightly larger than in 2020 (981 ± 49 ha) but Rodds Bay seagrass area was 382 ± 8 ha, lower than in 2020 (433 ± 18 ha). Dugong feeding trails were observed at meadows in the Western Basin and Mid Harbour zones.

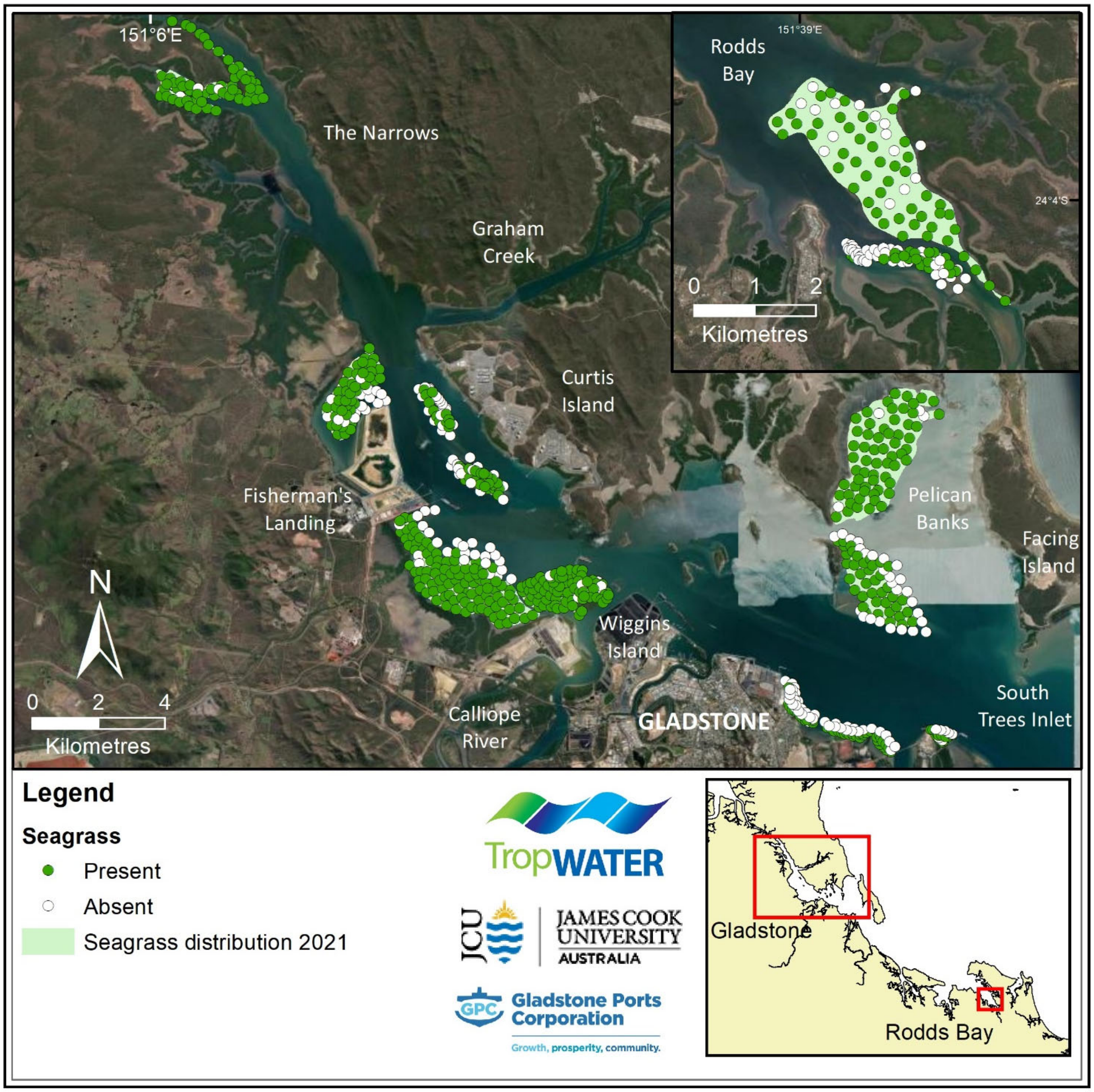
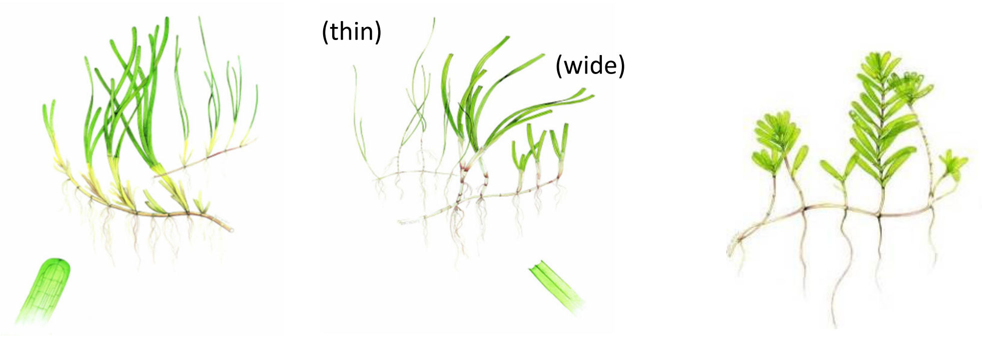


Figure 9. Seagrass presence/absence at seagrass assessment sites within Port Curtis and Rodds Bay in 2021.



Zostera muelleri *Halodule uninervis* *Halophila spinulosa*

Halophila ovalis *Halophila decipiens*

Figure 10. Seagrass species present in Port Curtis and Rodds Bay, 2021.

3.2 Seagrass condition in Port Curtis and Rodds Bay

The overall condition for Port Curtis and Rodds Bay seagrass in 2021 was good for the third consecutive year (Table 4). Individual monitoring meadow condition was predominantly in good or very good condition. There was a general increase in meadow biomass and species composition that resulted in improved condition scores at six meadows. Meadows that improved included the Pelican Banks meadow that was satisfactory after being in poor condition for the previous six years. There were two meadows that showed declines in 2021. At meadow 58 a change from persistent *Z. muelleri* to less stable species caused a decline in condition from satisfactory to poor. At Rodds Bay there was a large decline in all three condition metrics at meadow 94 causing the condition to be very poor.

Port Curtis and Rodds Bay has been partitioned into zones (see Figure 1) for the purposes of assessing water quality and for developing a regional report card (GHHP, 2021). We present the results for the 2021 seagrass monitoring for monitoring meadows in each of the zones.

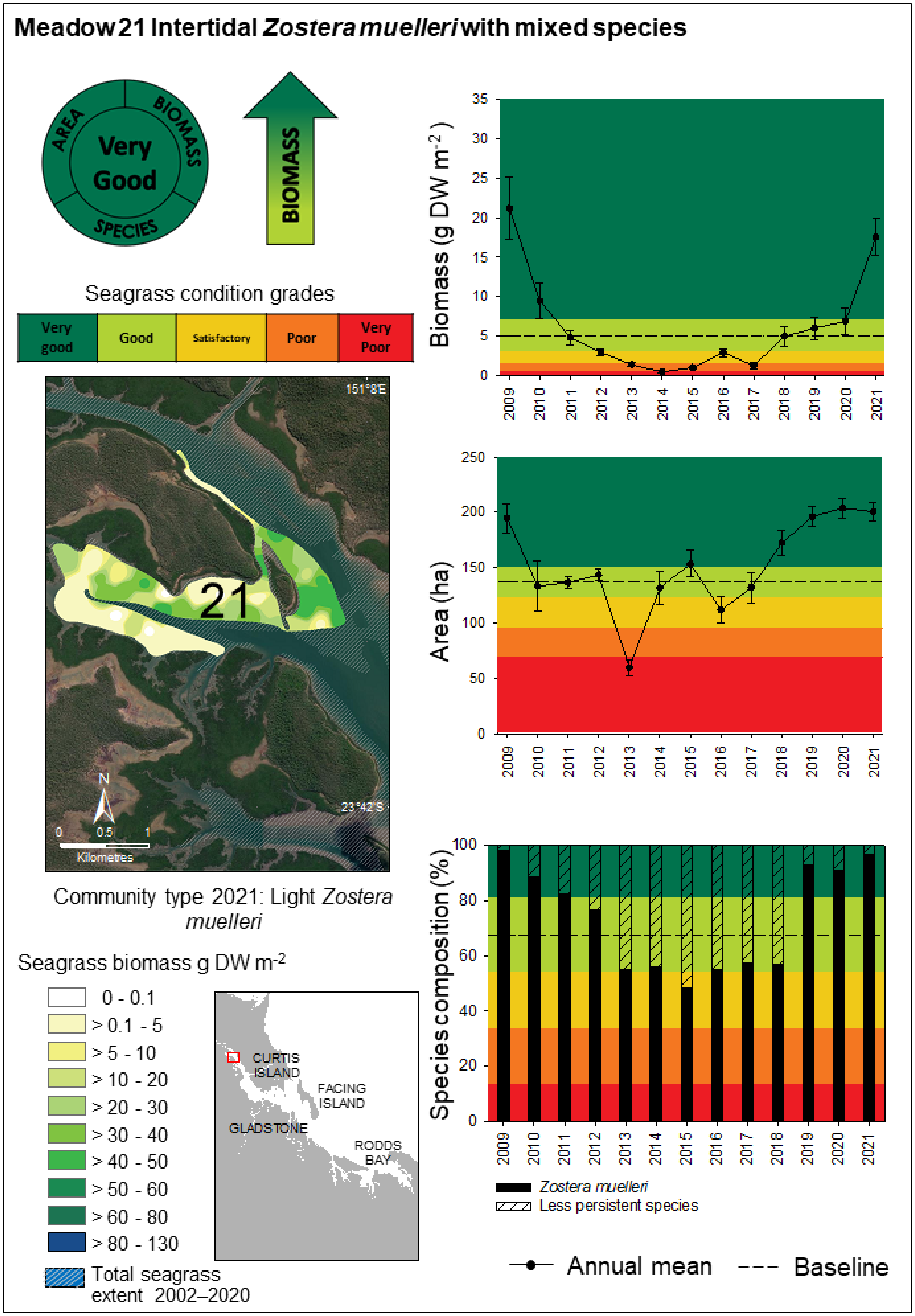
Table 4. Grades and scores for seagrass indicators (biomass, area and species composition) for Port Curtis and Rodds Bay seagrass monitoring meadows, 2021. 🟩 = very good condition, 🟩 = good condition, 🟨 = satisfactory condition, 🟧 = poor condition, 🟥 = very poor.

Monitoring meadow	Biomass score	Area score	Species composition score	Overall meadow score
4	1.00	1.00	0.93	0.97
5	0.93	1.00	0.86	0.89
6	0.89	0.93	0.74	0.82
7	0.61	0.77	1.00	0.61
8	0.92	0.73	0.77	0.73
21	0.94	0.98	0.98	0.94
43	0.54	0.81	0.78	0.54
48	0.85	0.80	0.89	0.80
52-57*	0.87	0.99	1.00	0.87
58	0.77	0.89	0.00	0.39
60	1.00	1.00	0.99	0.99
94	0.38	0.17	0.00	0.09
96	0.65	1.00	1.00	0.65
104	0.53	0.57	0.88	0.53
Overall score for Gladstone seagrass monitoring meadows				**0.70**

*Meadow 52-57 consists of several small meadows surrounding the Passage Islands that are grouped for reporting purposes (Figure 1).

3.2.1 The Narrows long-term monitoring meadows

The sole long-term monitoring meadow in The Narrows at Black Swan Island was in very good condition for the first time since 2009 (Meadow 21; Figure 11 & 12). Mean biomass was 17.52 ± 2.32 g DW m^{-2} in 2021, the highest meadow biomass since 2009 and more than twice as high as in 2020. Seagrass meadow area has been consistent over the last three years covering 200.45 ± 8.33 ha in 2021 and was in very good condition for the fourth consecutive year. Species composition remained in very good condition in 2021 and was dominated by *Z. muelleri* (Figure 12; Appendix 4).



Meadow 21 Intertidal *Zostera muelleri* with mixed species

Figure 11. Changes in meadow area, biomass and species composition for at Meadow 21, Black Swan (The Narrows Zone), 2009–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.2.2 Western Basin long-term monitoring meadows

There are six long-term monitoring meadows in the Western Basin Zone; five intertidal seagrass meadows and one subtidal meadow (Figures 1-3). All seagrass meadows in this zone were in satisfactory or better condition in 2021.

Meadow 4:

Meadow 4 at Wiggins Island was in very good condition for the third consecutive year (Figure 12). Meadow area increased for the eighth consecutive year to 44.80 ± 1.9 ha and is now the highest since monitoring began in 2002. Meadow biomass continues to be in very good condition for the tenth year in a row. The proportion of persistent *Z. muelleri* has been above the long-term average and in very good condition for three consecutive years now (Figure 12; Appendix 3).

Meadow 5:

The intertidal *Z. muelleri* meadow west of Wiggins Island was in very good condition in 2021 improving from good in 2020 (Figure 13). All three seagrass metrics increased in 2021 from 2020 (Figure 13). The proportion of persistent *Z. muelleri* in the meadow increased to be very good for only the second time since 2009 and meadow are returned to very good after a slight decrease in 2020 (Figure 13; Appendix 4).

Meadow 6:

Meadow 6 at South Fisherman's Landing is the largest meadow in the Western Basin covering 247.23 ± 6.11 ha. Overall meadow condition was good with biomass and area recording similar values to 2020 and recording very good scores. The proportion of persistent *Z. muelleri* increased to 45% and was in good condition for only the second time since 2016 (Figure 14; Appendix 4).

Meadow 7:

Meadow 7, the only subtidal monitoring meadow in the Western Basin was in satisfactory condition for the second year in a row (Figure 15). This meadow has been highly variable in both biomass and area over the years, a typical trend of subtidal *Halophila* meadows. Seagrass area and biomass have been steady for the past three years and meadow area increased slightly to 77.23 ± 23.37 ha, just above the long-term average for only the third time since 2008 (Figure 15; Appendix 3 & 4). There was an improvement in species composition to very good as only *H. decipiens* was recorded.

Meadow 8:

The intertidal meadow 8 at North Fisherman's Landing was in satisfactory condition in 2021. Biomass was in very good condition (2.97 ± 0.62 g DW m^{-2}) and was the third highest recorded in this meadow since monitoring began in 2002. Meadow area was in good condition for the third consecutive year (211.96 ± 3.55 ha) (Figure 16). Species composition improved to good and the proportion of *Z. muelleri* in the meadow was above the long-term average for the first time since 2010 (Figure 16).

Meadows 52-57:

The Passage Island meadows; meadows 52-57, are a group of predominantly intertidal meadows surrounding the Passage Islands. In 2021 overall meadow condition improved from good to very good (Figure 17). Biomass increased to 1.86 ± 0.42 g DW m^{-2} in 2021 and was in very good condition after being good for the previous two years. Meadow area and species composition were very similar to 2020 and were in very good and good condition respectively.

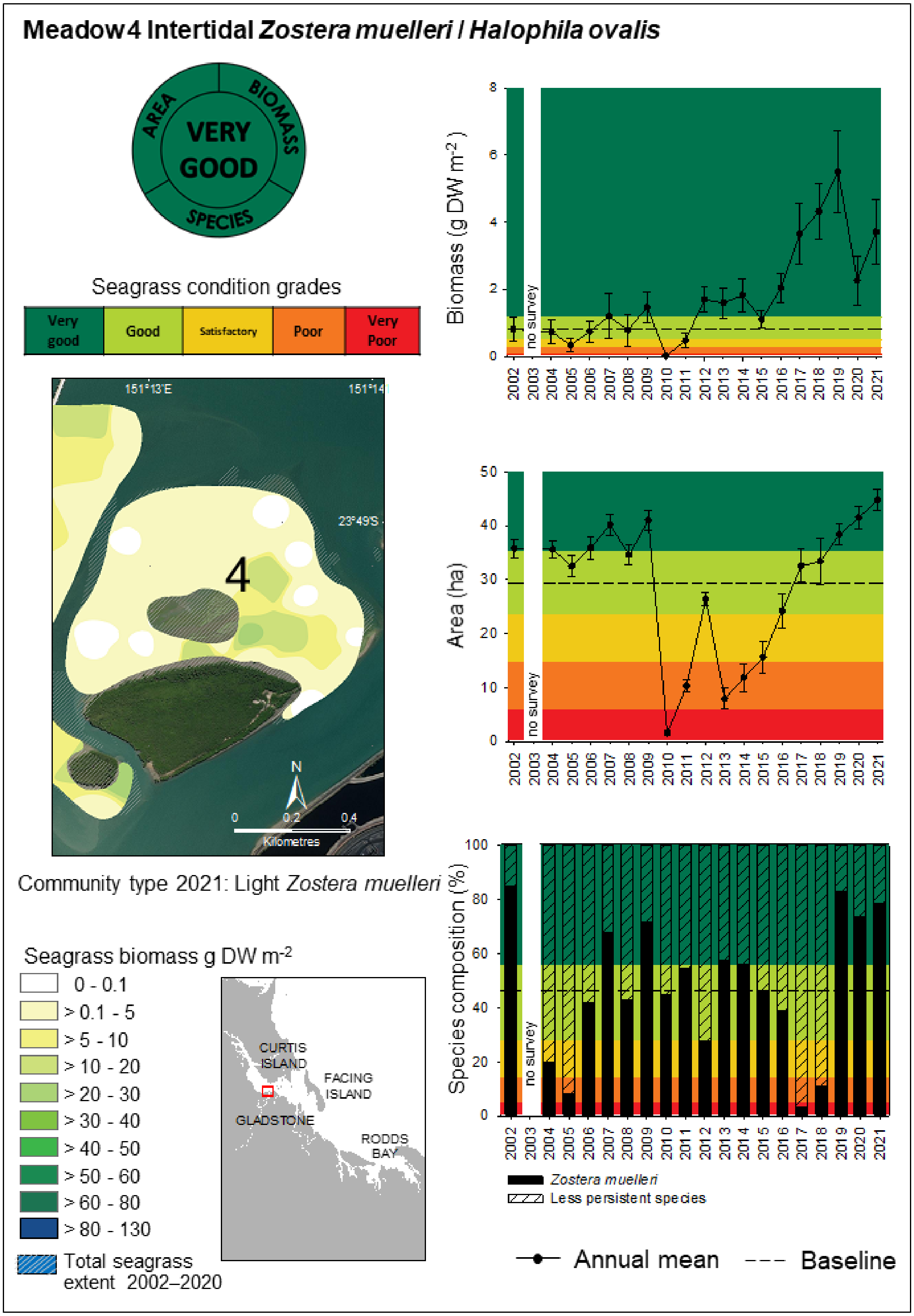


Figure 12. Changes in meadow area, biomass and species composition for Meadow 4, Wiggins Island (Western Basin Zone), 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

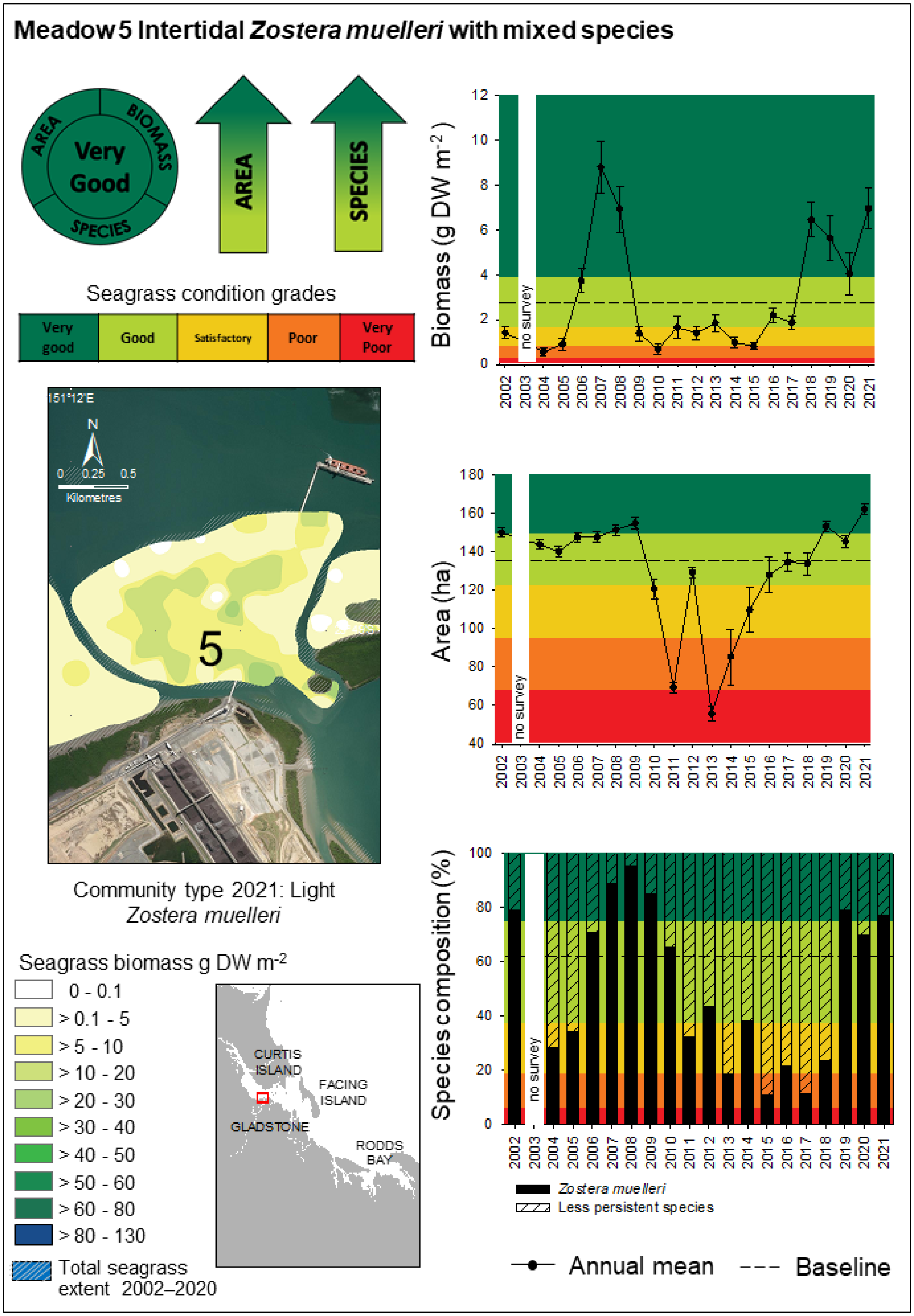


Figure 13. Changes in meadow area, biomass and species composition for Meadow 5, Wiggins Island (Western Basin Zone), 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

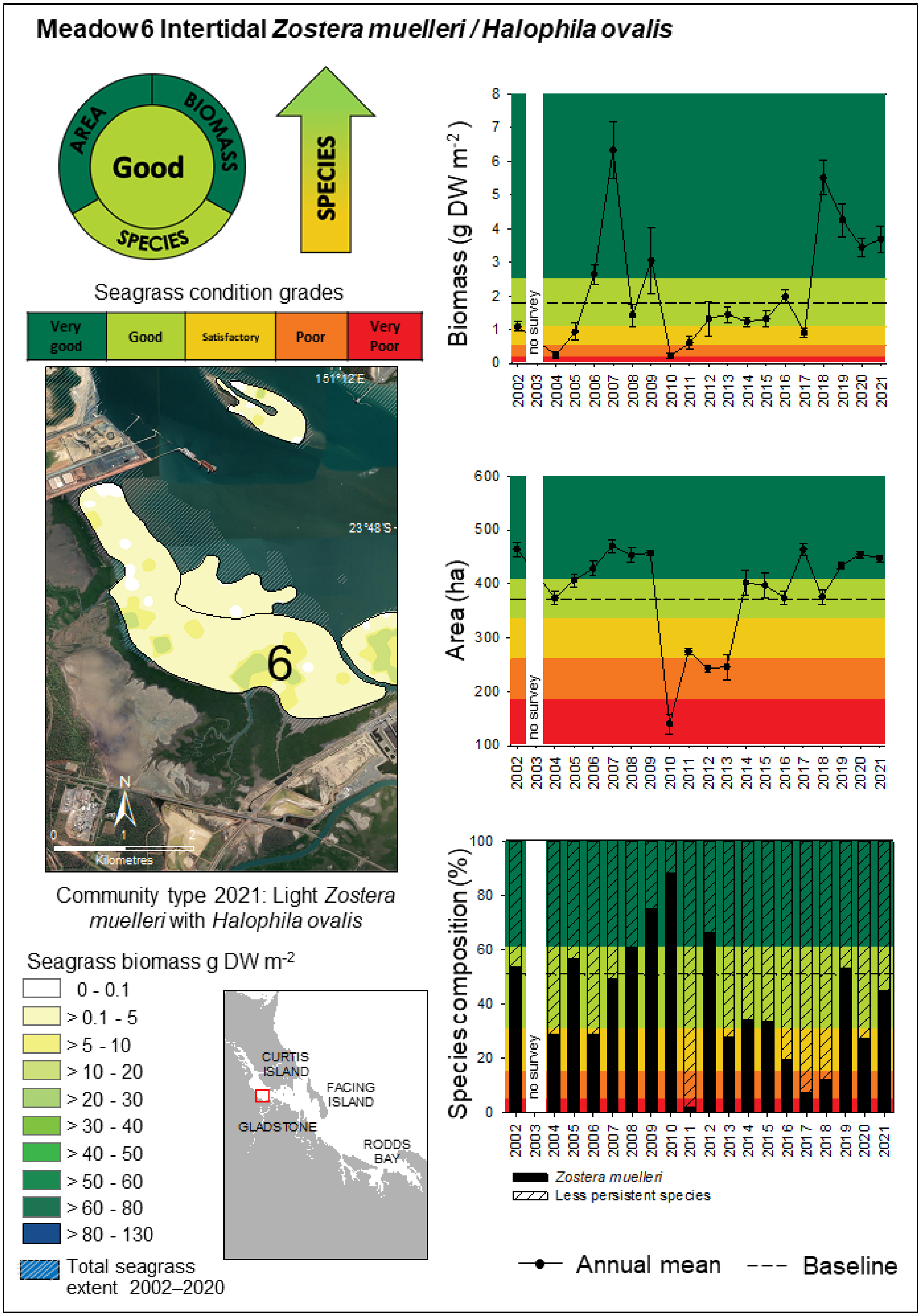


Figure 14. Changes in meadow area, biomass and species composition for Meadow 6, South Fisherman's Landing (Western Basin Zone), 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

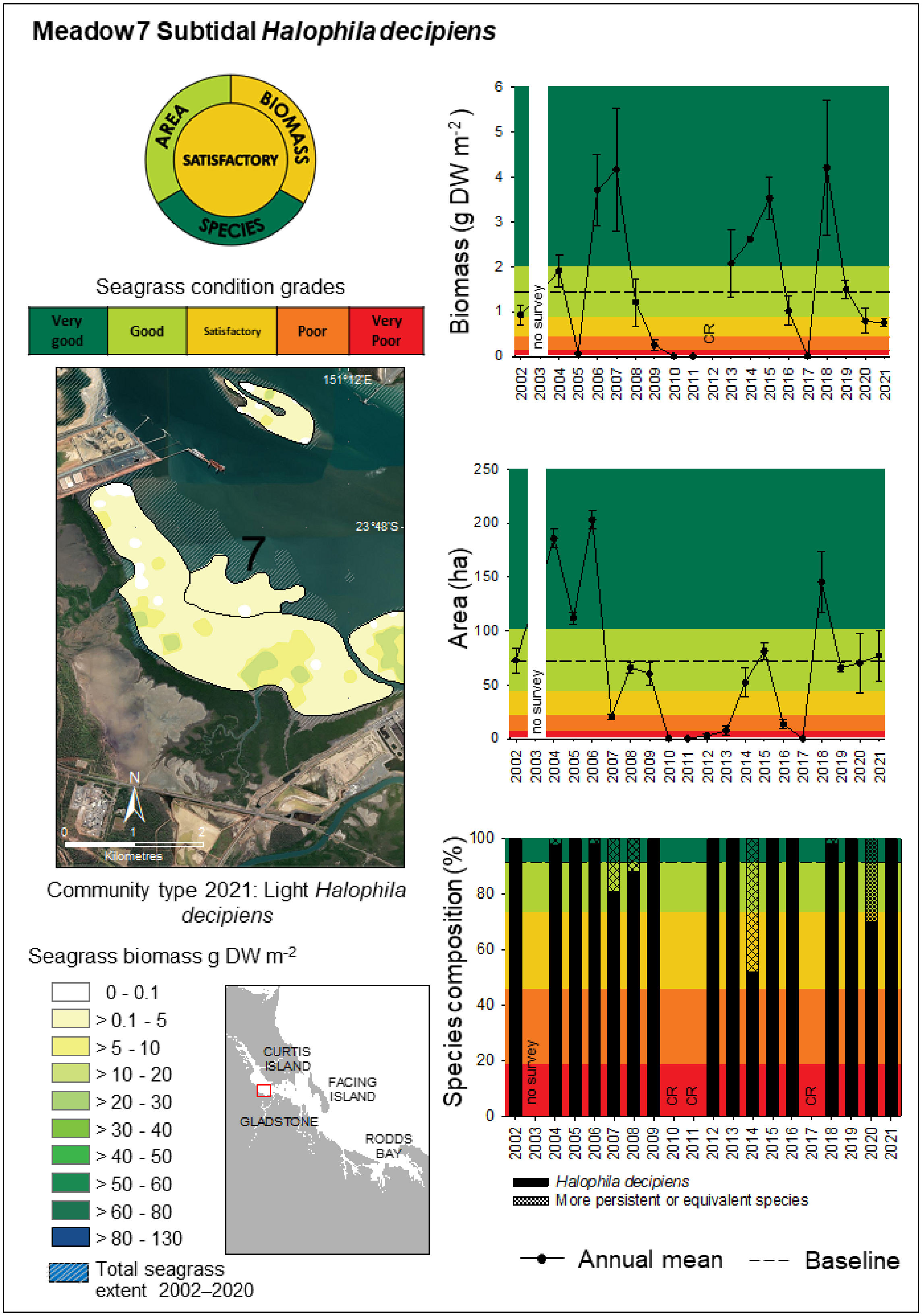


Figure 15. Changes in meadow area, biomass and species composition for Meadow 7, South Fisherman's Landing (Western Basin Zone), 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

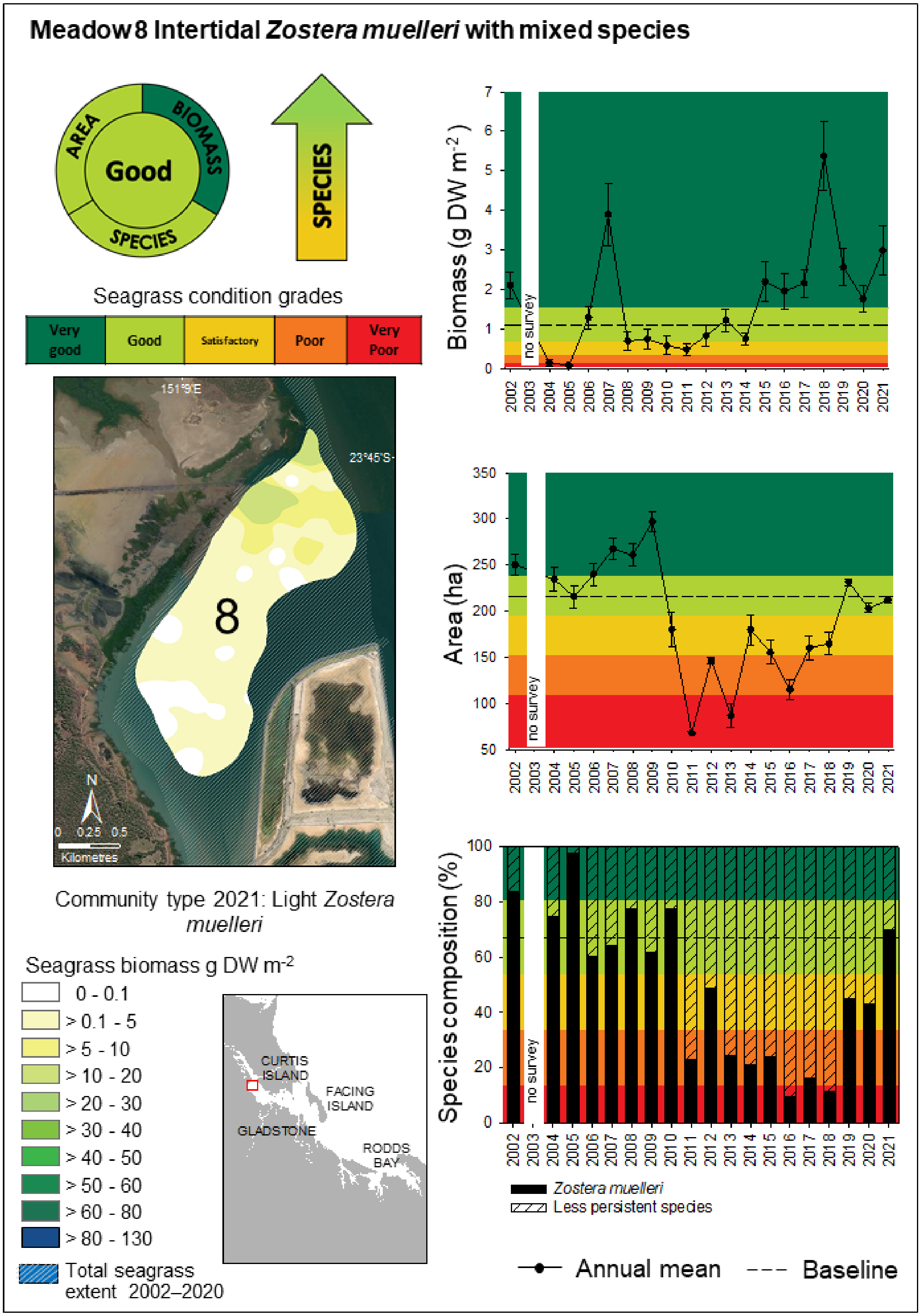


Figure 16. Changes in meadow area, biomass and species composition for Meadow 8, North Fisherman's Landing (Western Basin Zone), 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

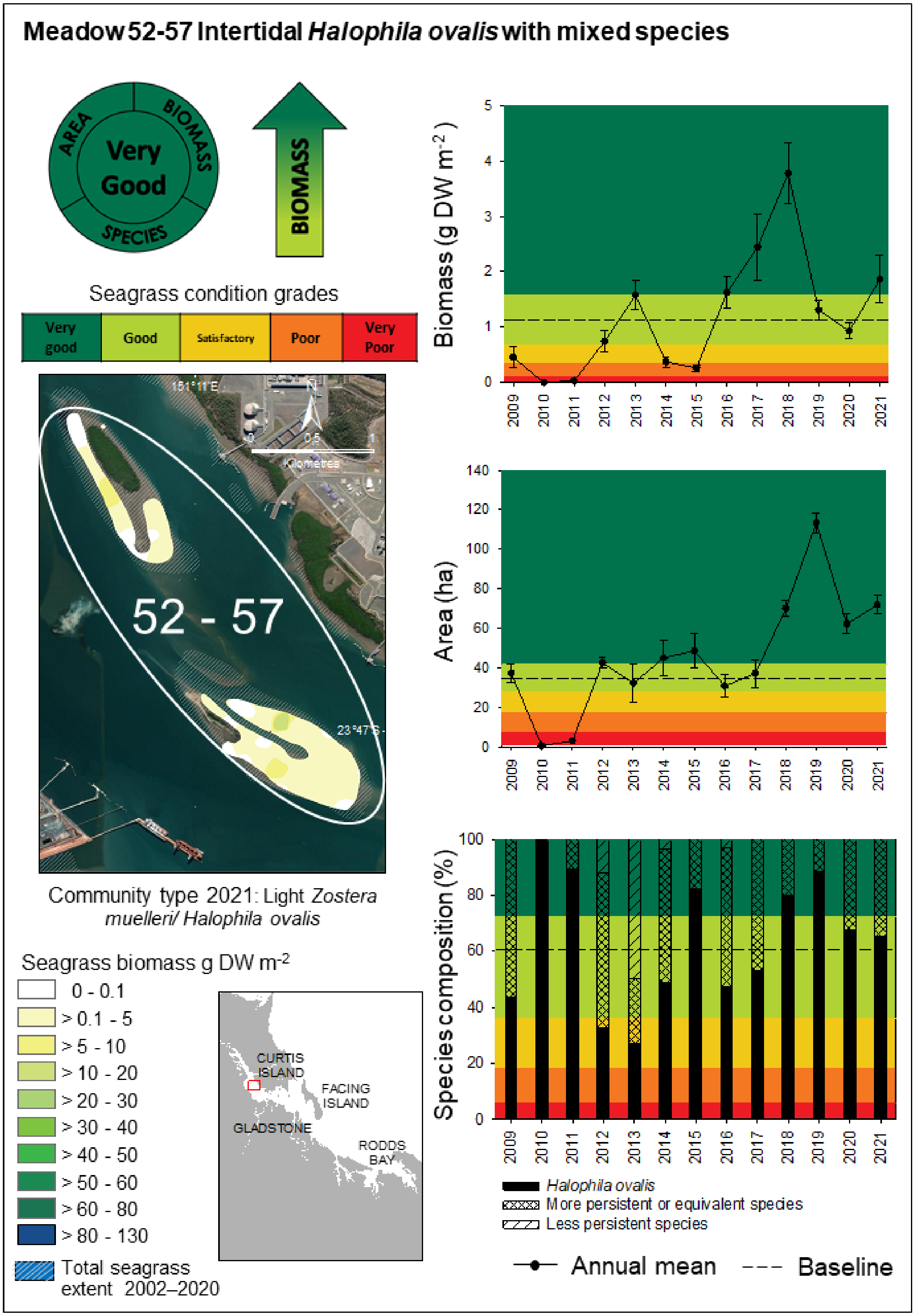


Figure 17. Changes in meadow area, biomass and species composition for Meadows 52-57, Passage Islands (Western Basin Zone), 2009–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.2.3 Inner Harbour long-term monitoring meadows

There is a single monitoring meadow at the Inner Harbour that stretches along the intertidal bank west from the mouth of the Calliope River (Meadow 58; Figure 18).

Meadow 58

Seagrass meadow condition was poor in 2021 after it was satisfactory in 2020. This is the first time it has been poor since 2016. The decline is due to changes in the meadow species composition with no persistent *Z. muelleri* recorded in the meadow in 2021 (Figure 23). Historically species composition within meadow 58 fluctuates and has been very poor over the past five years. Seagrass area remained in very good condition for the third consecutive year and biomass (2.24 ± 0.24 g DW m^{-2}) was above the long-term average for the first time since 2009 (Figure 23; Appendix 4).

3.2.4 Mid Harbour long-term monitoring meadows

There are two monitoring meadows in the Mid Harbour Zone, a large intertidal meadow on Pelican Banks (Meadow 43; Figure 19), and a subtidal meadow along the eastern side of Quoin Island (Meadow 48; Figure 20).

Meadow 43:

Meadow 43 is recognised as the largest, most productive, and most stable seagrass meadow in Port Curtis and Rodds Bay based on a 19 year monitoring dataset. In 2021, the meadow's overall score was satisfactory after 6 years of being in poor or very poor condition (Figure 19). The improvement in meadow score is due to an increase in meadow biomass from 5.51 ± 0.67 g DW m^{-2} in 2020 to 10.74 ± 1.05 g DW m^{-2} in 2021. This is the highest biomass has been in meadow 43 since 2014. Species composition was in good condition for the first time in seven years after a steady decline of *Z. muelleri* since 2014. In 2020, *Z. muelleri* represented 49% of the meadow biomass but in 2021 it has increased to 91% of biomass (Figure 19; Appendix 4). Meadow area was in good condition and covered 646.07 ± 6.67 ha. This is slightly lower than in 2020 when area was in very good condition and covered 667.31 ± 12.97 ha (Figure 19).

Meadow 48:

Meadow 48 is a predominantly subtidal meadow on the eastern side of Quoin Island. Overall meadow condition was good driven by an increase in biomass above baseline levels to very good condition (Figure 20). Meadow biomass was 3.83 ± 0.42 g DW m^{-2} the second highest biomass since 2007. Meadow area was in good condition for the second year in a row and above the ten year base line. Species composition continued to be very good and was dominated by *H. uninervis* (Figure 20).

3.2.5 South Trees Inlet long-term monitoring meadows

Meadow 60, the only monitoring meadow in this zone, is located between the two wharves at South Trees Inlet (Figure 21). The intertidal meadow traditionally comprises of continuous *Z. muelleri*.

Meadow 60

The intertidal meadow was in very good condition for the fifth consecutive year (Figure 21). Meadow biomass, area and species composition were all above baseline levels and considered to be in very good condition. Both meadow area and biomass where the highest recorded since monitoring began. Meadow area was 12.84 ± 0.87 ha and biomass was 18.22 ± 2.28 g DW m^{-2} the highest recorded across all meadows in 2021 (Figure 21). The meadow comprised nearly entirely of the persistent *Z. muelleri* (Figure 21).

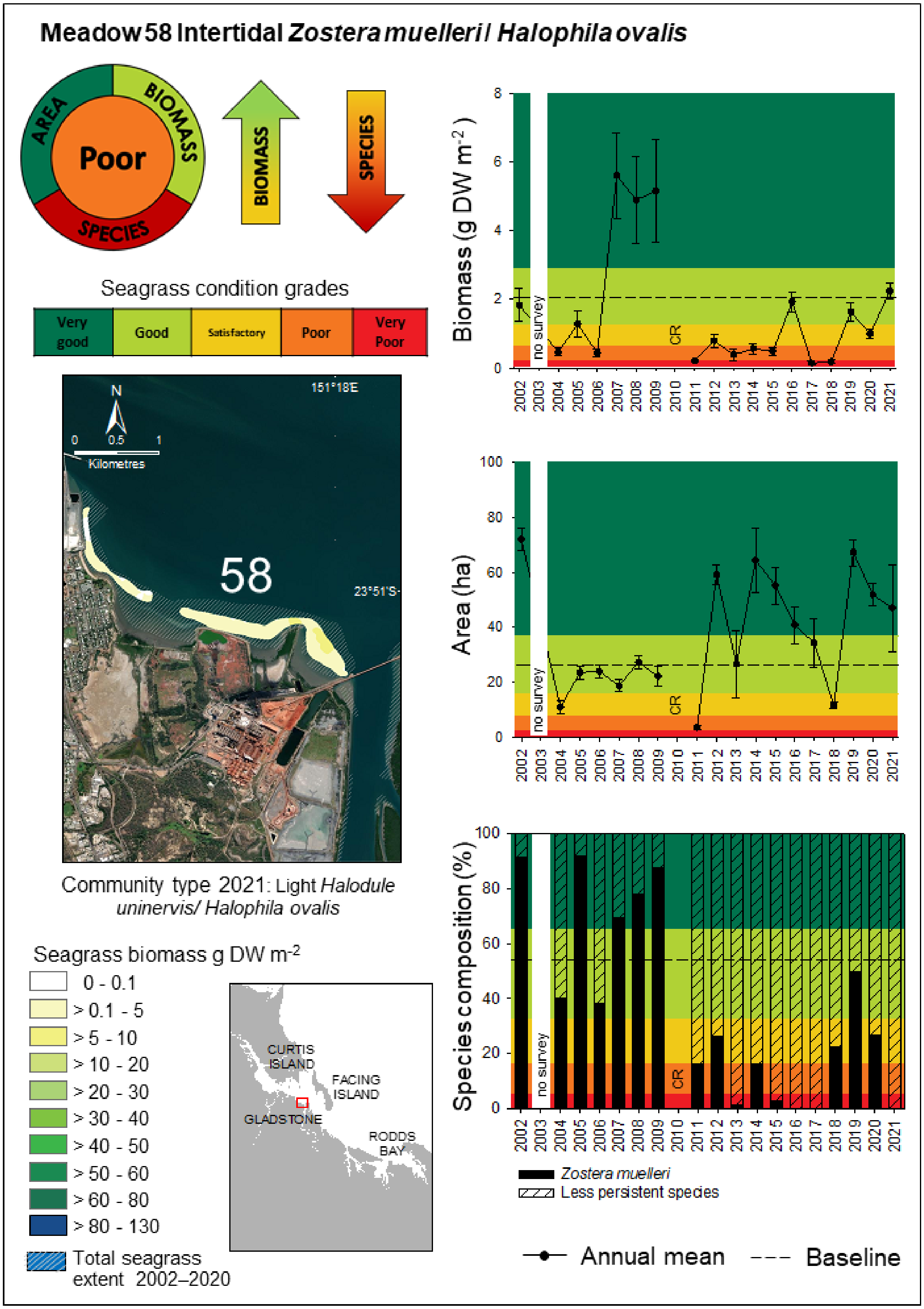


Figure 18. Changes in meadow area, biomass and species composition for Meadow 58, (Inner Harbour Zone), 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate). CR = calculation restriction due to the absence of seagrass.

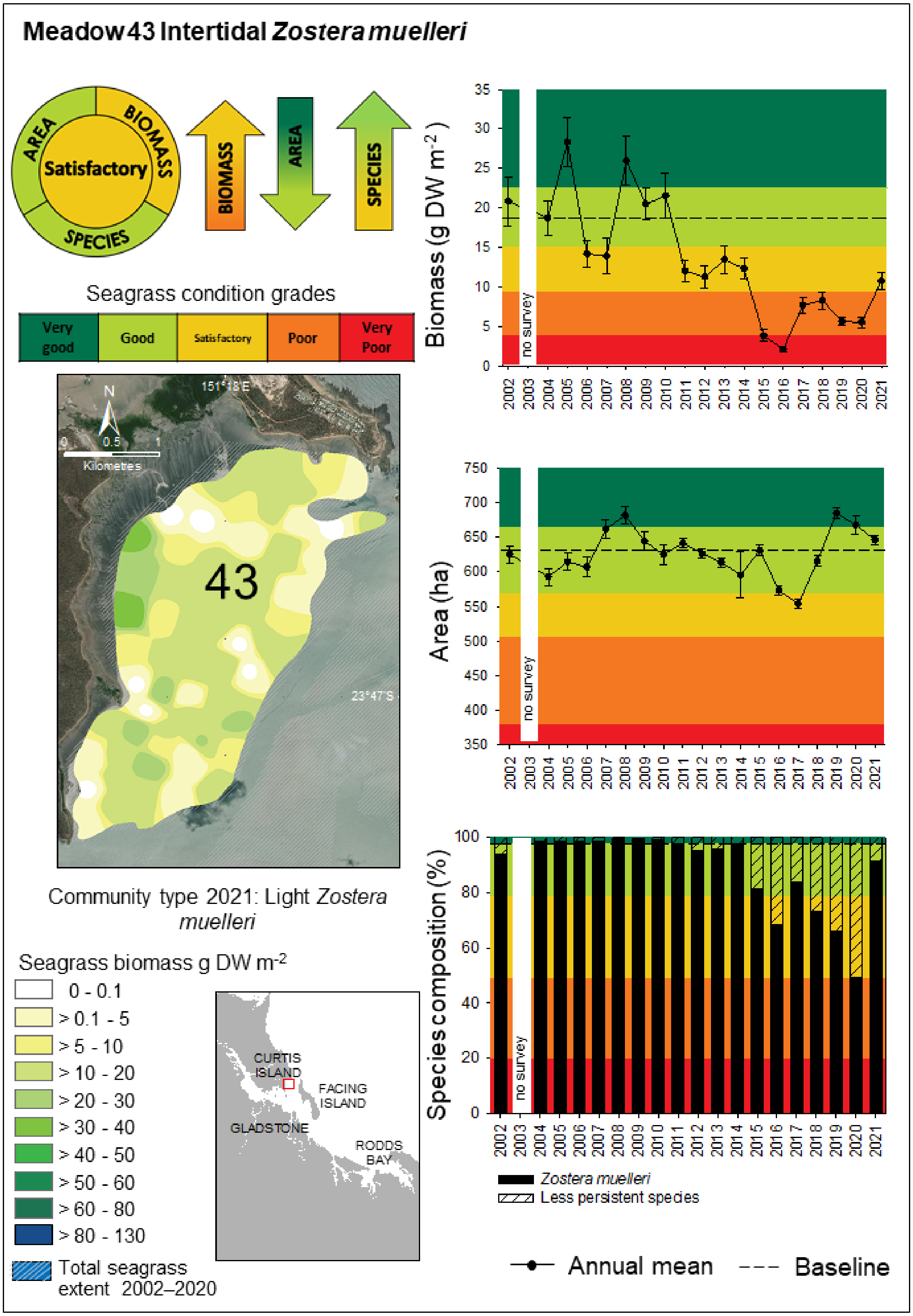


Figure 219. Changes in meadow area, biomass and species composition Meadow 43, Pelican Banks (Mid Harbour Zone), 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

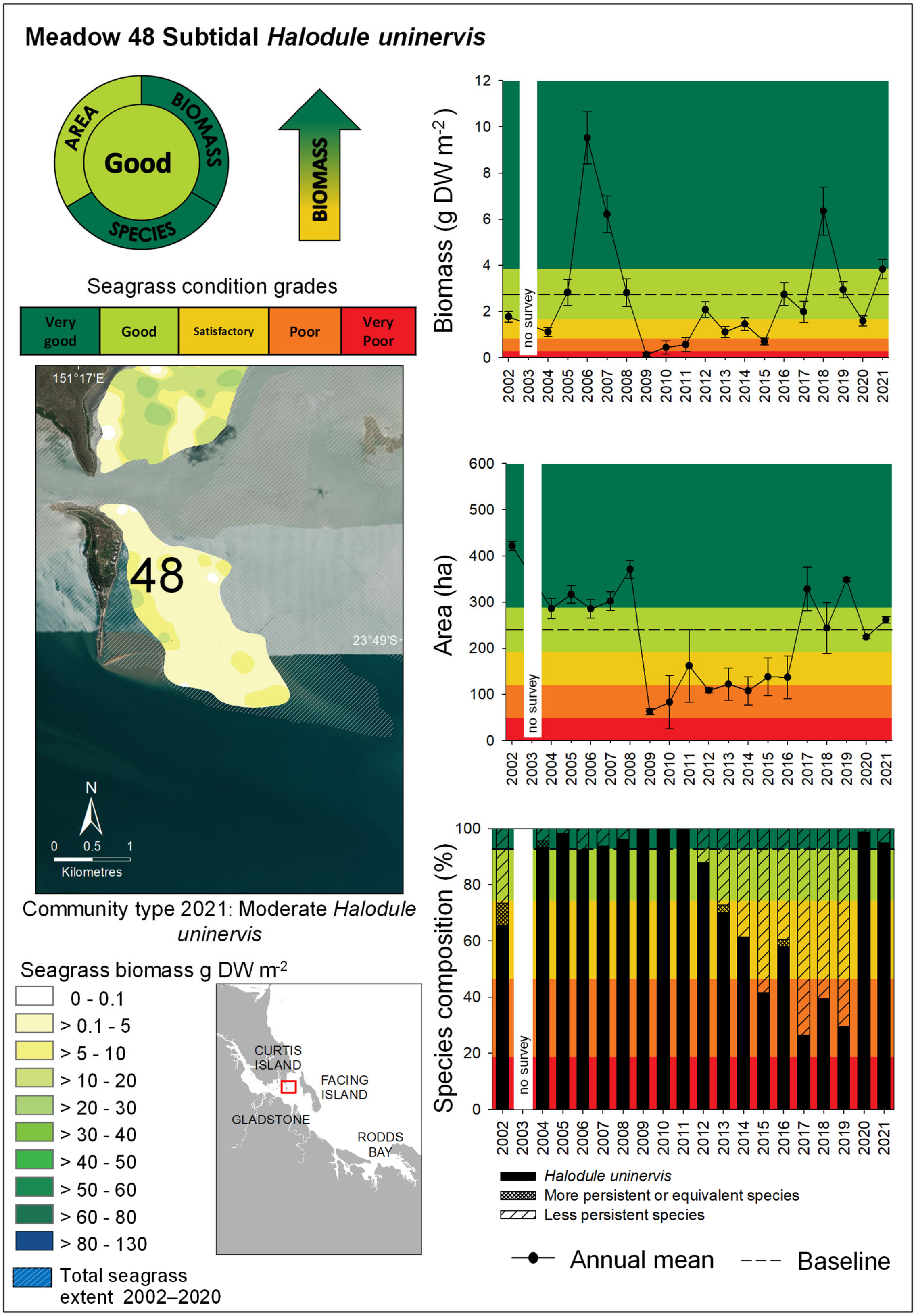


Figure 20. Changes in meadow area, biomass and species composition Meadow 48, Quoin Island (Mid Harbour Zone), 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

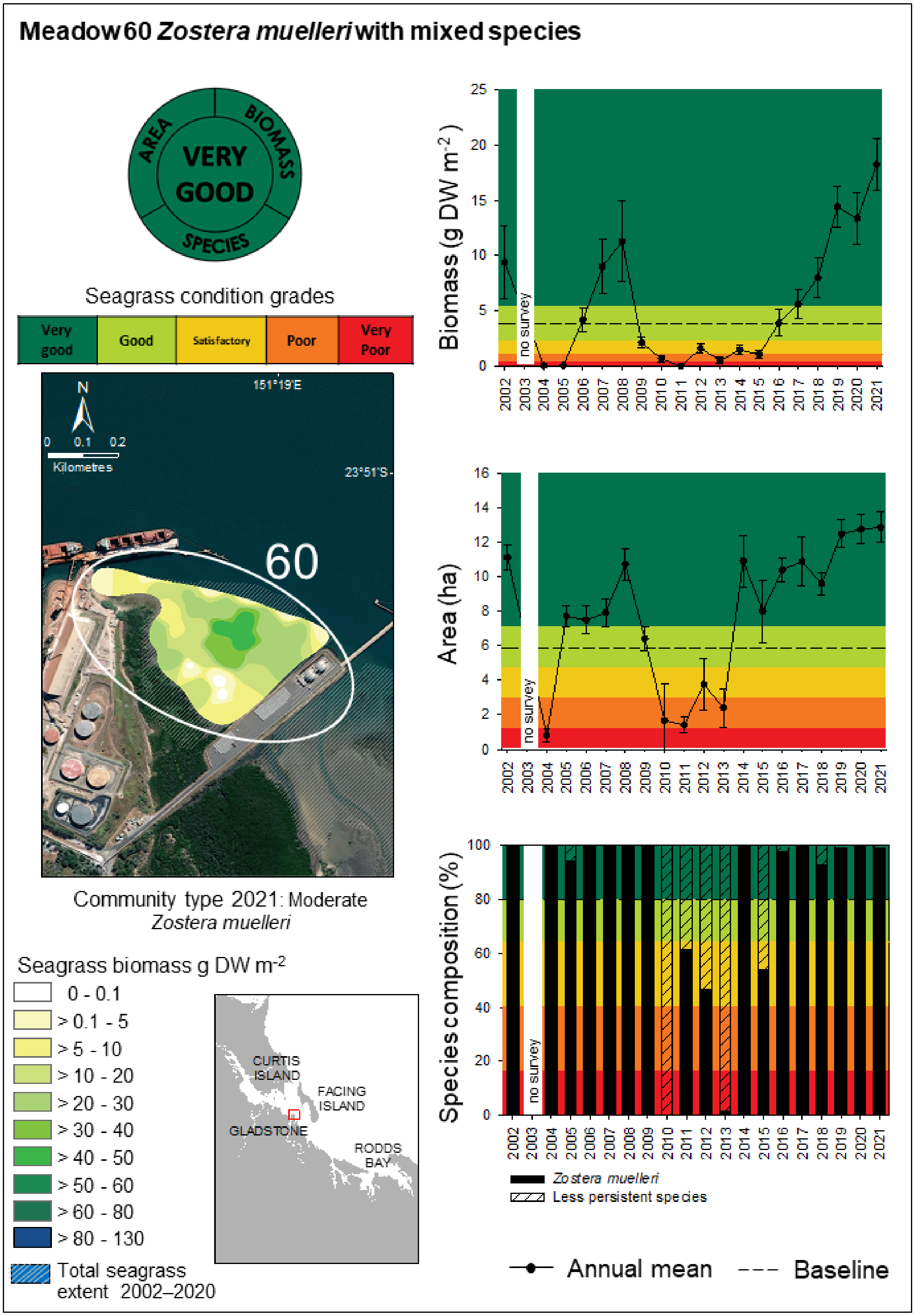


Figure 21. Changes in meadow area, biomass and species composition for Meadow 60, South Trees Inlet Zone, 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.2.6 Rodds Bay long-term monitoring meadows

Monitoring seagrass in Rodds Bay provides an opportunity to measure seagrass health in an area that is not exposed to port activities. Since the inception of the monitoring program three meadows in Rodds Bay have been monitored as reference areas to compare to meadows within the port (Figures 22-24).

Meadow 94:

Meadow 94 is a small monitoring meadow in Rodds Bay that historically consists of continuous *Z. muelleri*. In 2021 there was a large decline in seagrass area, biomass and species composition resulting in a very poor meadow score. No persistent *Z. muelleri* was recorded in the meadow, only *H. ovalis* resulting in species composition being very poor (Figure 22). Meadow area decreased from 3.25 ± 0.39 ha in 2020 to 0.92 ± 0.21 ha in 2021 and biomass decreased from 12.25 ± 3.08 g DW m^{-2} to 1.83 ± 0.94 g DW m^{-2} in 2021. No persistent *Z. muelleri* was recorded in the meadow, only *H. ovalis* resulting in species composition being very poor (Figure 22).

Meadow 96:

Meadow 96 is the largest meadow in Rodds Bay and covers an area of 354.52 ± 6.03 ha (Figure 23). There was no change in meadow conditions however both meadow area and biomass decreased in 2021. Meadow biomass was 4.55 ± 0.62 g DW m^{-2} the lowest it has been in three years (Figure 23). Species composition was almost exclusively (99%) *Z. muelleri* and for the third consecutive year was above baseline levels.

Meadow 104:

Overall condition of Meadow 104 was satisfactory for the second year in a row (Figure 24). Biomass was 2.90 ± 0.68 g DW m^{-2} and showed little variation for 2020 (2.60 ± 0.90 g DW m^{-2}). Area decreased from good in 2020 to be satisfactory in 2021 (Figure 24). Species composition was at baseline levels and considered in very good condition with the persistent *Z. muelleri* contributing 98% of meadow biomass (Figure 24).

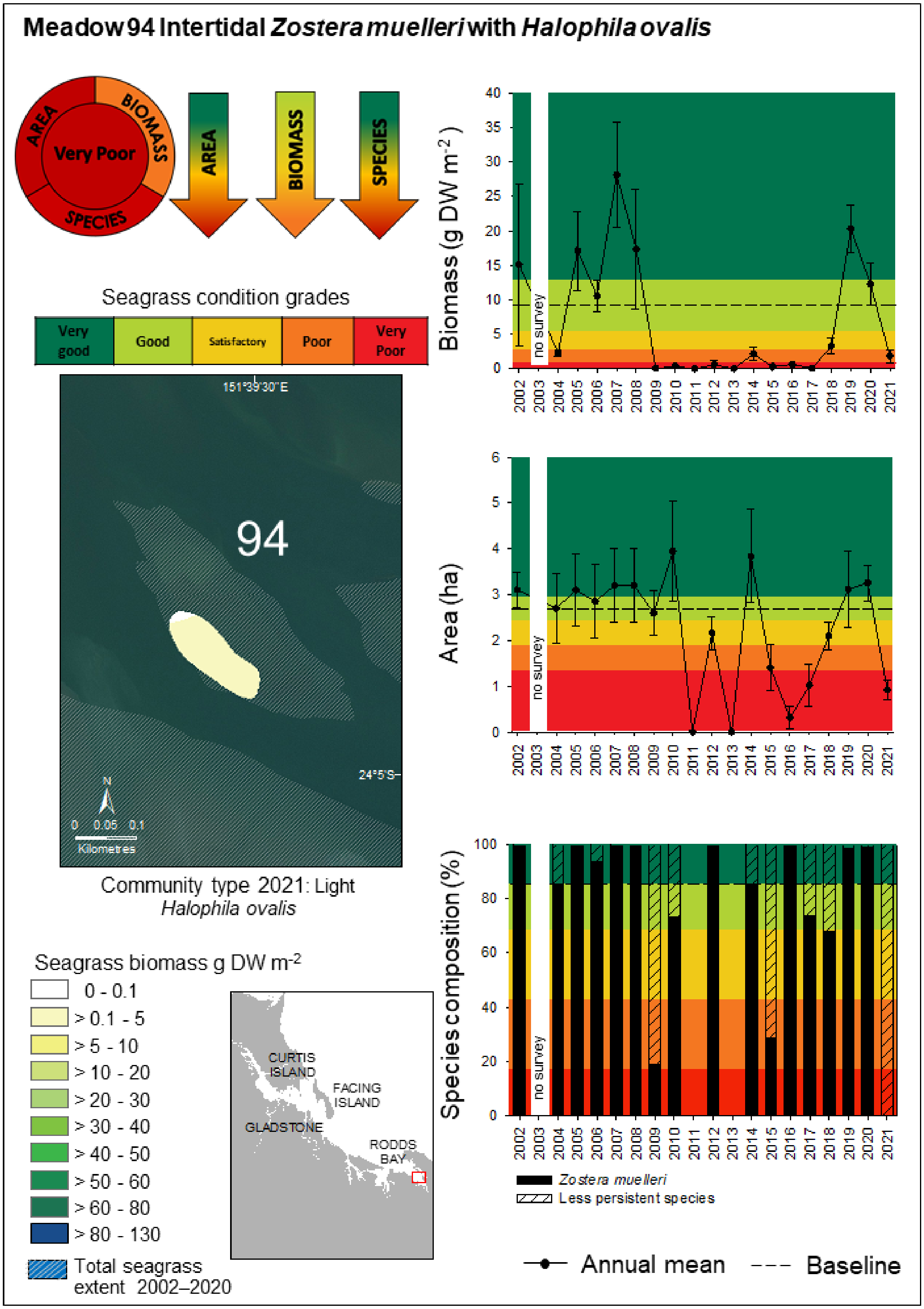


Figure 22. Changes in meadow area, biomass and species composition for Meadow 94, Rodds Bay Zone, 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

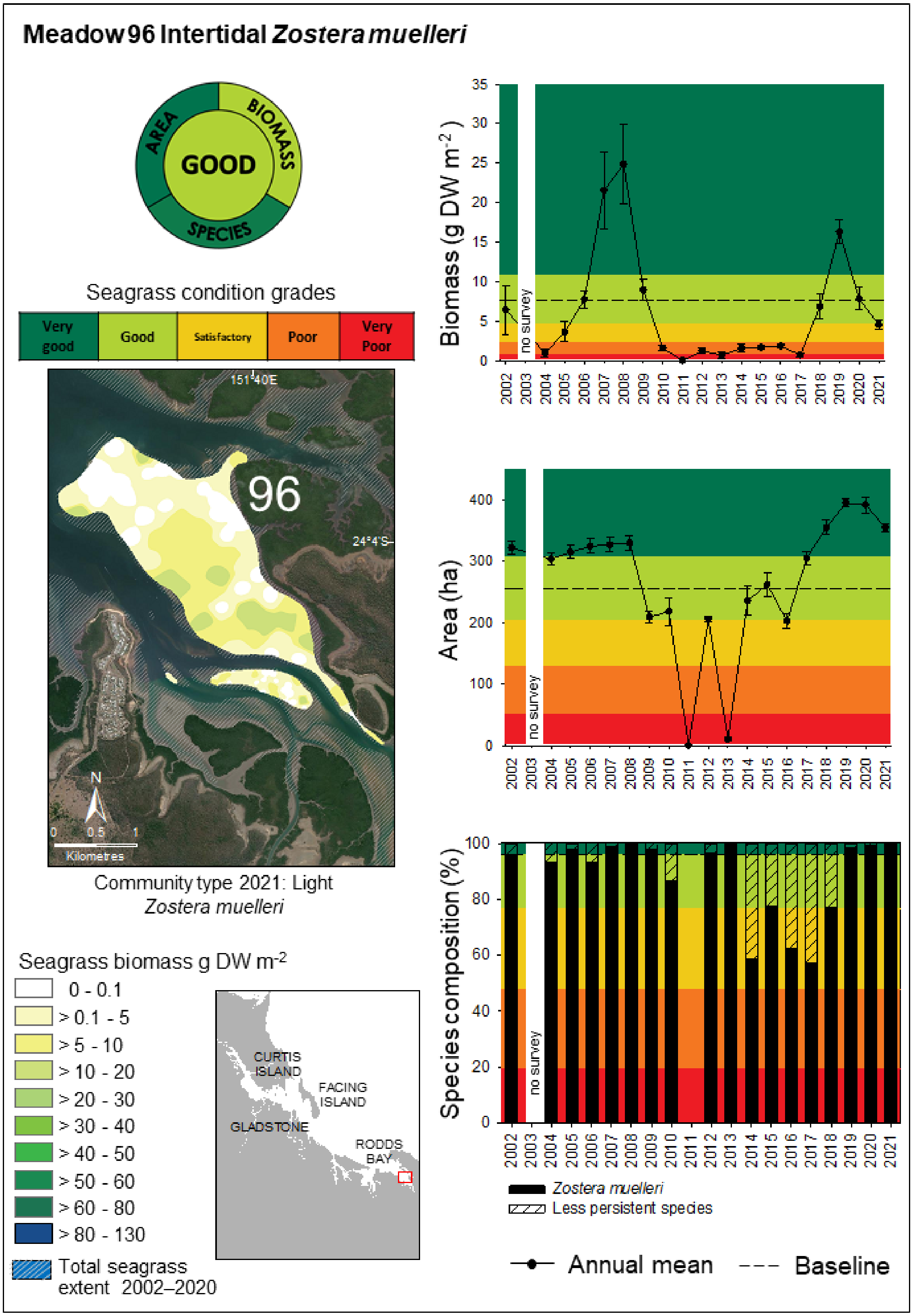


Figure 23. Changes in meadow area, biomass and species composition for Meadow 96, Rodds Bay Zone, 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

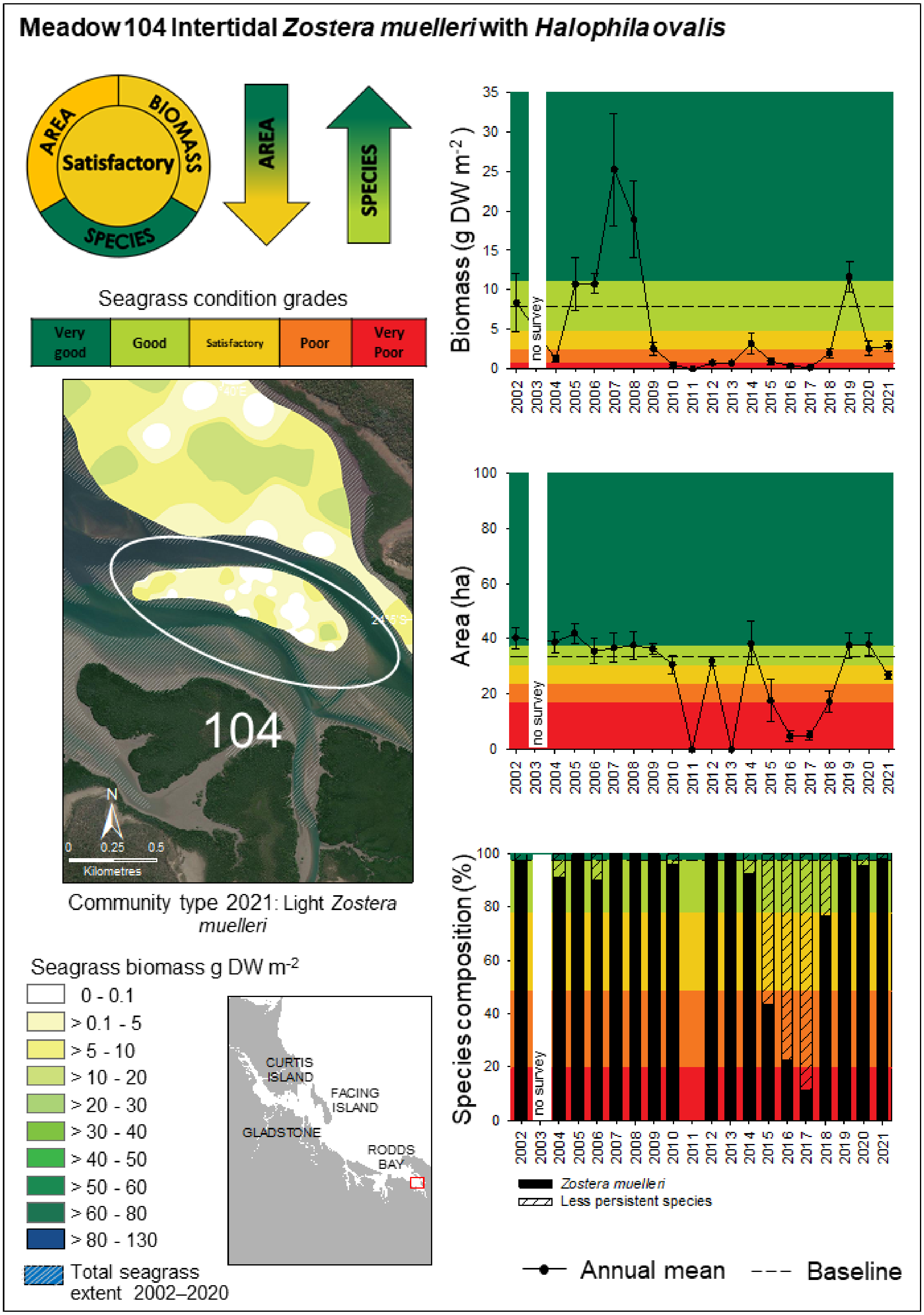


Figure 24. Changes in meadow area, biomass and species composition for Meadow 104, Rodds Bay Zone, November 2002–2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.3 Gladstone environmental conditions

Total annual rainfall in the 12 months preceding the November 2021 survey was below average for the fourth consecutive year (Figure 25a). Wet season conditions were mild over the 2020/21 wet season with below average rainfall in January and February (Figure 29b). During the dry season there was above average rainfall in June and October just prior to the survey in November. River flow from the Calliope River continues to be very low for the fourth year in a row (Figure 26). In all months, outflow was very low (<10 thousand megalitres) and did not exceed the monthly average. Annual total daytime exposure of seagrass meadows was below average for the third year in a row (Figure 27).

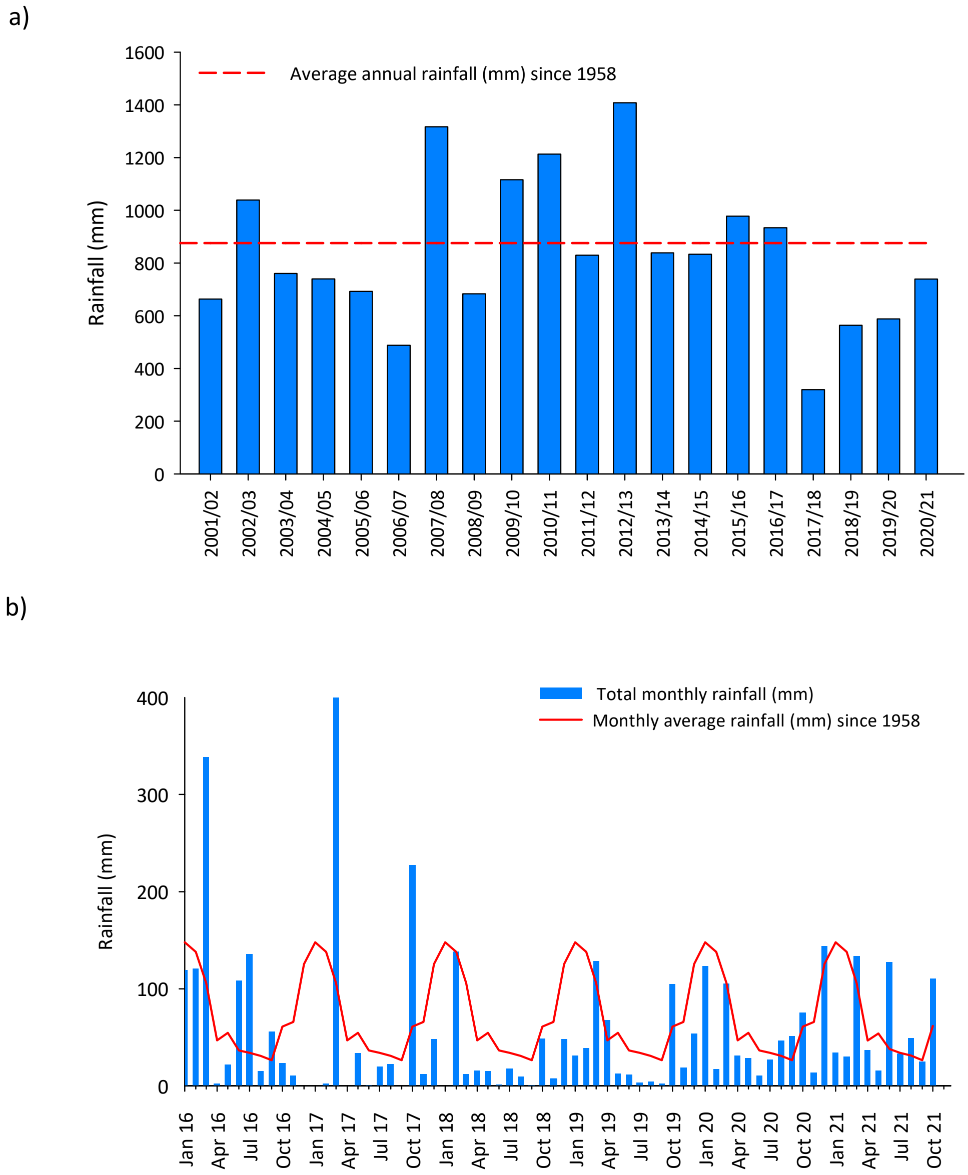


Figure 25. a) Gladstone annual rainfall (mm) and b) monthly rainfall (mm) totals; January 2016–November 2021.

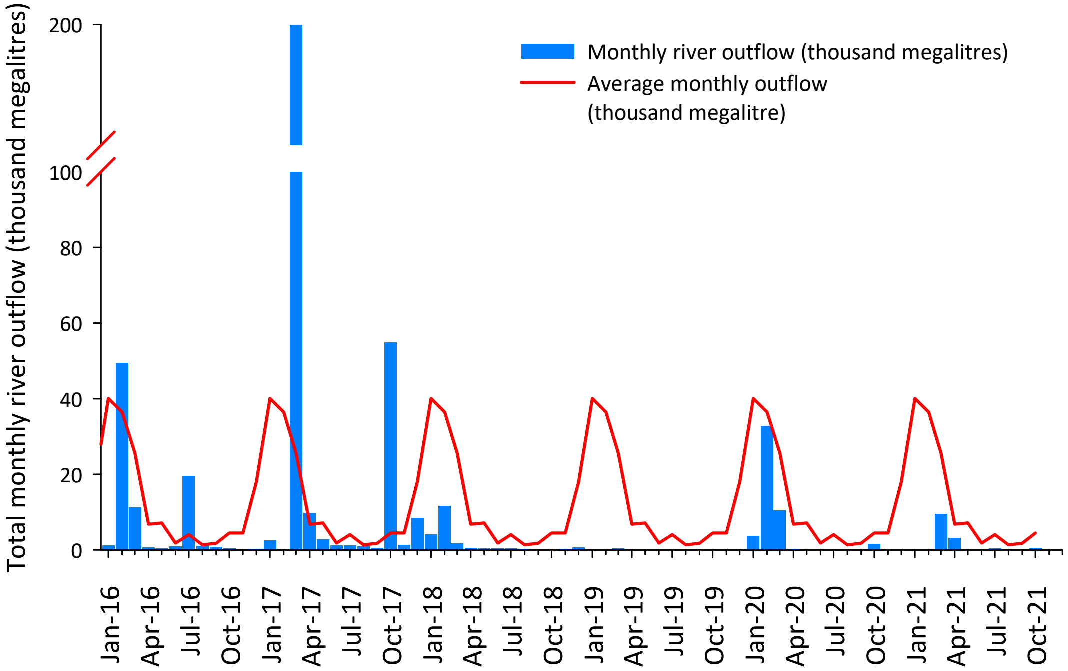


Figure 26. Monthly total river outflow for the Calliope River (thousand megalitres); January 2016–November 2021.

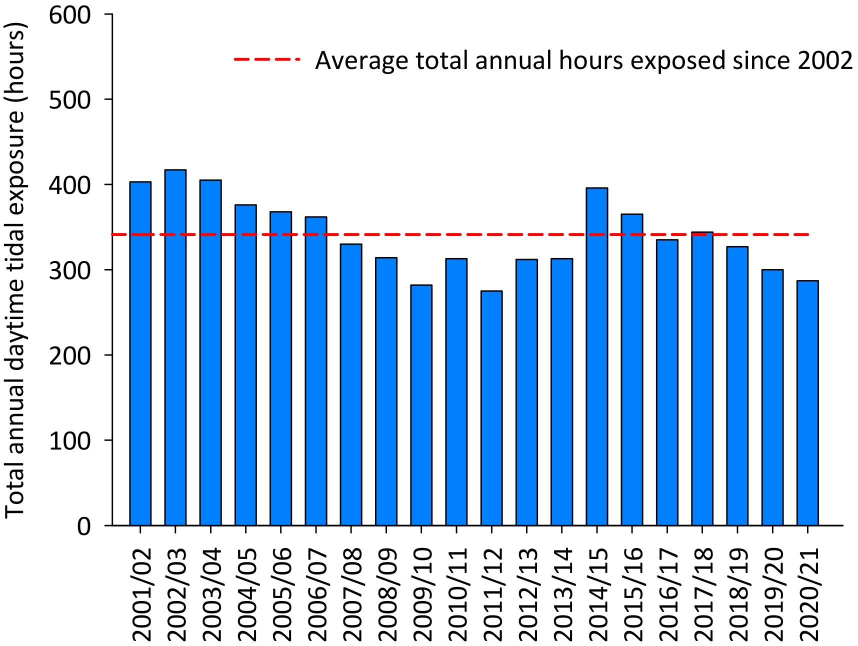


Figure 27. Total annual daytime hours seagrass meadows exposed to air 2001/02 - 2020/21 (daytime hours used 0600 – 1800; <1.0 m below mean sea level).

4 DISCUSSION

4.1 Gladstone seagrass

Seagrass meadows in Port Curtis and Rodds Bay were in an overall good condition for the third consecutive year. This is the first time that seagrass has been in good condition over three consecutive years since 2009, prior to La Niña and large flooding events that led to significant seagrass declines in 2010-2011. Intertidal meadows in the Western Basin, Narrows, Mid Harbour and South Trees Inlet increased in seagrass biomass, area and species composition compared to the 2020 survey and were at or near record highs in some meadows. Monitoring meadows in Rodds Bay and the Inner Harbour however recorded some declines in biomass, area and species composition that resulted in two meadows being in poor or very poor condition.

Local environmental conditions are a key factor in determining seagrass distribution, biomass and health. Long-term trends in seagrass condition over the past 20 years of annual monitoring reveal a strong relationship with river flow and rainfall in the region. Flow from the Calliope River over the past four years has been below average with very low outflow during the 2021 wet season. Similarly, rainfall has been below average since 2017. Seagrass has specific light requirements for photosynthesis and growth (Chartrand et al. 2016, 2018). Turbidity associated with rainfall and river outflow reduces benthic light conditions inhibiting seagrass growth and ultimately leads to plant death. Under low rainfall and river outflow conditions light quantity remains high allowing seagrass growth and recovery such as in Port Curtis and Rodds Bay over the last four years and culminated in continual good condition of the seagrass. Additionally, reduced tidal exposure in 2021 also protected intertidal seagrasses from any extreme desiccation and thermal stress enabling growth and survival (Unsworth et al. 2012). If dry conditions persist in 2022, we would expect seagrass condition to continue to improve.

Port dredging operations may alter benthic light conditions which can result in seagrass decline (Chartrand et al. 2016, Wu et al. 2018). The methodology, timing, frequency and duration of dredging operations play a major role in determining what impact, if any, they have on seagrass meadows and careful management of dredging operations can limit these (Chartrand et al. 2016, Wu et al. 2018). Maintenance dredging in Gladstone is carefully managed to ensure minimal reductions in benthic light and subsequent impacts to seagrass meadows (GPC, 2019). Dredging occurs over relatively short timeframes that restrict the extent of the dredge plumes and occurs within the period of resilience to light impacts for local seagrasses. Meadows in close proximity to the dredging activity in the Western Basin and South Trees Inlet were in good condition or very good condition and biomass was at or near the highest recorded at meadows 4, 5, 6, 8, 52-57 and 60. High biomass and the good or very good condition of these meadows indicates that maintenance dredging was not having any detectable impact on these meadows in 2021. The exceptions were subtidal meadow 7 in the Western Basin and meadow 58 at the Inner Harbour. Meadow 7 was in satisfactory condition for the second year in a row. Subtidal *Halophila* meadows such as meadow 7 are highly ephemeral and biomass and area can change rapidly (Rasheed et al. 2014). Meadow biomass in meadow 7 was in satisfactory condition and area has been in good condition for the last three years and was above the long-term average in 2021. Maintaining consistently good meadow area is important as biomass fluctuates and provides a basis for increasing biomass. Meadow 58 in the Inner Harbour was in poor condition. While meadow area was very good and biomass was in good condition there was a total absence of the foundation species *Z. muelleri*, which was replaced with less persistent *H. uninervis* and *H. ovalis*. The absence of *Z. muelleri* led to a very poor species composition score and poor overall score for the meadow. Prior to 2010 when meadow 58 underwent severe decline after high rainfall and river flow *Z. muelleri* contributed 40-90% of the meadow biomass. Since the meadow was lost in 2010 it has transformed to predominantly *H. uninervis*/*H. ovalis* resulting in consistent species composition scores below satisfactory. Ongoing low contributions of *Z. muelleri* to the meadow biomass suggest that it has not been able to re-establish and persist in the meadow and is being replaced by the fast-growing *H. uninervis* and *H. ovalis*.

The largest seagrass meadow in Port Curtis, Pelican Banks meadow (Meadow 43) has improved to be in satisfactory condition after 6 years in poor condition. Pelican Banks is historically the largest, high biomass seagrass meadow in Port Curtis. The contribution of *Z. muelleri* to the meadow biomass improved to 90% and good condition for species composition after consistent declines over the past 6 years. Increases in *Z. muelleri* across the meadow had a direct impact on meadow biomass which increased to be satisfactory for the first time since 2014. *Zostera muelleri* has much greater biomass than the other species in the meadow (e.g. *H. uninervis*, *H. ovalis*) and therefore biomass should continue to improve as the contribution of *Z. muelleri* improves. The Pelican Banks meadows typically experience the best water quality conditions for seagrass meadows in the region based on historical monitoring of benthic light (Chartrand et al. 2016) and therefore meadow condition should be consistent or better than those elsewhere in Port Curtis. While patterns of seagrass biomass and condition are similar to elsewhere in the harbour in 2021 the decline in seagrass condition at Pelican Banks over the previous 6 years could not be explained by environmental conditions. Megaherbivore (green turtles and dugong) grazing has been suggested as a possible cause of previous seagrass decline at Pelican Banks. The Pelican Banks meadow has high levels of herbivory from dugong and turtle with dugong feeding trails regularly observed within the meadow (Rasheed et al. 2017) and direct observations of green turtles also feeding on the meadow (direct observations and Hamann et al. 2016; Limpus et al. 2017). Recent research using herbivore exclusion cages has found the impact of herbivores on both seagrass biomass and canopy height were greater at Pelican Banks than other meadows within Port Curtis and Rodds Bay (Scott et al. 2021a). It has been suggested that megaherbivores target areas of high biomass which may explain high levels of herbivory in the past (Smith et al. 2021, Rasheed et al. 2017) and major meadow losses have occurred in other locations around the world as a direct result of turtle herbivory (Christianen et al. 2014). Improvements in seagrass biomass and species composition at Pelican Banks may have occurred as Pelican Banks is released from grazing pressure as megaherbivores move off Pelican Banks due to seagrass quality declines prior to 2021 or some other environmental factors.

Widespread use of the Port Curtis and Rodds Bay seagrass meadows by feeding dugong and green turtles indicate seagrass in the region is a valuable food source to megaherbivore populations (Scott et al. 2021a, b). The prevalence of dugong feeding trails and turtle sightings in the harbour suggest megaherbivore grazing/cropping may be an important component of the overarching drivers of seagrass condition in not just the Pelican Banks meadow, but in other port zones (Scott et al. 2021a, b).

While seagrass biomass and area generally increased in Port Curtis, seagrass in Rodds Bay had a general decline in biomass and area. There were slight decreases in biomass and area in meadow 96 and 104 but there was a large decrease in all metrics in meadow 94 which was in very poor condition. Meadow 94 is a small sand bar meadow where biomass and area have undergone large fluctuations since large scale seagrass loss in 2010. Ongoing monitoring is required to determine if low biomass and area of this meadow is permeant or it recovers rapidly as in previous years.

4.2 Comparisons with Queensland-wide monitoring program

The continued good condition of seagrass meadows in Port Curtis and Rodds Bay was consistent with seagrass trends along Queensland's east coast between Cairns and Port Curtis. Seagrass has generally returned to healthy conditions recorded before widespread losses of seagrasses occurred along the east coast in 2009/2010 coinciding with above average rainfall, river flow, and severe tropical cyclones (TC) from extended La Niña weather patterns (York et al. 2016; Reason et al. 2017a; McKenna et al. 2017; Bryant et al. 2019). While there has been a trend of recovery over recent years, localised climate events have had a major impact on seagrass outcomes around the state. Seagrass in the Gulf of Carpentaria in Weipa and Karumba were in a good and very good condition (McKenna et al. 2021; Scott et al. 2022). On the east coast, Both Cairns and Townsville were in good condition for the second year in a row after consecutive years of receiving below average rainfall and mild climate conditions (Reason et al. 2022a; McKenna et al. 2022). This is in contrast to severe localised flooding occurred in the Townsville region in 2019, which led to a decline in seagrass meadows in that year (McKenna et al. 2020). In contrast, Mourilyan Harbour has shown little recovery after complete meadow loss in 2010/2011 and seagrass remains in very poor condition with little prospect of seagrass recovery without some form of restoration (Reason et al. 2022b). In this context the Port Curtis and Rodds Bay seagrasses were one of the better outcomes for seagrass condition in Queensland in 2021 particularly if seagrass condition at Pelican Banks continues to improve.

4.3 Implications for port management

Results of this latest annual survey, have found seagrasses to be in a good condition compared with the 20 year monitoring history. With the exception of meadow 94 in the out of port reference area in Rodds Bay, all seagrass monitoring meadows were at satisfactory to very good condition with the majority of meadows having recovered to pre 2010 condition. The seagrass dynamics observed in Port Curtis and Rodds Bay over the past 4 years is consistent with the major climate drivers of seagrass change seen elsewhere in North Queensland and the continued use of the meadows by dugongs and green turtles are signs of a healthy functioning seagrass ecosystem. As recognised indicators of overall marine environmental health (Dennison et al. 1993), the good condition of seagrasses in 2021 point toward a healthy marine environment for Port Curtis and Rodds Bay.

In Port Curtis and Rodds Bay, maintenance of seagrass species composition and biomass above baseline levels, and the continual improvement in spatial footprint over the past three years is likely to have increased the resilience of seagrass meadows to future impacts. Sustained periods of high biomass will lead to increased reproductive effort and replenish seed banks in the region, particularly for *Z. muelleri.* Larger seed banks further increase seagrass meadow resilience to impacts by increasing their capacity for recovery (Reason et al. 2017b). Continuing high levels of resilience mean seagrasses were well placed to cope with major weather events and anthropogenic pressures in 2022 including planned maintenance dredging activities.

Maintaining light environments that are sufficient for seagrass growth is the key driver of seagrass condition in Port Curtis and Rodds Bay, and elsewhere in Queensland. Activities that could reduce water quality in Port Curtis and Rodds Bay should be managed in such a way as to ensure water quality and particularly benthic light is sufficient for seagrass growth. In Port Curtis, substantial work has been done to develop relevant light requirement thresholds for the local seagrasses and these are implemented by GPC as part of routine management requirements during port activities to protect seagrasses (Chartrand et al. 2012; 2016).

Over the past decade seagrass meadows in Port Curtis and Rodds Bay have undergone repeated disturbances from climate, floods, cyclones and anthropogenic activities but have maintained their historical extent and have now recovered biomass and species composition to pre disturbance levels. Improvements in biomass and the return of more persistent species to meadows over the past three years, suggest seagrasses will be more resilient to future pressures or impacts than over the previous decade. The improvement in seagrasses is a strong foundation supporting marine productivity and species reliant on seagrasses for food and shelter and we expect that their condition would be maintained in 2022 should favourable environmental conditions continue.

5 REFERENCES

Abal, E. G., and Dennison, W. C. 1996. Seagrass depth range and water quality in southern Moreton Bay, Queensland, Australia. Marine and Freshwater Research, **47**(6), 763–771.

Agawin, N., Duarte, C. M., Fortes, M. D., Uri, J. and Vermaat, J. 2001. Temporal changes in the abundance, leaf growth and photosynthesis of three co-occurring Philippine seagrasses. Journal of Experimental Marine Biology and Ecology, 260, 217-239

BTM, 2017, Port of Gladstone maintenance dredging assessment of potential impacts, BTM WBM, Brisbane, 278 pp.

BTM, 2019, Monitoring of maintenance dredging plumes – Gladstone Harbour, November and December 2018 – final report, BTM WBM, Brisbane, 178 pp

Bryant, C. V., Wells, J. and Rasheed, M. A. 2019. Port of Townsville annual seagrass monitoring survey: October 2018. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 19/01, James Cook University, Cairns, 47 pp.

Bryant, C. V., Carter, A. B., Jarvis, J. C., Reason, C. and Rasheed, M. A. 2016. Port Curtis seagrass seed bank density and viability studies - Year 2. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 16/46, James Cook University, Cairns, 29 pp.

Bryant, C. V., Davies, J., Sankey, T. and Jarvis, J. C. 2014a. Long term seagrass monitoring in the Port Curtis Western Basin: Quarterly seagrass assessments and permanent transect monitoring progress report 2009 to 2013. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 14/18, James Cook University, Cairns, 84 pp.

Bryant, C. V., Davies, J. D., Jarvis, J. C., Tol, S. and Rasheed, M. A. 2014b. Seagrasses in Port Curtis and Rodds Bay 2013: Annual long term monitoring, biannual Western Basin surveys and updated baseline survey. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 14/23, James Cook University, Cairns, 71 pp.

Carter, A. C., Bryant, C. V., Davies, J. and Rasheed, M. A. 2016. Gladstone Healthy Harbour Partnership 2016 report card, ISP011: Seagrass. Centre for Tropical Water and Aquatic Ecosystem Research Publication 16/23, James Cook University, Cairns, 62 pp.

Carter, A. B., Davies, J. D., Bryant, C. V., Jarvis, J. C., McKenna, S. A. and Rasheed, M. A. 2015a. Seagrasses in Port Curtis and Rodds Bay 2014: Annual long-term monitoring, biannual Western Basin, and updated baseline survey. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), James Cook University, Cairns, 72 pp.

Carter, A. B., Jarvis, J. C., Bryant, C. V. and Rasheed, M. A. 2015b. Development of seagrass indicators for the Gladstone Healthy Harbour Partnership Report Card, ISP011: Seagrass. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 15/29, James Cook University, Cairns, 71 pp.

Chartrand K. M., Wells J., Carter A. C. and Rasheed M. A. 2019. Seagrasses in Port Curtis and Rodds Bay 2018: Annual long-term monitoring. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 19/02, James Cook University, Cairns, 63 pp.

Chartrand K. M., Szabó M., Sinutok S., Rasheed M. A. and Ralph P. J. 2018. Living at the margins–The response of deep-water seagrasses to light and temperature renders them susceptible to acute impacts. Marine Environmental Research, 136: 126-138.

Chartrand, K. M., Bryant, C. V., Carter, A., Ralph, P. J. and Rasheed, M. A. 2016. Light thresholds to prevent dredging impacts on the Great Barrier Reef seagrass, *Zostera muelleri* spp. *capricorni*. Frontiers in Marine Science, 3(106)

Chartrand, K. M., Ralph, P. J., Petrou, K. and Rasheed, M. A. 2012. Development of a light-based seagrass management approach for the Gladstone Western Basin dredging program. DEEDI Publication, Fisheries Queensland, Northern Fisheries Centre, Cairns, 92 pp.

Chartrand, K. M., McCormack, C. V. and Rasheed, M. A. 2011. Port Curtis and Rodds Bay seagrass monitoring program, November 2010. DEEDI Publication, Fisheries Queensland, Northern Fisheries Centre, Cairns, Australia, 57 pp.

Christianen, M. J. A., Herman, P. M. J., Bouma, T. J., Lamers, L. P. M., van Katwijk, M. M., van der Heide, T., Mumby, P. J., Silliman, B. R., Engelhard, S. L., van de Kerk, M., Kiswara, W. and van de Koppel, J. 2014. Habitat collapse due to overgrazing threatens turtle conservation in marine protected areas. Proceedings of the Royal Society B: Biological Sciences, **281**(1777) 20132890.

Collier, C. J., Chartrand, K. M., Honchin, C., Fletcher, A. and Rasheed, M. A. 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, 41 pp.

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

Davies, J., McCormack, C. V. and Rasheed, M. A. 2013. Port Curtis and Rodds Bay seagrass monitoring program, biannual Western Basin & annual long term monitoring November 2012. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 13/08, James Cook University, Cairns, 54 pp.

Davies, J., Sankey, T., Jarvis, J. C., Bryant, C. V. and Rasheed, M. A. 2015. Long term seagrass monitoring in Port Curtis: Quarterly permanent transect monitoring progress report, 2009 to 2014. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 15/05, James Cook University, Cairns, 59 pp.

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

Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Gladstone Ports Corporation. 2019. Long-term maintenance dredging management plan for the Port of Gladstone. Gladstone Ports Corporation Limited. Gladstone, 86pp.

Hamann, M., Limpus, C. J., Shimada, T. and Preston, S. 2016. Annual report on green turtle tracking and habitat use in Port Curtis – Year 2 2015. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Cairns, 19 pp.

Hemminga, M. A. and Duarte, C. M. 2000. *Seagrass Ecology*. Cambridge, Cambridge University Press. doi:10.1017/CBO9780511525551

Kilminster, K., McMahon, K., Waycott, M., Kendrick, G. A., Scanes, P., McKenzie, L., O'Brien, K. R., Lyons, M., Ferguson, A., Maxwell, P., Glasby, T. and Udy, J. 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.

Lee Long, W. J., Coles, R. G., Miller, K. J., Vidler, K. P. and Derbyshire, K. J. 1992. Seagrass beds and juvenile prawn and fish nursery grounds: Water Park Point to Hervey Bay, Queensland. Information Series. Queensland Department of Primary Industries, Brisbane, 39 pp.

Limpus, C. J., FitzSimmons, N., Finlayson, K., Harmonn, C., McKinnon, A., Sergeev, J. and Shimada, T. 2017. Increase the understanding of the Green Turtle population in Port Curtis. Brisbane: Department of Environment and Science, Queensland Government. Report produced for the Ecosystem Research and

Monitoring Program Advisory Panel as part of Gladstone Ports Corporation Ecosystem Research and Monitoring Program. 28 pp.

Maritime Safety Queensland. 2018. Queensland tide tables, standard port times 2019, State of Queensland, Brisbane, 129 pp. https://www.msq.qld.gov.au/Tides/Tide-Tables

McCormack, C. V., Rasheed, M. A., Davies, J., Carter, A., Sankey, T. and Tol, S. 2013. Long term seagrass monitoring in the Port Curtis Western Basin: Quarterly seagrass assessments and permanent transect monitoring progress report November 2009 to November 2012. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), Publication 13/16, James Cook University, Cairns, 88 pp.

McKenna, S.A., Smith T.M., Reason, C.L. & Rasheed, M.A. 2021, Port of Weipa long-term seagrass monitoring program, 2000 - 2021. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), JCU Cairns.

McKenna, S.A., Van De Wetering, C., and Wilkinson, J. 2022, Port of Townsville Seagrass Monitoring Program: 2021, James Cook University Publication, Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), Cairns.

McKenna S. A., Chartrand, K. M., Van De Wetering, C., Wells, J. N., Carter, A. B. and Rasheed, M. A. 2020. Port of Townsville seagrass monitoring program: 2019, Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 20/16, James Cook University, Cairns. 57 pp

McKenna, S. A., Scott, E. and Rasheed, M. A. 2017. Port of Abbot Point long-term seagrass monitoring: annual report 2015-2016. James Cook University Publication, Centre for Tropical Water and Aquatic Ecosystem Research Publication (TropWATER). Cairns, 46 pp.

McKenna, S. A., Jarvis, J. C., Sankey T., Reason C., Coles R. and Rasheed M. A. 2015. Declines of seagrasses in a tropical harbour, North Queensland, Australia, are not the result of a single event. Journal of Biosciences **40**(2): 389-398.

McKenna, S. M., Bryant, C. V., Tol, S. and Rasheed, M. A. 2014. Baseline assessment of benthic communities (algae and macro-invertebrates) in the Port Curtis Region November 2014. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 14/54, James Cook University. Cairns, 27 pp.

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

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

Rasheed, M. A, O'Grady, D., Scott, E., York, P. H. and Carter, A. B. 2017. Dugong feeding ecology and habitat use on intertidal banks of Port Curtis and Rodds Bay – Final Report 2016. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 16/14, James Cook University, Cairns, 65 pp.

Rasheed, M. A., McKenna, S. A., Carter, A. B. & Coles, R. G. 2014. Contrasting recovery of shallow and deep water seagrass communities following climate associated losses in tropical north Queensland, Australia. *Marine Pollution Bulletin*, 83, 491-499.

Rasheed, M. A., Reason, C. L., McCormack, C. V., Chartrand, K. M. and Carter, A. B. 2012. Port Curtis and Rodds Bay seagrass monitoring program, November 2011. DAFF Publication, Fisheries, Queensland, Cairns, 54 pp.

Rasheed, M. A., McKenna, S. A. and Thomas, R. 2005. Long-term seagrass monitoring in Port Curtis and Rodds Bay, Gladstone - October 2004. Department of Primary Industries and Fisheries Information Series QI05032. Department of Primary Industries and Fisheries, Cairns, 30 pp.

Rasheed, M. A. 2004. Recovery and succession in a multi-species tropical seagrass meadow following experimental disturbance: the role of sexual and asexual reproduction. Journal of Experimental Marine Biology and Ecology, 310: 13-45.

Rasheed, M. A., Thomas, R., Roelofs, A. J., Neil, K. M. and Kerville, S. P. 2003. Port Curtis and Rodds Bay seagrass and benthic macro-invertebrate community baseline survey - November/December 2002. DPI&F, Fisheries Queensland, Cairns, 48 pp.

Reason C. L., York P. H. & Rasheed M.A. 2022a. Seagrass habitat of Cairns Harbour and Trinity Inlet: Cairns Shipping Development Program and Annual Monitoring Report 2021. JCU Publication, Centre for Tropical Water & Aquatic Ecosystem Research Publication 22/03, Cairns.

Reason, C.L., York, P.H., Rasheed, M.A. 2022b, Seagrass habitat of Mourilyan Harbour: Annual Monitoring Report – 2021, Centre for Tropical Water & Aquatic Ecosystem Research, JCU Publication 22/04, Cairns, 36pp.

Reason C. L., Smith T. M. and Rasheed M. A. 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 Publication 21/09, Cairns, 54 pp.

Reason, C. L., Sozou, A., York, P. H. and Rasheed, M. A. 2017a. Seagrass habitat of Mourilyan Harbour: Annual Monitoring Report – 2016. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 17/28, James Cook University, Cairns, 38 pp.

Reason, C. L., Rasheed, M. A., Carter, A. B. and Jarvis, J. C. 2017b. Port Curtis seagrass seed bank density and viability studies - Final Report. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation’s Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 17/40, James Cook University, Cairns, 36pp.

Scott, A.L., McKenna, S.A., & Rasheed, M.A. 2022. Port of Karumba Long-term Annual Seagrass Monitoring 2021, Centre for Tropical Water & Aquatic Ecosystem Research Publication Number 21/70, James Cook University, Cairns, 28 pp.

Scott A. L, York P. H, Macreadie P. I. and Rasheed M. A. 2021a. Spatial and temporal variability of green turtle and dugong herbivory in seagrass meadows of the southern Great Barrier Reef. Marine Ecology Progress Series https://doi.org/10.3354/meps13703

Scott A. L, York P. H. and Rasheed M. A 2021b. Herbivory Has a Major Influence on Structure and Condition of a Great Barrier Reef Subtropical Seagrass Meadow. Estuaries and Coasts 44, 506-521 https://doi.org/10.1007/s12237-020-00868-0

Schliep, M., Pernice, M., Sinutok, S., Bryant, C. V., York, P. H., Rasheed, M. A., and Ralph, P. J. 2015. Evaluation of reference genes for RT-qPCR studies in the seagrass *Zostera muelleri* exposed to light limitation. Scientific Reports 5: 17051.

SKM. 2004. Port Curtis Integrated Monitoring Program: Sampling design and statistical methods package. Report to PCIMP. 128 pp

Smith T. M., Reason C., McKenna S., and Rasheed M. A. 2021. Seagrasses in Port Curtis and Rodds Bay 2019: Annual long-term monitoring and whole of port survey. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 20/02, James Cook University, Cairns, 54 pp.

Thomas, R., Unsworth, R. K. F. and Rasheed, M. A. 2010. Seagrasses of Port Curtis and Rodds Bay and long term seagrass monitoring, November 2009. DEEDI Publication. Fisheries Queensland, Cairns, 58 pp.

Unsworth, R. K. F., Rasheed, M. A., Chartrand, K. M. and Roelofs, A. J. 2012. Solar radiation and tidal exposure as environmental drivers of *Enhalus acoroides* dominated seagrass meadows. PLoS ONE, 7: e34133.

Wu, P. P., K. McMahon, M. A. Rasheed, G. A. Kendrick, P. H. York, K. Chartrand, M. J. Caley and Mengersen, K. 2018. Managing seagrass resilience under cumulative dredging affecting light: Predicting risk using dynamic Bayesian networks. Journal of Applied Ecology 55(3): 1339-1350.

York, P. H., Reason, C., Scott, E. L., Sankey, T. and Rasheed, M. A. 2016. Seagrass habitat of Cairns Harbour and Trinity Inlet: Annual Monitoring Report 2015. Cairns, Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 16/13, James Cook University, 58 pp.

APPENDICES

Appendix 1. Seagrass Condition Index

Baseline Calculations

Baseline conditions for seagrass biomass, meadow area and species composition were established from annual means calculated over the first 10 years of monitoring (2002–2012; nb. no survey conducted in 2003). This baseline was set based on results of the Port Curtis and Rodds Bay 2014 pilot report card (Bryant et al. 2014b). The 2002–2012 period incorporates a range of conditions present in Port Curtis and Rodds Bay, including El Niño and La Niña periods, and multiple extreme rainfall and river flow events (Carter et al. 2015a). The 10 year long-term average will be reassessed each decade.

Baseline conditions for species composition were determined based on the annual percent contribution of each species to mean meadow biomass of the baseline years. The meadow was 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 contained an approximately equal split in two dominant species (i.e. both species accounted for 40–60% of the baseline), the baseline was set according to the percent composition of the more persistent/stable species of the two (see Grade and Score Calculations section and Figure A1).

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 was used to determine historical variability. Meadow biomass and species composition were classified as either stable or variable (Table A1). Meadow area was classified as either highly stable, stable, variable, or highly variable (Table A1). The CV was calculated by dividing the standard deviation of the baseline years by the baseline for each condition indicator.

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

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

Threshold Definition

Seagrass condition for each indicator was assigned one of five grades (very good (A), good (B), satisfactory (C), poor (D), very poor (E)). Threshold levels for each grade were set relative to the baseline and based on meadow class. This approach accounted for historical variability within the monitoring meadows and expert knowledge of the different meadow types and assemblages in the region (Table A2).

Table A2. 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	↑ BIOMASS		Decrease below threshold from previous year	↓ BIOMASS	

Grade and Score Calculations

A score system (0–1) and score range was applied to each grade to allow numerical comparisons of seagrass condition among meadows, Port Curtis Zones, and for the Port Curtis region (Table A3; see Carter et al. 2016; Carter et al. 2015b for a detailed description).

Score calculations for each meadow's condition required calculating the biomass, area and species composition for that year (see Baseline Calculations section), allocating a grade for each indicator by comparing 2017 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 A3). Within each meadow, the upper limit for the very good grade (score = 1) for species composition was set as 100% (as a species could never account for >100% of species composition). For biomass and area the upper limit was 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 satisfactory condition is provided in Appendix 2.

Table A3. Score range and grading colours used in the Port Curtis and Rodds Bay 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 was determined to be anything less than in "perfect" condition (i.e. a score <1), a decision tree was used to determine whether equivalent and/or more persistent species were driving this grade/score (Table A1). If this was the case then the species composition score and grade for that year was 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). 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 *Z. muelleri* subsp. *capricorni* 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 *Cymodocea rotundata* and *Cymodocea 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 was 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 *Syringodium 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*, the most marginal species found in Port Curtis, 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).

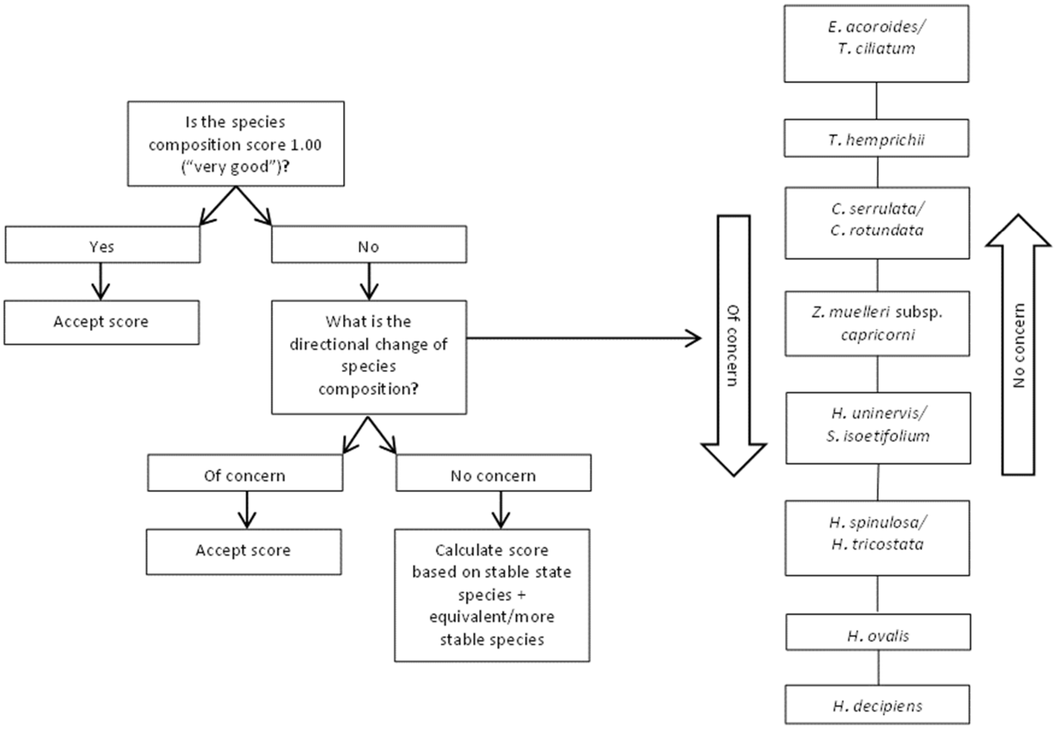


Figure 10. (a) Decision tree and (b) directional change assessment for grading and scoring seagrass species composition.

Score Aggregation

A review in 2017 of how meadow scores were aggregated from the three indicators (biomass, area and species composition) led to a slight modification from previous years' annual report. This change was applied to correct an anomaly that resulted in some meadows receiving a zero score due to species composition, despite having substantial area and biomass. The change acknowledges that species composition is an important characteristic of a seagrass meadow in terms of defining meadow stability, resilience, and ecosystem services, but is not as fundamental as having some seagrass present, regardless of species, when defining overall condition. The overall meadow score was previously defined as the lowest of the three indicator scores (area, biomass or species composition). The new method still defines overall meadow condition as the lowest indicator score where this is driven by biomass or area as previously; however, where species composition was the lowest score, it contributes 50% of the overall meadow score, and the next lowest indicator (area or biomass) contributes the remaining 50%. The calculation of individual indicator scores remains unchanged.

Both seagrass meadow area and biomass are fundamental to describing the condition of a seagrass meadow. A poor condition of either one, regardless of the other, describes a poor seagrass meadow state. Importantly they can and do vary independently of one another. Averaging the indicator scores is not appropriate as in some circumstances the area of a meadow can reduce dramatically to a small remnant, but biomass within the meadow is maintained at a high level. Clearly such a seagrass meadow is in poor condition, but if you were to take an average of the indicators it would come out satisfactory or better. The reverse is true as well, under some circumstances the spatial footprint of a meadow is maintained but the biomass of seagrass within is reduced dramatically, sometimes by an order of magnitude. Again, taking an average of the two would lead to a satisfactory or better score which does not reflect the true state of the meadow. As both of these characteristics are so fundamental as to the condition of a seagrass meadow, the decision was to have the overall meadow score be the lowest of the indicators rather than an average. This method allowed the most conservative estimate of meadow condition to be made (Bryant et al. 2014b).

Seagrass species composition is an important modifier of seagrass meadow state. A change in species to more colonising forms can be a key indicator of disturbance and a meadow in recovery from pressures. As not all seagrass species provide the same services a change in species composition can lead to a change in the function and services a meadow provides. Originally the species composition indicator was considered in the same way as biomass and area, if it was the lowest score, it would inform the overall meadow score. However, while seagrass species is an important modifier it is not as fundamental as the actual presence of seagrass (regardless of species). While the composition may have changed there is still seagrass present to perform at least some of the roles expected of the meadow such a food for dugong and turtle for example. The old approach led to some unintended consequences with some meadows receiving a “0” score despite having good area and biomass simply because the climax species for that meadows base condition had not returned after losses had occurred. So, while it is an important modifier, species composition should not be the sole determinant of the overall meadow score (even when it is the lowest score). As such, the method for rolling up the three indicator scores was modified so that in the circumstances where species composition is the lowest of the three indicators, it contributes 50% of the score, with the other 50% coming from the lower of the two fundamental indicators (biomass and area). This maintains the original design philosophy but provides a 50% reduction in weighting that species composition could effectively contribute.

The change in weighting approach for species composition was tested across all previous years and meadows in Port Curtis as well the other seagrass monitoring locations where we use this scoring methodology (Cairns, Townsville, Abbot Point, Mackay, Hay Point, Mourilyan Harbour, Torres Strait, Weipa and Karumba). A range of different weightings were examined, but the 50% weighting consistently provided the best outcomes. The change resulted in sensible outcomes for meadows where species composition was poor and resulted in overall meadow condition scores that remained credible with minimal impact to the majority of meadow scores across Gladstone (and the other locations), where generally meadow condition has been appropriately described. Changes only impacted the relatively uncommon circumstance where species composition was the lowest of the three indicators. The reduction in weighting should not allow a meadow with very poor species composition to achieve a rating of good, due to the reasons outlined above, and the 50% weighting provided enough power to species composition to ensure this was the achieved compared with other weightings that were tested.

Overall Port Curtis grades/scores were determined by averaging the overall meadow scores for each monitoring meadow within the port, and assigning the corresponding grade to that score (Table A2). Where multiple meadows were present within the port, meadows were not subjected to a weighting system at this stage of the analysis. The meadow classification process applied smaller and therefore more sensitive thresholds for meadows considered stable, and less sensitive thresholds for variable meadows. The classification process served therefore as a proxy weighting system where any condition decline in the (often) larger, stable meadows was more likely to trigger a reduction in the meadow grade compared with the more variable, ephemeral meadows. Port grades are therefore more sensitive to changes in stable than variable meadows.

Appendix 2. Example of Score Calculation

An example of calculating a meadow score for biomass in satisfactory condition.

1. Determine the grade for the current year area value (i.e. satisfactory).

2. Calculate the difference in area (A_{diff}) between the current area value ($A_{current}$) and the area value of the lower threshold boundary for the satisfactory grade ($A_{satisfactory}$):

$$\mathrm{A_{diff}} = \mathrm{A_{current}} - \mathrm{A_{satisfactory}}$$

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

3. Calculate the range for area values (A_{range}) in that grade:

$$\mathrm{A_{range}} = \mathrm{A_{good}} - \mathrm{A_{satisfactory}}$$

Where $A_{satisfactory}$ is the upper threshold boundary for the satisfactory 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 maximum value of the mean plus the standard error (i.e. the top of the error bar) for a given year during the baseline period for that indicator and meadow.

4. Calculate the proportion of the satisfactory grade (A_{prop}) that $A_{current}$ takes up:

$$\mathrm{A_{prop}} = \frac{\mathrm{A_{diff}}}{\mathrm{A_{range}}}$$

5. Determine the area score for the current year ($Score_{current}$) by scaling A_{prop} against the score range (SR) for the satisfactory grade ($SR_{satisfactory}$), i.e. 0.15 units:

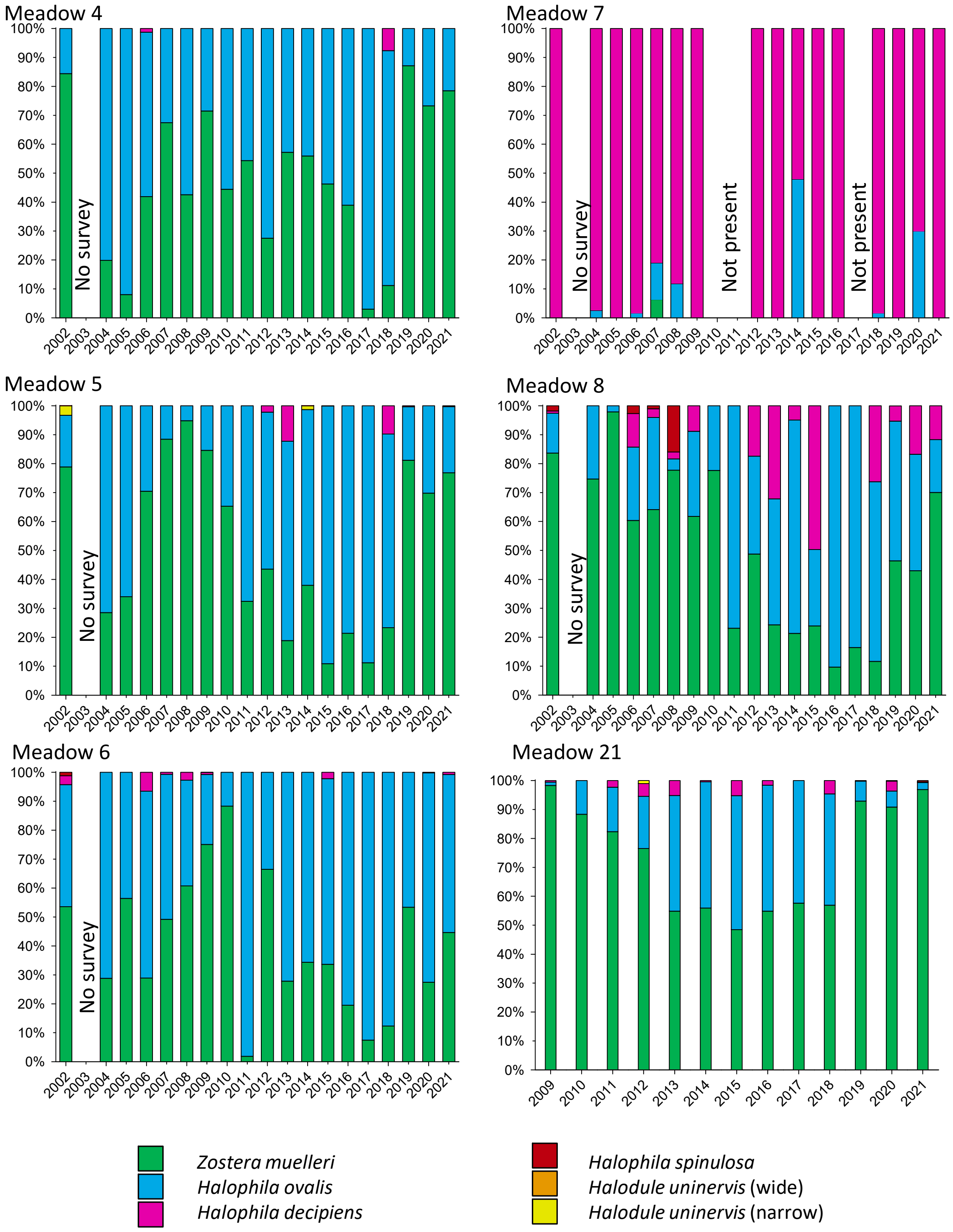
$$\mathrm{Score}_{\mathrm{current}} = \mathrm{LB_{satisfactory}} + \left(\mathrm{A_{prop}} \times \mathrm{SR_{satisfactory}}\right)$$

Where $LB_{satisfactory}$ is the defined lower bound (LB) score threshold for the satisfactory grade, i.e. 0.50 units.

Appendix 3. Meadow area and above-ground biomass of Port Curtis and Rodds Bay seagrass meadows 2021

Meadow ID	Biomass ± SE (g DW m^{-2})	Area ± R (ha)	Community Type	Landscape Category	Species Present	Zone
21	17.52 ± 2.23	200.45 ± 8.33	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens, H. spinulosa*	The Narrows
4	3.71 ± 0.97	44.80 ± 1.94	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*	Western Basin
5	6.94 ± 0.91	162.08 ± 3.02	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*	Western Basin
6	3.68 ± 0.38	447.23 ± 6.11	Light *Z. muelleri* with *H. ovalis*	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*	Western Basin
7	0.75 ± 0.08	77.23 ± 23.37	Light *H. decipiens*	Aggregated patches	*H. decipiens*	Western Basin
8	2.98 ± 0.62	211.96 ± 3.55	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*	Western Basin
52-57	1.87 ± 0.42	71.75 ± 4.63	Light *Z. muelleri/H. ovalis*	Isolated patches	*Z. muelleri, H. ovalis*	Western Basin
43	10.75 ± 1.05	646.07 ± 6.67	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. uninervis thin, H. ovalis*	Mid Harbour
48	3.83 ± 0.42	261.58 ± 4.10	Moderate *H. uninervis* thin	Aggregated patches	*H. uninervis, H, ovalis, H. spinulosa*	Mid Harbour
58	2.24 ± 0.24	47.02 ± 15.73	Light *H. uninervis* thin/*H. ovalis*	Isolated patches	*H. uninervis, H. ovalis, H. decipiens*	Inner Harbour
60	18.22 ± 2.28	12.84 ± 0.87	Light *Z. muelleri*	Continuous cover	*Z. muelleri, H. ovalis*	South Trees
94	1.83 ± 0.93	0.92 ± 0.21	Light *H. ovalis*	Isolated patches	*H. ovalis*	Rodds Bay
96	4.55 ± 0.62	354.52 ± 6.03	Light *Z. muelleri*	Aggregated patches	*Z. muelleri*	Rodds Bay
104	2.90 ± 0.68	26.90 ± 1.34	Light *Z. muelleri*	Isolated patches	*Z. muelleri*	Rodds Bay

Appendix 4. Detailed species composition for long term monitoring meadows; 2021




Meadow 43
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
No survey
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
Meadow 58
No survey
Not present
Meadow 48
No survey
Meadow 60
No survey
Meadow 52-57
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
Meadow 94
No survey
Not present
Not present
Meadow 96
No survey
Not present
Meadow 104
00%
No survey
Not present
Zostera muelleri
Halophila ovalis
Halophila decipiens
Halophila spinulosa
Halodule uninervis (wide)
Halodule uninervis (narrow)