Centre for Tropical Water and Aquatic Ecosystem Research

Seagrasses in Port Curtis and Rodds Bay 2019 Annual long-term monitoring and whole of port survey

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Carter AB, & Rasheed MA

Report No. 20/02

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A Report for Gladstone Ports Corporation

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KEY FINDINGS

Seagrass Condition 2019

1. Seagrasses in Port Curtis and Rodds Bay were surveyed as part of a long-term annual monitoring program and expanded five yearly, whole of port survey from the 24th October–6th November 2019.

2. Overall, **seagrass was in the best condition of the past decade** and one of the best conditions ever recorded in the 18 years that monitoring has been conducted.
    - The majority of individual annual monitoring meadows were in a good to very good condition for seagrass biomass, area and species composition.
    - For the first time since 2008 all three Rodds Bay monitoring meadows were in very good condition.
    - The **total area of seagrasses** in the Port Curtis and Rodds Bay region was the **highest ever recorded** and 26% greater than the last time the entire region was surveyed in 2014.

3. The only exception was the large Pelican Banks meadow adjacent to Curtis Island where condition remained poor. While meadow area increased in 2019, biomass remained low and the proportion of colonising species was higher than its baseline average.

4. A consistent high level of herbivory from turtles and dugong on the Pelican Banks meadow may explain its continued low biomass.

5. The overall greatly improved seagrass condition was likely due to a lack of major rainfall events and low river flows over the last two years, leading to favorable light conditions supporting seagrass growth.

6. Large deepwater seagrass meadows were present adjacent to the East Bank Sea Disposal Site (EBSDS) and there has been little change in seagrass condition over the preceding 10 years. The continued presence of seagrass in this area indicates that the EBSDS is having little impact on adjacent seagrasses.

7. There was no obvious relationship between proximity of port and anthropogenic activities and the condition of meadows suggesting regional environmental conditions rather than anthropogenic activity influenced seagrass changes in 2019.

8. In 2019 the robust condition of seagrasses in the region meant they will be **resilient to pressures in 2020** including planned maintenance and capital dredging.

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 and their condition reported annually 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. In addition to annual monitoring, periodic reassessment of all seagrass meadows in the entire Port Curtis and Rodds Bay region has been undertaken at various times during the monitoring program history. In 2019 both the annual monitoring meadows and seagrasses in the broader Port Curtis and Rodds Bay region were assessed including intertidal and shallow subtidal waters and deeper offshore waters of the port limits (Figure 2).

Overall seagrass condition in 2019 was good for the 14 monitoring meadows. A dramatic improvement over recent years with seagrass in the best condition recorded for the past decade and one of the best recorded in the 18 years of seagrass monitoring.

After several years of poor condition seagrasses had shown positive signs of recovery in 2018 and this trend continued in 2019 with all but two of the 14 individual monitoring meadows rated as being in good or very good condition (Figures 3 & 4 and section 3.4 for more details). Nine meadows increased to pre 2010 conditions and five monitoring meadows reached record biomass and/or area scores in 2019.

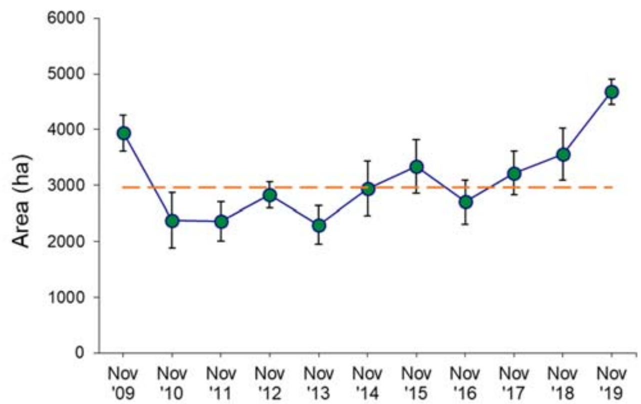

Figure 1. Annual variation in total seagrass area of the Port Curtis region (Narrows to Facing Island), and mean area 2009-2019 (red dashed line).

The healthy state of seagrasses in the annual monitoring meadows was reflected more broadly across the region where a record 16,880 ha of seagrass was mapped (Figure 2). This is the largest area of seagrass recorded since monitoring began in 2002 and a 26% increase since the last time the broader region was assessed in 2014. The area that encompasses the majority of port activity between The Narrows and Facing Island has been mapped annually between 2009 and 2018 and in 2019 also had the highest recorded area of seagrass since intensive monitoring began there in 2009 (Figure 1).

In the out of port reference area at Rodds Bay seagrass was nearly lost between 2011 – 2013 but has now recovered to cover a greater area and highest seagrass biomass since 2009. The recovery of seagrasses here and elsewhere in the Port Curtis region is likely linked to more favourable environmental conditions over the last two years, with below average rainfall and local river flows, an absence of floods or major cyclone impacts, leading to ideal conditions for seagrass growth (Figure 5).

The seagrass meadow at Pelican Banks is the only area in the Port Curtis and Rodds Bay region that remained in poor overall condition in 2019. This meadow experienced significant reductions in biomass and the proportion of the foundation species over the past five years, consistently being scored as poor or very poor. While meadow area increased in 2019, overall condition remained poor as a result of continued low biomass and poor species composition. It is possible this is due to high levels of herbivory from green turtles and dugongs, with recent studies indicating they have a major influence on seagrass condition in the Gladstone region. However, given this meadow's importance as a key seagrass resource in Port Curtis, continued recovery remains key to overall marine environmental health in the region.

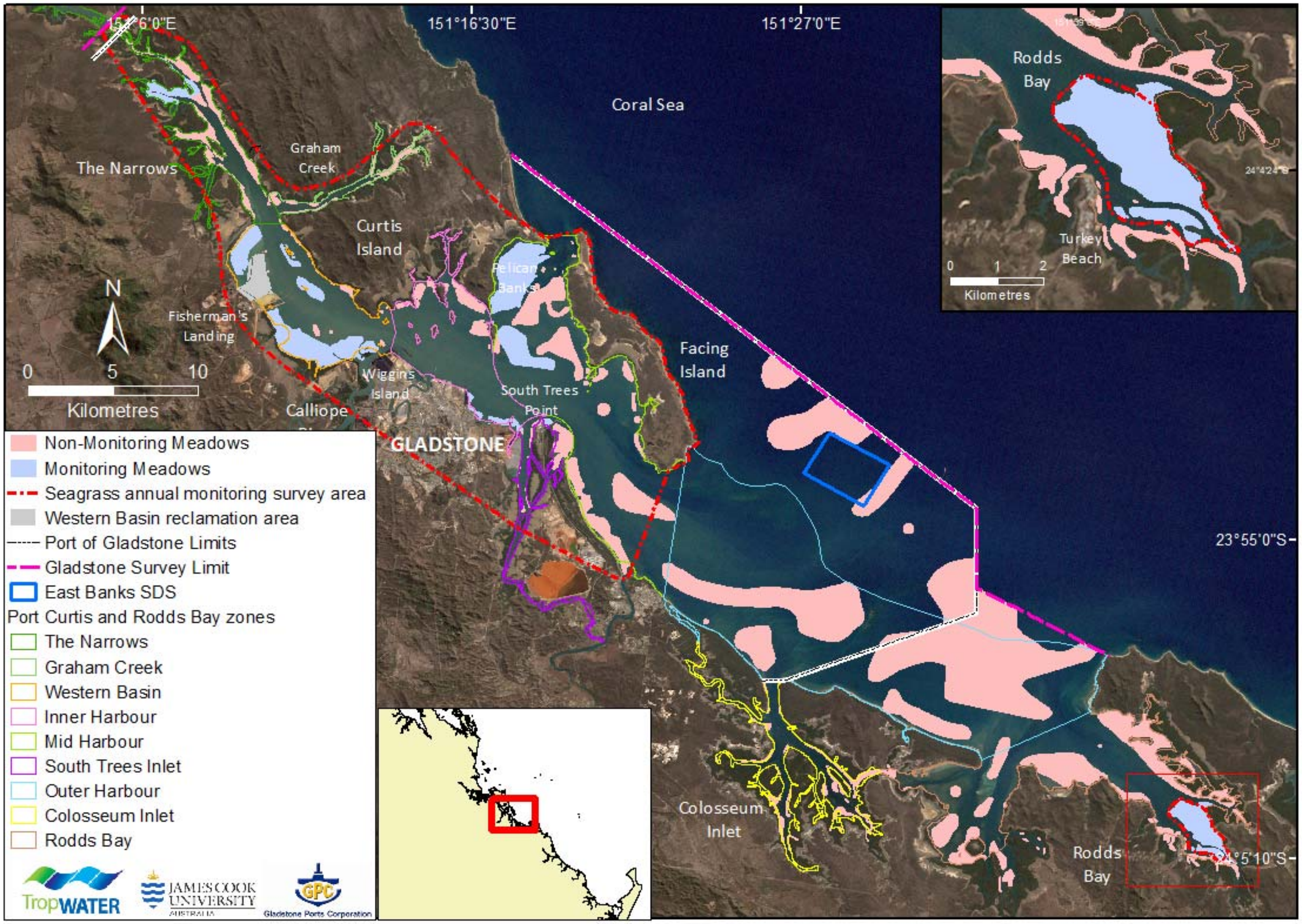

Figure 2. Seagrass distribution within the Port Curtis and Rodds Bay whole of port monitoring areas, November 2019.

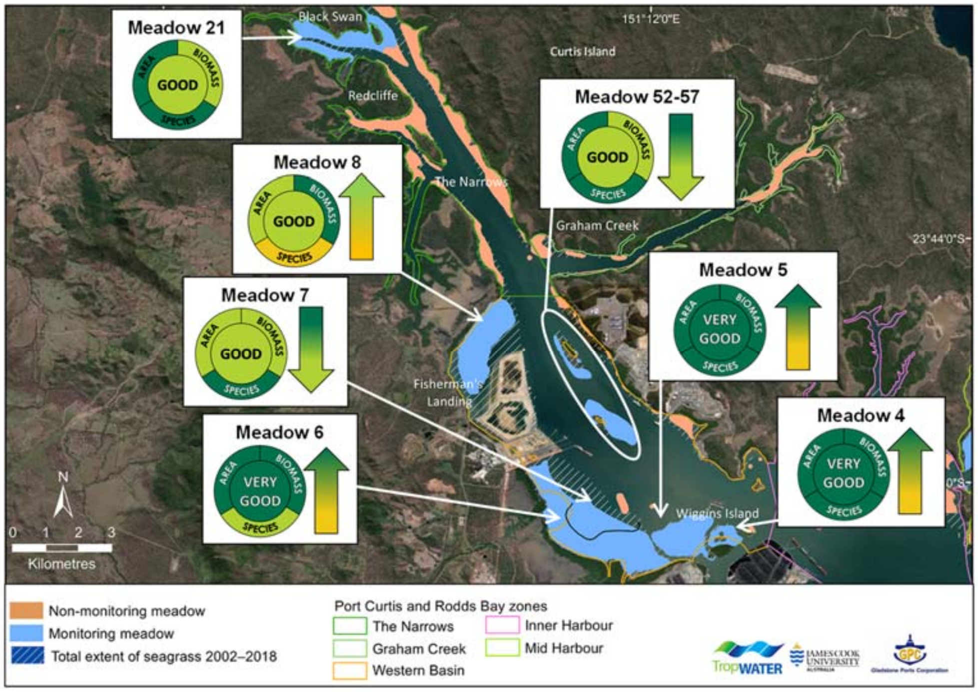

Figure 3. Seagrass distribution and meadow condition in The Narrows and Western Basin Zones (Port Curtis), November 2019. Arrows indicate an overall grade change from 2018.

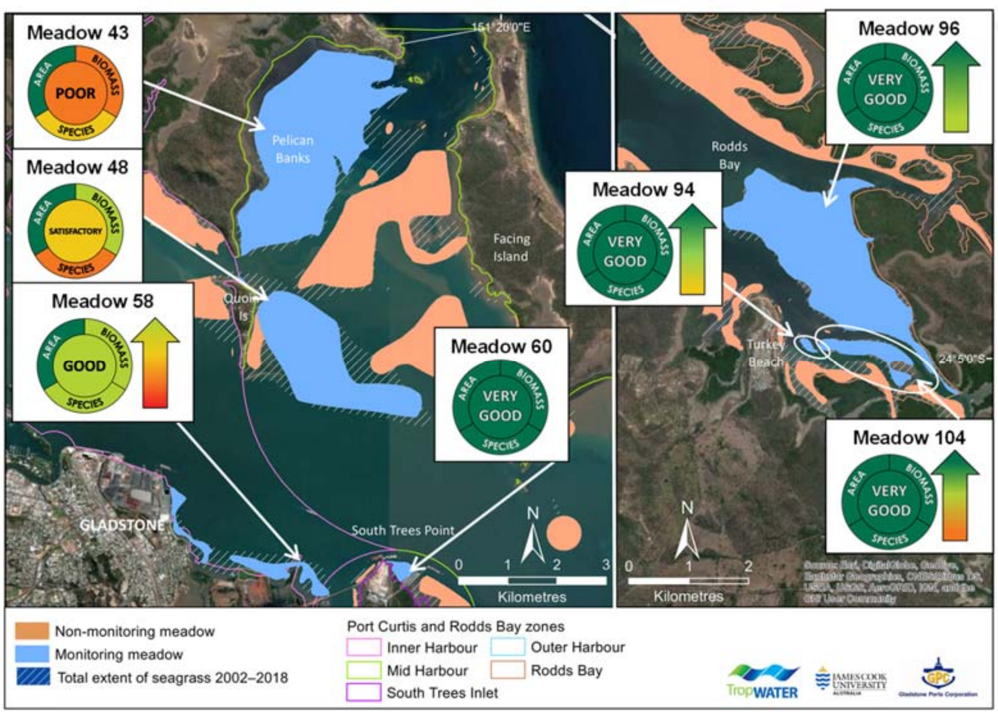

Figure 4. Seagrass distribution and meadow condition in the Inner Harbour, Mid Harbour, and South Trees Inlet Zones (Port Curtis), and Rodds Bay, November 2019. Arrows indicate an overall grade change from 2018.

Resilience of seagrasses in Port Curtis and Rodds Bay to further natural or anthropogenic impacts in 2020 including planned maintenance and capital dredging will have improved due to the increase in seagrass biomass and area recorded in 2019.

The recovery of seagrasses in Port Curtis and Rodds Bay is in line with trends in other seagrass areas monitored as part of the network of seagrass monitoring in Queensland. Where local environmental and weather conditions have been favourable such as in Cairns and Mackay/Hay Point seagrasses have similarly recovered. In Townsville and Karumba where localised floods occurred in 2019 seagrasses declined. For full details of the Queensland ports seagrass monitoring program see: www.tropwater.com/project/management-of-ports-and-coastal-facilities/

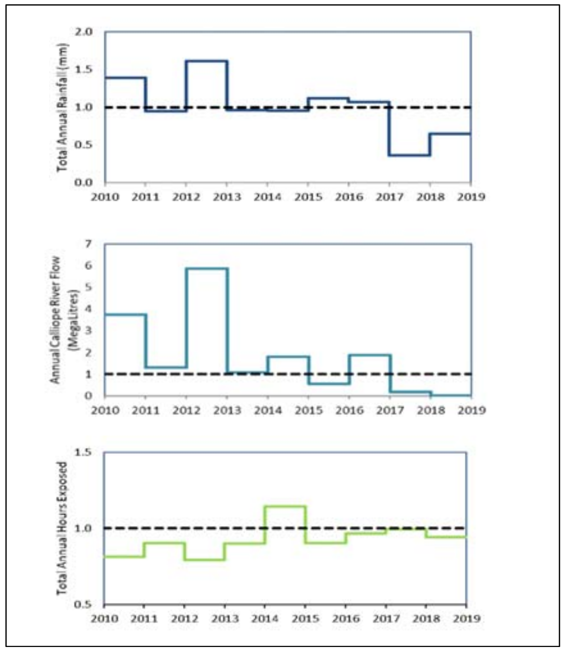

Figure 5. Climate trends in Port Curtis, 2009 to 2019. Annual average (solid coloured line) expressed as a relative change where 1.0 equals the long-term average (dashed line). Long-term averages calculated for rainfall (1958-2019), river flow (1974-2019), hours daytime tidal exposure hours (2002-2019). See Section 5.3 for detailed climate data.

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ACRONYMS AND ABBREVIATIONS

dbMSL	Depth below Mean Sea Level
DFT	Dugong Feeding Trail
DPA	Dugong Protection Area
DW	Dry Weight
EBSDS	Eastern Bank Sea Disposal Site
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 Monitoring Program
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 is 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. A common method and rationale provides a network of seagrass monitoring locations comparable across the State (Figure 6).

Figure 6. Location of Queensland ports where seagrass monitoring occurs. Red dots: long-term monitoring; blue dots: baseline mapping only.

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.

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 in this report (Carter et al. 2015a; Bryant et al. 2014c; Thomas et al. 2010).

The current program has been developed to meet GPC's obligations pertaining to the Long Term Maintenance Dredging Monitoring Plan and includes annual mapping and monitoring of the 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 include biannual surveys of Port Curtis and Rodds Bay monitoring areas from 2010-2014 (Carter et al. 2015a; Bryant et al. 2014c; 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), and the establishment of seagrass light requirements and investigations of sub-lethal indicators of seagrass stress (Schliep et al. 2015; Chartrand et al. 2012; 2016).

Annual monitoring and the additional programs have demonstrated considerable 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 also are 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). Seagrass biomass and area is at its lowest around June, and peaks between October and November (Chartrand et al. 2017). Annual monitoring is scheduled to coincide with that peak.

High rainfall, river outflow and tropical cyclones from La Nina events in 2009 and 2010 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 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 conditions, low rainfall and river outflow saw an improvement in meadow condition in 2018 (Chartrand et al. 2019). In this report, we update seagrass condition for the established monitoring meadows in 2019, as well as conducting a reassessment of all seagrasses within the Port Curtis and Rodds Bay region last conducted in 2014.

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 24th October– 6th November 2019 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
- All intertidal and shallow subtidal seagrasses within Port Curtis and the Rodds Bay (updated coastal and whole of port survey)
- Deep-water areas within Port Curtis and the Rodds Bay (updated deep-water survey)

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 7a). Shallow subtidal meadows were sampled by boat using camera drops and 0.03 m^2 van Veen grab (Figure 7b, 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. Random sites also were surveyed within 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 2.3.1.

At each deep-water offshore sampling site an underwater camera system was towed for approximately 100 m while footage was observed on a monitor and recorded. Benthos on the seafloor was captured in the net and used to confirm seagrass species observed on the monitor. The technique ensures that a large area of seafloor was sampled at each site so that patchily distributed seagrass typically found in deep-water habitats was detected. Seagrass species composition was measured from the sled net sample and from the video screen and species identified according to Waycott et al. (2014). Seagrass biomass estimates were made from video images using a calibrated visual estimates technique (see below).

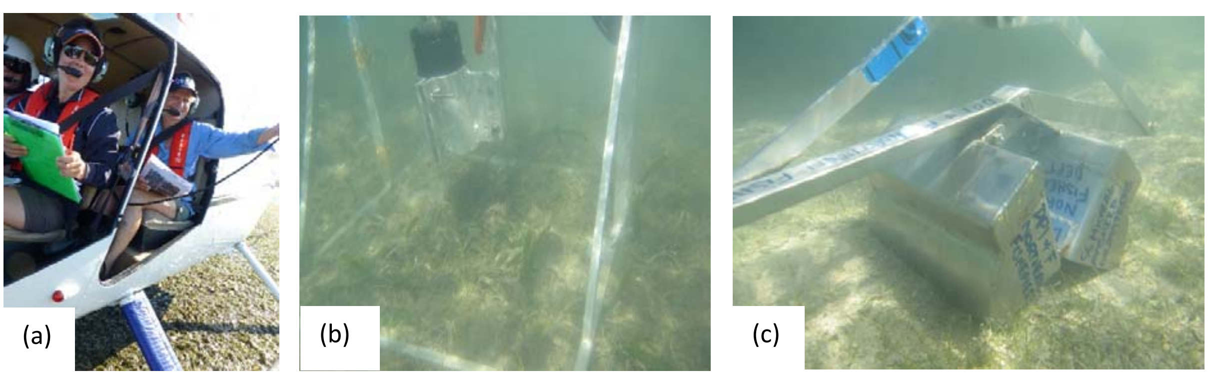

Figure 7. Seagrass monitoring methods in 2019. (a) helicopter survey of intertidal seagrass, (b, c) boat-based camera drops and van Veen grab for subtidal seagrass.

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 randomly three times. For deep-water video transect analysis 10 randomly assigned 0.25 m^2 quadrats were assessed for each 100m transect. 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 using ArcGIS 10.7®. 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 $\pm$ standard error (SE), meadow area (hectares) $\pm$ 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 8).
- 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: Landsat 2019, courtesy ESRI), and aerial photographs taken during helicopter surveys. Meadow area was determined using the calculate geometry function in ArcGIS®. 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
<10 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.

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.

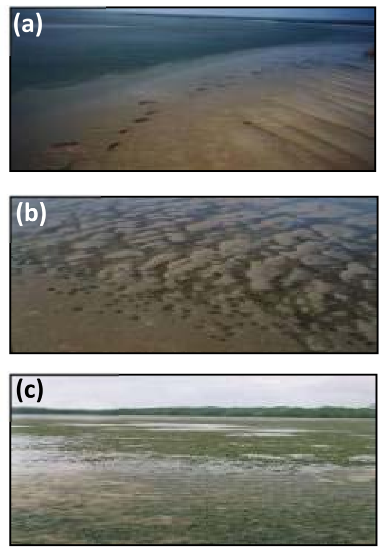

Figure 8. Seagrass meadow landscape categories: (a) Isolated seagrass patches, (b) aggregated seagrass patches, (c) continuous seagrass cover.

2.4 Environmental data

Environmental data were collated for the 12 months preceding each survey. Tidal data was provided by Maritime Safety Queensland (© The State of Queensland (Department of Transport and Main Roads) 2019, 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 Airport station #039123; http://www.bom.gov.au/climate/data/). Calliope River water flow data (total monthly megalitres) was obtained from the Department of Natural Resources and Mines (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 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 9 summarises the methods used to calculate seagrass condition. See Appendix 1 and 2 for full details of score calculation.

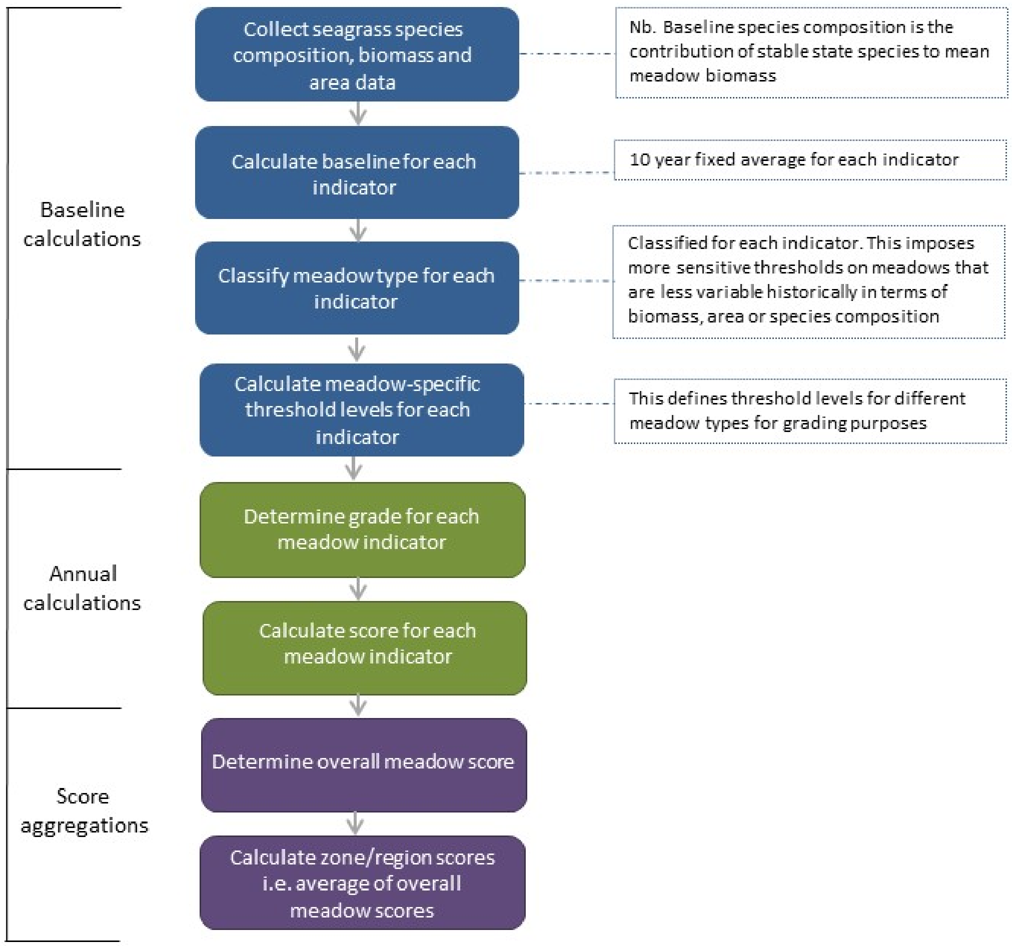

Figure 9. Flow chart used to determine monitoring meadow condition.

3 RESULTS

3.1 Seagrasses in Port Curtis and Rodds Bay

A total of 2,384 coastal sites and 116 deep water transects were surveyed in the Port Curtis and Rodds Bay whole of port monitoring survey area in 2019 (Figure 10). Five seagrass species from three families were observed during the survey (Figure 11). A total seagrass area of 16,879 ± 1,868 ha was mapped across the entire survey area including 1,107 ± 38 ha in the Western Basin, 2,490 ± 153 ha in Rodds Bay, 9,434 ± 1,438 ha of deep-water seagrass which hasn't been mapped since 2014 and 289 ± 57 ha in Colosseum Inlet. Dugong feeding trails were observed throughout the Port Curtis and Rodds Bay survey areas with the exception of Graham Creek, Rodds Bay, Colosseum Inlet and deep water meadows.

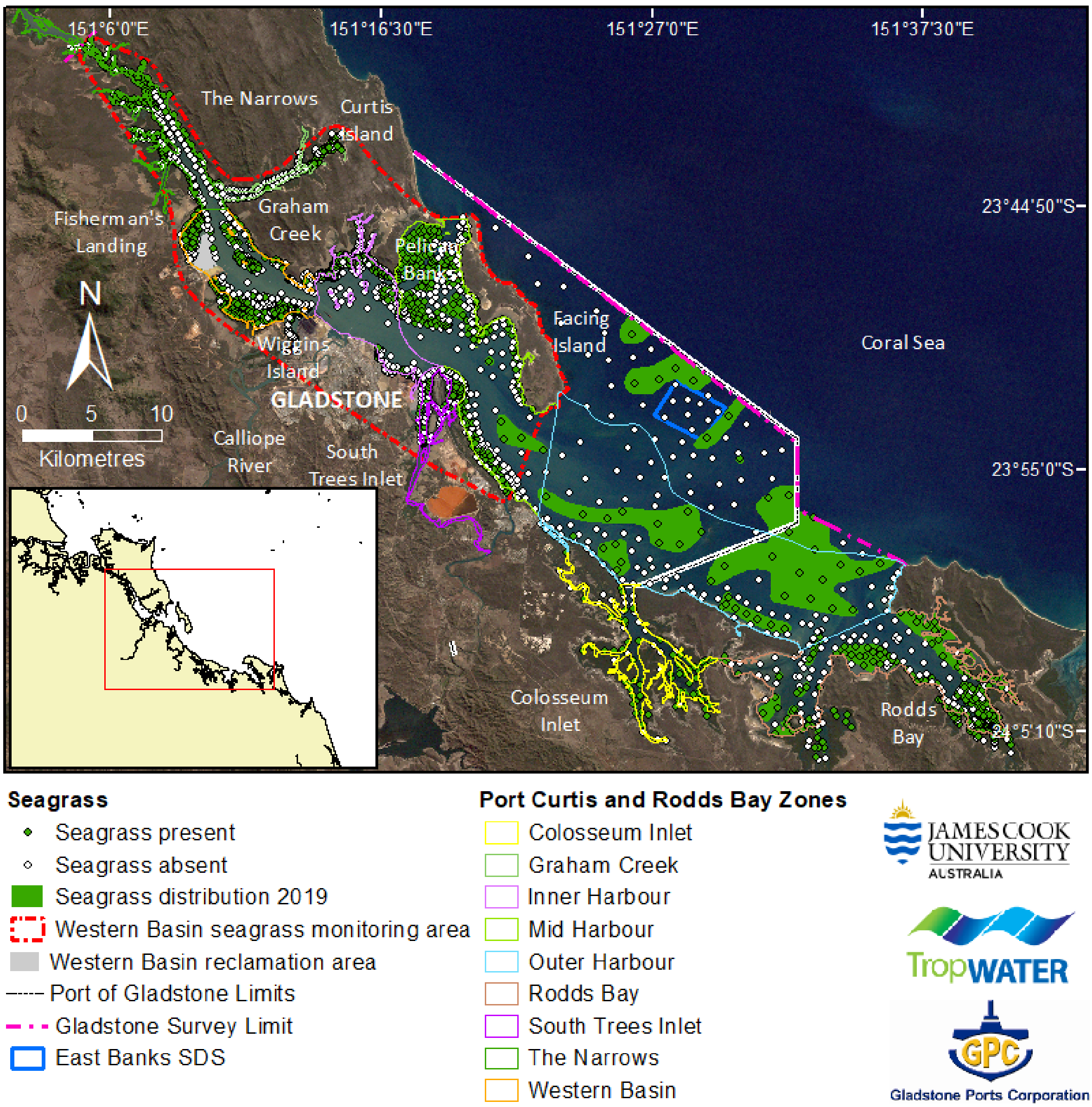

Figure 10. Seagrass presence/absence at sites surveyed within Port Curtis and Rodds Bay survey areas, 2019.

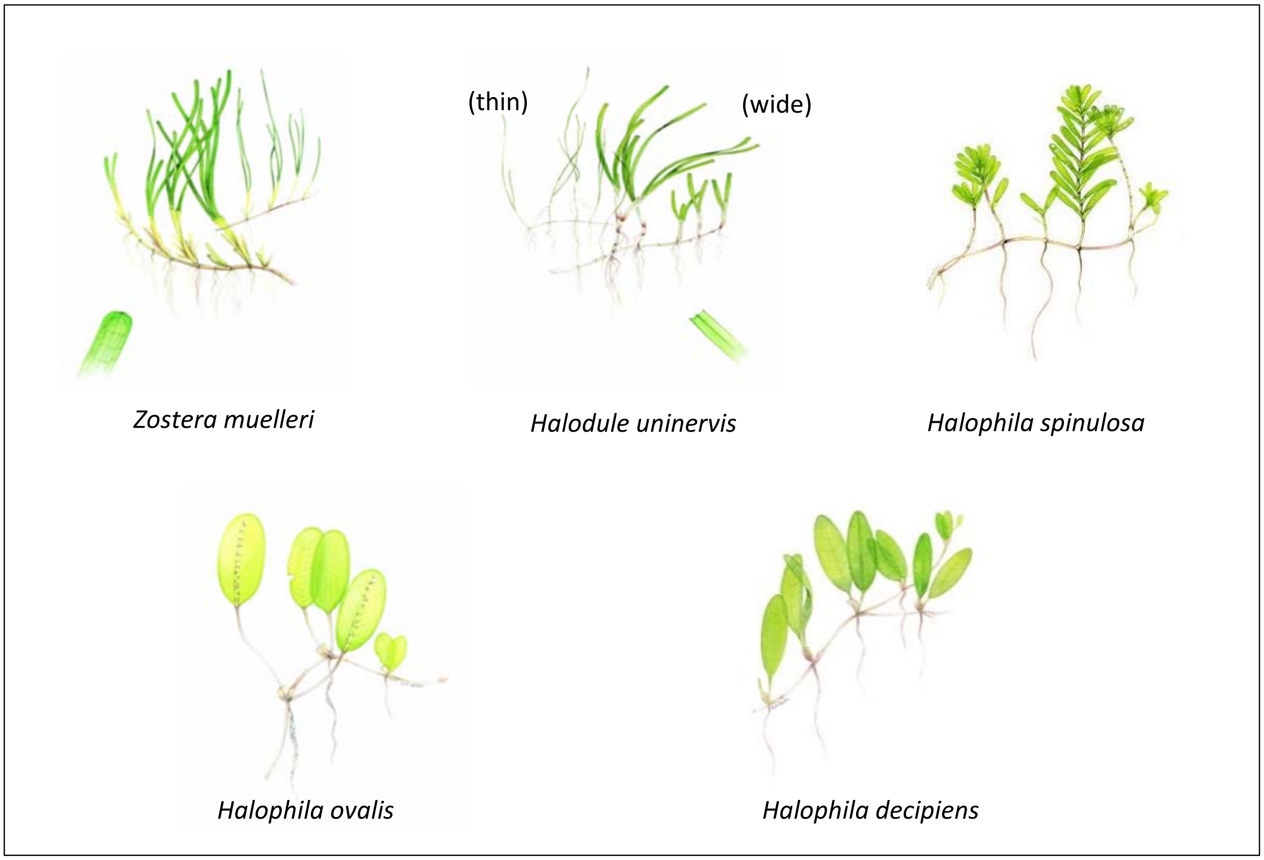

Figure 11. Seagrass species present in Port Curtis and Rodds Bay, 2019.

3.2 Seagrass condition for individual meadows and zones

The overall condition score for Port Curtis and Rodds Bay seagrass was good, an improvement following a satisfactory score in 2018 and consistently poor condition score from 2015-2017 (Table 4). Individual annual monitoring meadow condition improved or remained stable from 2018 for 12 of the 14 meadows. The two meadows that declined (Meadows 7 and 52-57) still remained in good condition. Seven meadows were in very good condition (Table 4).

Port Curtis and Rodds Bay has been partitioned into zones (see Figure 2) for the purposes of assessing water quality and for developing a regional report card. We present the results for the 2019 seagrass monitoring for each of the zones where we have seagrass information. For each zone we present the results for annual monitoring meadows used to generate seagrass condition scores as well as the results from the expanded whole of port mapping that captures all seagrasses present for a particular zone.

Table 4. Grades and scores for seagrass indicators (biomass, area and species composition) for Port Curtis and Rodds Bay seagrass monitoring meadows. Overall meadow score is the lowest of the biomass or area scores, or where species composition is the lowest score it makes up 50% of the score with the other 50% from the next lowest indicator (see Appendix 1 and Table A3 for a full description of scores and grades).

Monitoring meadow	Biomass score	Area score	Species composition score	Overall meadow score
4	1.00	0.91	0.94	0.91
5	0.89	0.92	0.88	0.88
6	0.90	0.90	0.78	0.84
7	0.76	0.73	1.00	0.76
8	0.90	0.82	0.59	0.71
21	0.80	0.97	0.94	0.80
43	0.33	0.95	0.59	0.33
48	0.77	0.91	0.35	0.56
52-57*	0.79	1.00	1.00	0.79
58	0.70	0.97	0.76	0.70
60	0.99	1.00	0.99	0.99
94	0.90	0.86	0.99	0.86
96	0.89	1.00	0.94	0.89
104	0.85	0.85	0.91	0.85
Overall score for Gladstone seagrass monitoring meadows				**0.78**

* Meadow 52-57 consists of several small meadows surrounding the Passage Islands that are grouped for reporting purposes (Figure 2).

3.2.1 The Narrows

Seagrass meadow area in The Narrows increased by 70 ha from 2018, with 13 meadows covering 711 ± 67 ha. The largest meadows were on exposed banks at Black Swan Island and Redcliffe (Meadows 21 and 23), and along the banks of Curtis Island (Meadows 19 and 33, Figure 12, Appendix 3). Seagrass communities were continuous or aggregated patches of light *Z. muelleri* with some *Halophila ovalis* and *H. decipiens* meadows. Meadow biomass ranged from 12.15 ± 3.19 g DW m^{-2} for aggregated patches of *Z. muelleri* at the northernmost survey area (Meadows 10 and 17) to 0.27 ± 0.17 g DW m^{-2} for isolated patches of *H. decipiens* in subtidal isolated patches on the eastern subtidal banks of The Narrows (Meadow 13) (Figure 12 and Appendix 3).

Long-Term Monitoring Meadows

The sole long-term monitoring meadow in The Narrows at Black Swan Island was in very good condition (Meadow 21; Figure 13). Mean biomass increased from 5.01 ± 1.22 g DW m^{-2} in 2018 to 6.04 ± 1.41 g DW m^{-2}. Meadow area remained in very good condition while species composition improved to very good in 2019; the dominant species *Z. muelleri* comprised 93% of mean meadow biomass (Figure 13; Appendix 4).

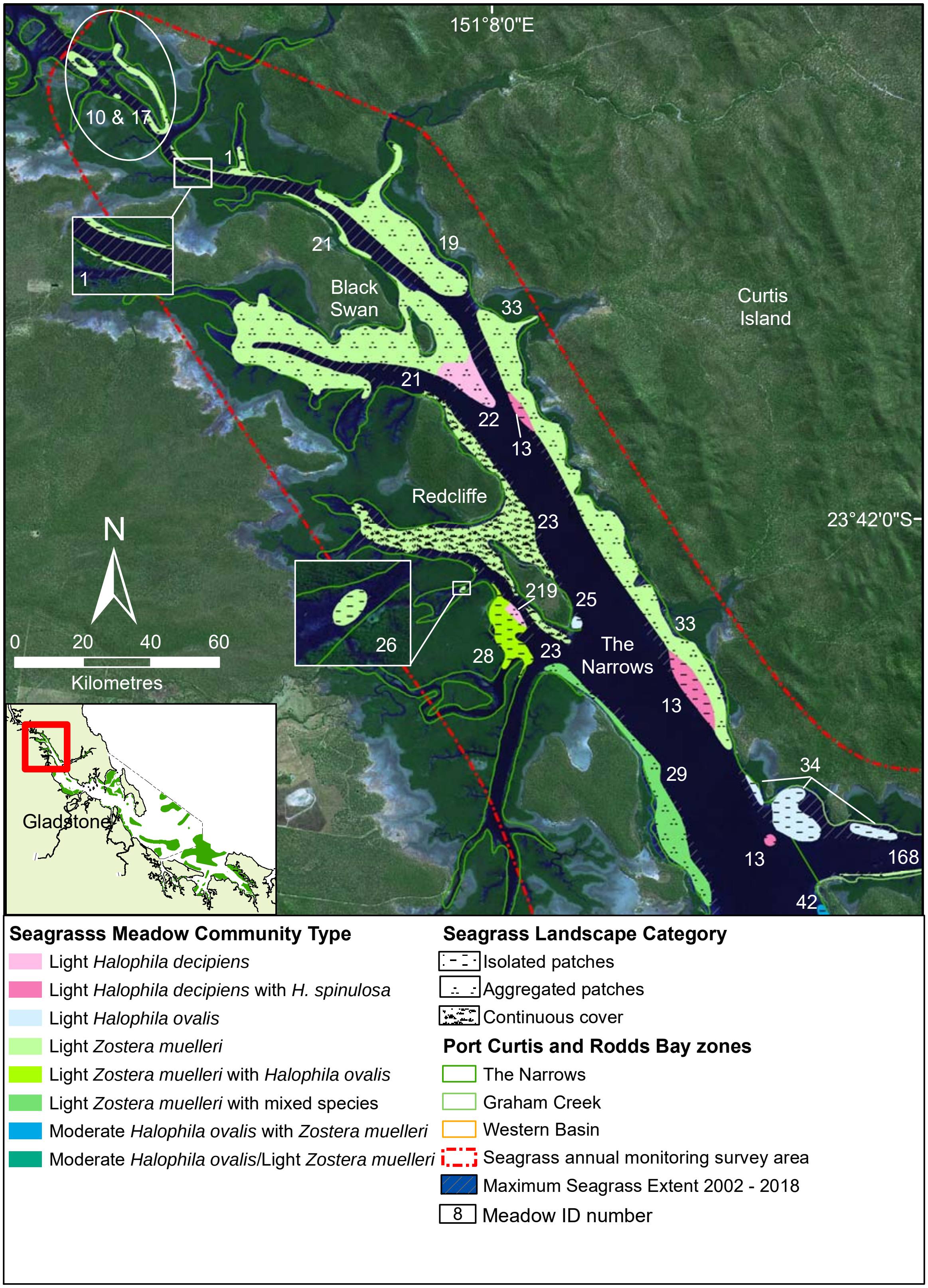

Figure 12. Seagrass distribution and community types in The Narrows, 2019.

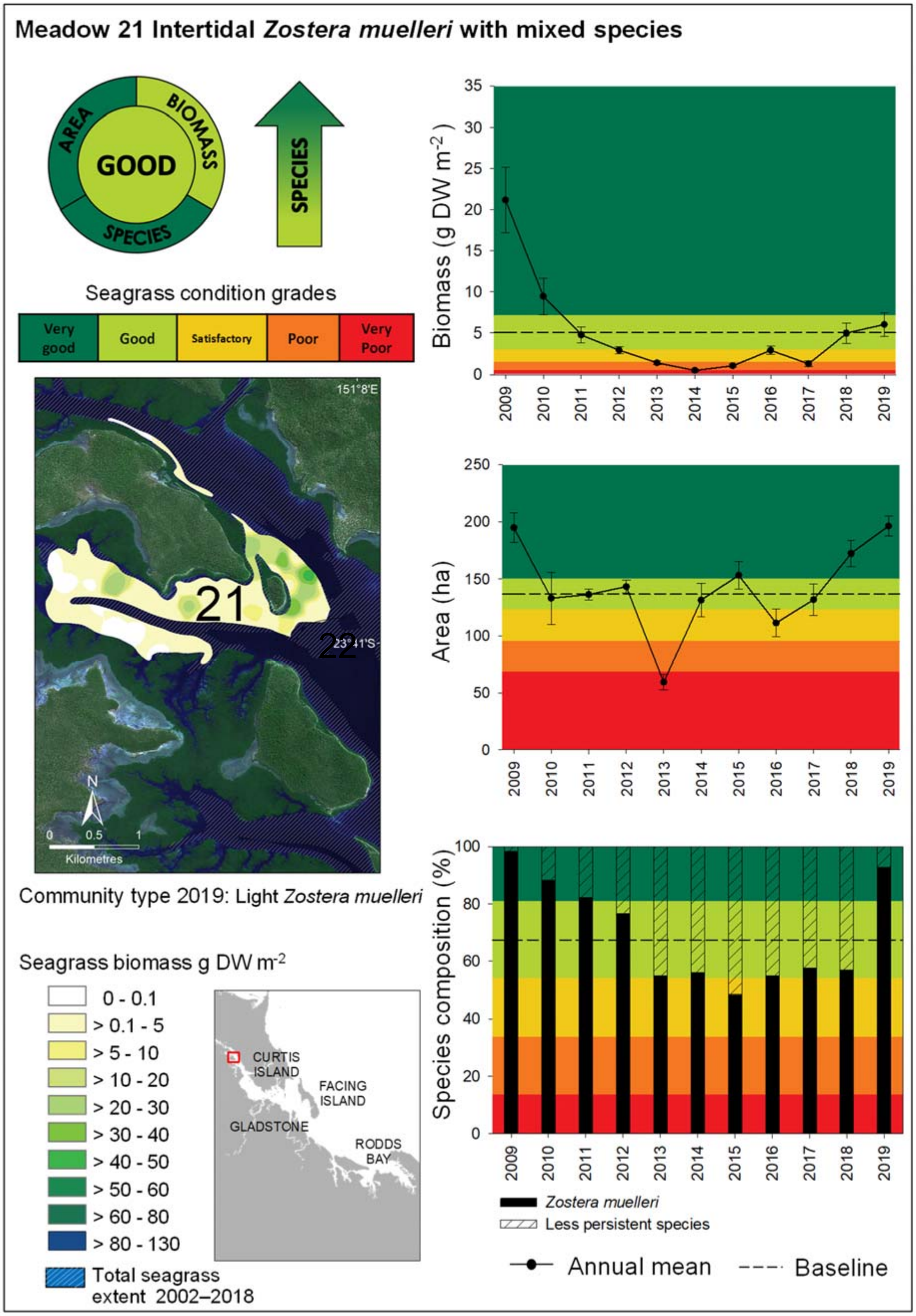

Figure 13. Changes in meadow area, biomass and species composition for seagrass at Meadow 21, Black Swan (The Narrows Zone), 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.2.2 Graham Creek (Upper and Lower)

Seagrasses in the Graham Creek (Upper and Lower) Zone formed eleven individual meadows covering 107 ± 15 ha. The majority of meadows were isolated or aggregated patches of *Z. muelleri* or *H. ovalis* covering less than 2 ha. The largest meadow covered 76 ± 6 ha at the top of the creek, and also had the highest biomass, 2.73 ± 1.14 g DW m^{-2} (Meadow 37 and 41; Figure 14 and Appendix 3). Biomass was low for all other meadows in Graham Creek (< 2.5 g DW m^{-2}).

Meadows in Graham Creek have been dominated by *Halophila* spp. over the last two monitoring periods following the decline in dominance by *Z. muelleri* in 2016 (Figure 14, Chartrand et al 2009). Prevalence of *Z. muelleri* has increased in 2019 being the dominant species in 45% of meadows. The presence of *H. decipiens* in the Graham Creek meadows has decreased since 2018 and remains reduced compared to 2015 levels. Graham Creek has no long-term monitoring meadows.

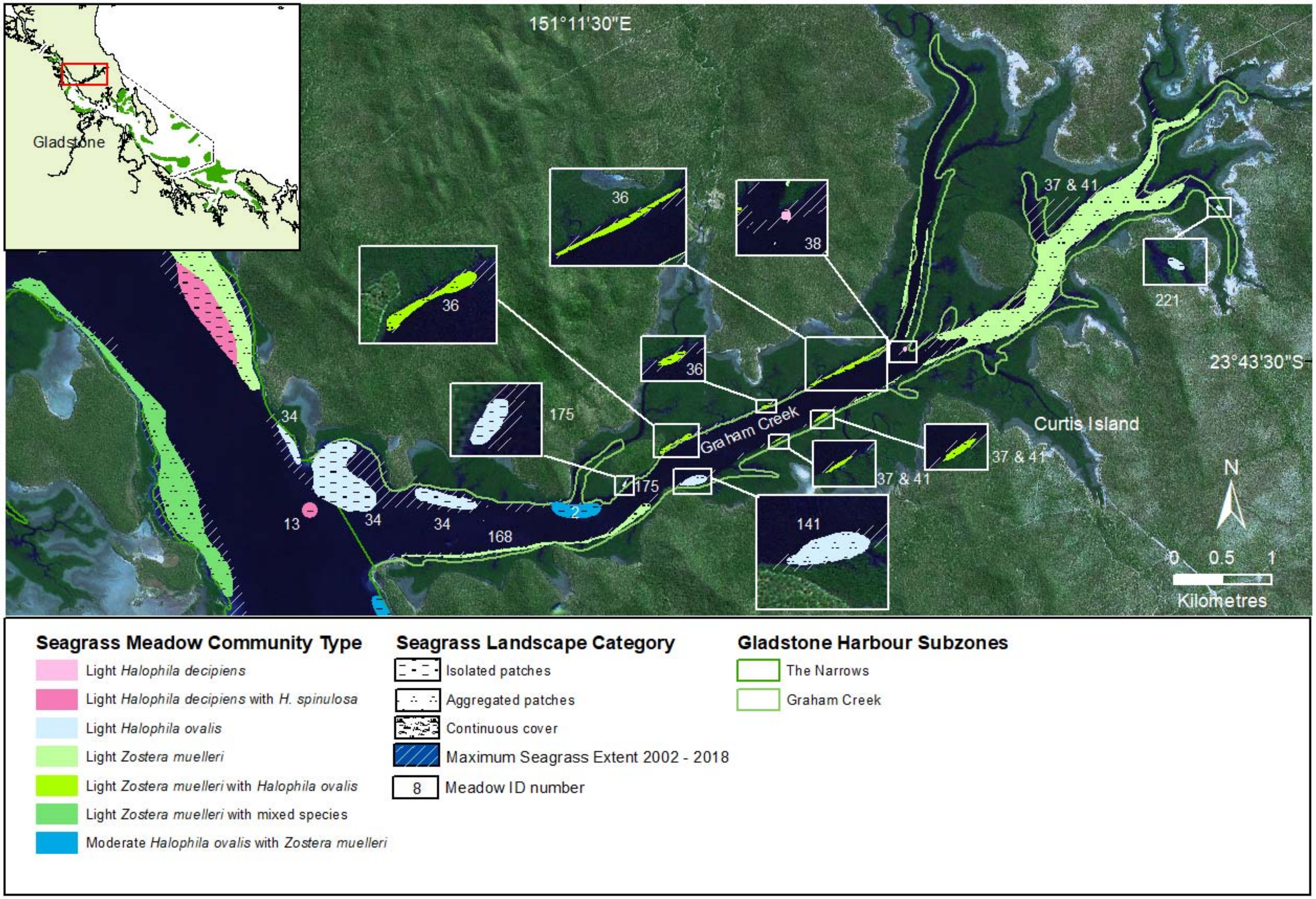

Figure 14. Seagrass distribution and community types in Graham Creek Zone, 2019.

3.2.3 Western Basin

Seagrasses in the Western Basin covered 1107 ± 38 ha in 2019, increasing from 943 ± 73 in 2018. *H. ovalis* continued to dominate most meadows with light to moderate biomass across the Zone (Figure 15; Appendix 3). Meadow biomass ranged from very low *H. decipiens* and *H. ovalis* patches to 5.74 ± 1.01 g DW m^{-2} in a *Z. muelleri* meadow at Wiggins Island (Meadow 4; Figure 15).

In contrast to 2018, intertidal meadows along the developed Curtis Island shoreline increased in size and number. Small patches of subtidal *H. decipiens* and *H. ovalis* persisted along the eastern boundary of the Western Basin Reclamation Area, an area previously dominated by subtidal *H. decipiens* and part of the long-term monitoring program (see Thomas et al. 2010; Meadow 9; Figure 15). The South Fisherman's Landing intertidal meadow (Meadow 6, Figure 15) remained the largest in area at 434 ha and formed continuous cover over the mud bank.

Long-Term Monitoring Meadows

There are six long-term monitoring meadows in the Western Basin Zone, including five intertidal and one subtidal meadow.

Meadow 4:

Meadow 4 at Wiggins Island was in very good condition (Figure 16; Appendix 3). The improvement from satisfactory to very good was caused by an increase in the presence of *Z. muelleri*, the historically persistent species in the meadow and the steady continual increase in area over recent years (Figure 16; Appendix 3). Overall meadow biomass rose to 5.51 ± 1.22 g DW m^{-2}, the highest biomass recorded since monitoring began in 2002 (Figure 16; Appendix 3).

Meadow 5:

The intertidal *Z. muelleri* meadow west of Wiggins Island also improved to very good condition in 2019 (Figure 17; Appendix 3). The Meadow 5 score was driven by *Z. muelleri* dominating the species composition (81%) for the first time since 2010. Meadow area also increased to pre-2010 levels while biomass was stable (Figure 17).

Meadow 6:

Meadow 6 at South Fisherman's Landing improved to very good condition in 2019 (Figure 18; Appendix 3). The improvement in the score can be attributed to an improvement in the species composition score to baseline levels of *Z. muelleri*. There was also an increase in meadow area to very good and biomass was stable.

Meadow 7:

The only subtidal monitoring meadow in the Western Basin, Meadow 7, was in good condition, a decrease from very good in 2018 (Figure 19). Both biomass and area decreased to baseline levels after decadal highs in 2018. There was no change in species composition (Figure 19; Appendix 3).

Meadow 8:

The intertidal meadow 8 at North Fisherman's Landing improved to good condition in 2019. Unlike other intertidal monitoring meadows in the Western Basin, the historically dominant *Z. muelleri* increased but remained below the baseline level of 67% (Figure 20; Appendix 4). Biomass has been in good or very good condition since 2012 and was very good in 2019. Meadow area improved to above baseline levels for the first time since 2009 (Figure 20).

Meadows 52-57:

Meadows 52-57, are a group of predominantly intertidal meadows surrounding the Passage Islands. In 2019 the overall condition for these meadows was very good (Figure 21). Meadow area was the highest it has been since monitoring began in 2009. *H. ovalis* was the dominant species followed by the more persistent *Z. muelleri*. There was a decline in biomass from 2018 to baseline levels, the first time in 4 years biomass has been below very good (Figure 21; Appendix 3). The decline in biomass led to a decrease in the overall meadow score from very good to good.

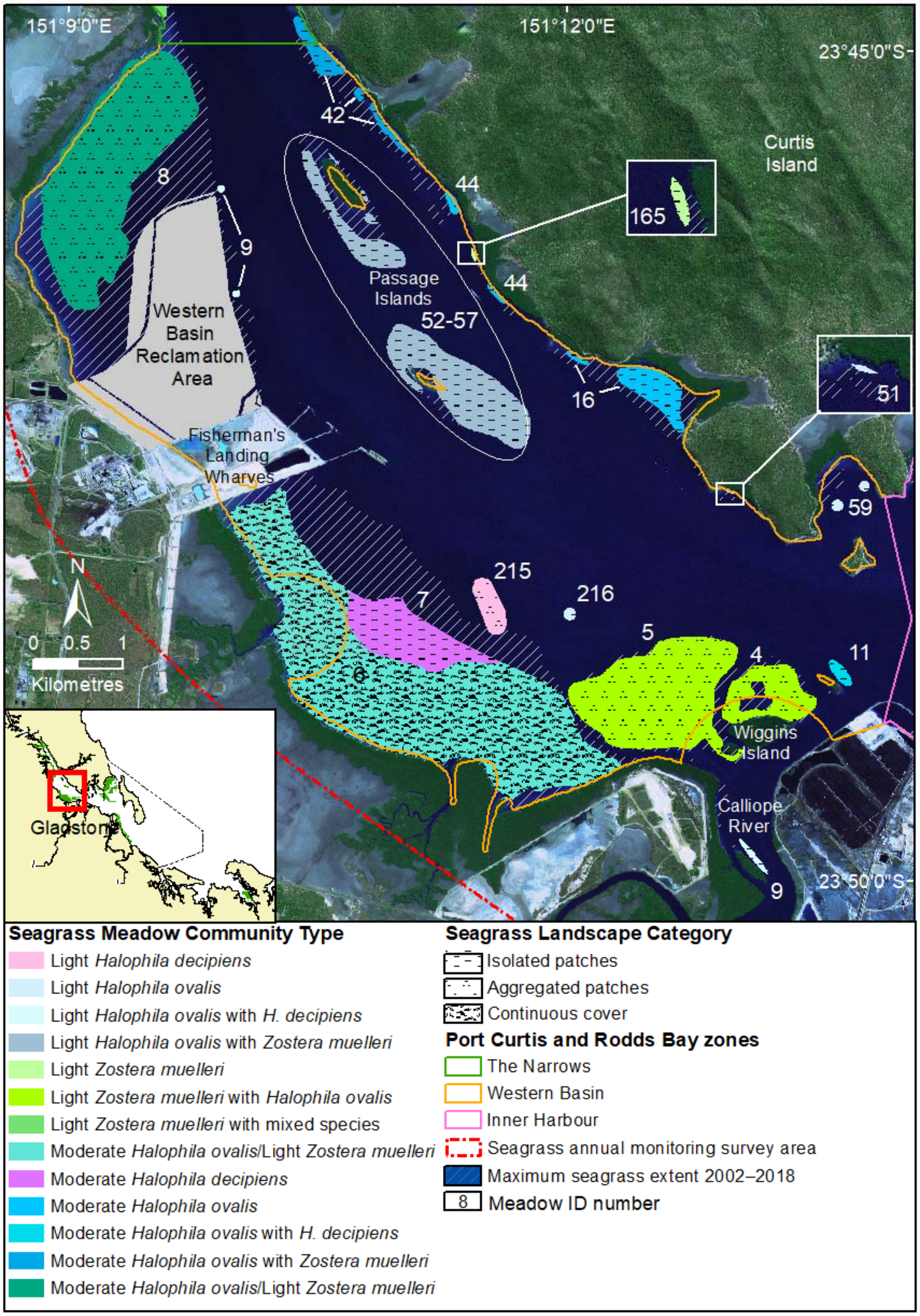

Figure 15. Seagrass distribution and community types in the Western Basin Zone, 2019.

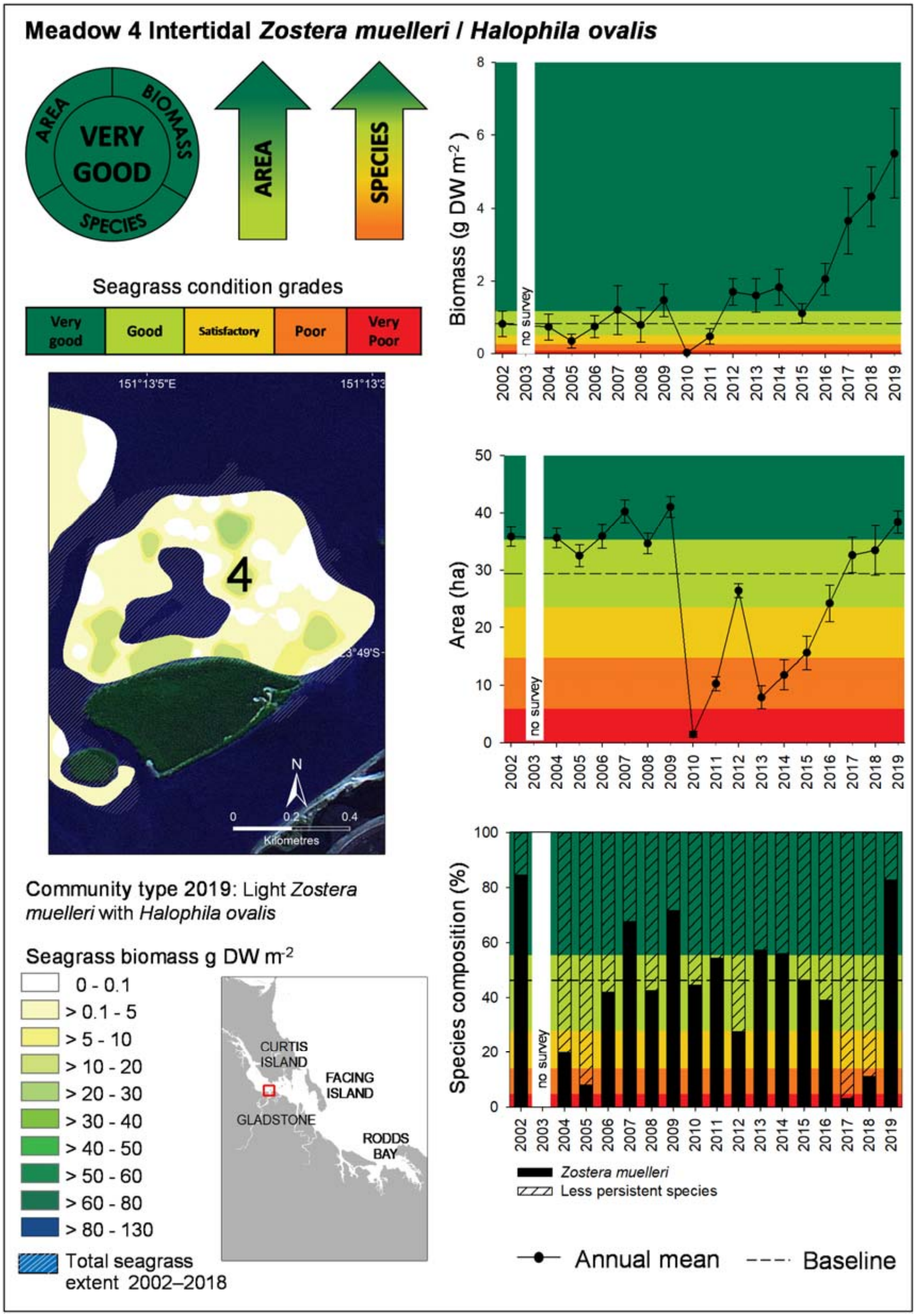

Figure 16. Changes in meadow area, biomass and species composition for seagrass at Meadow 4, Wiggins Island (Western Basin Zone), 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate).

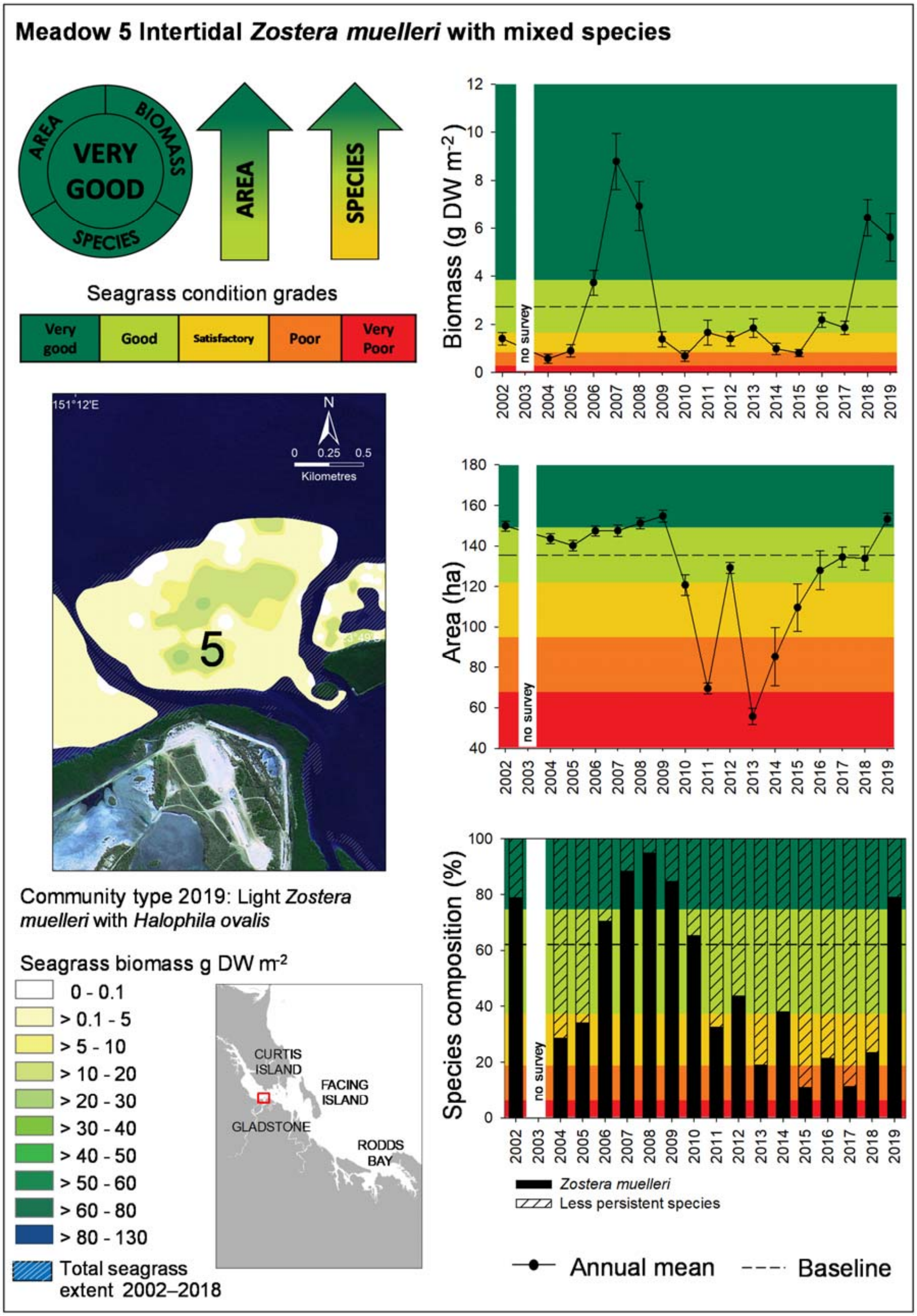

Figure 17. Changes in meadow area, biomass and species composition for seagrass at Meadow 5, Wiggins Island (Western Basin Zone), 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate).

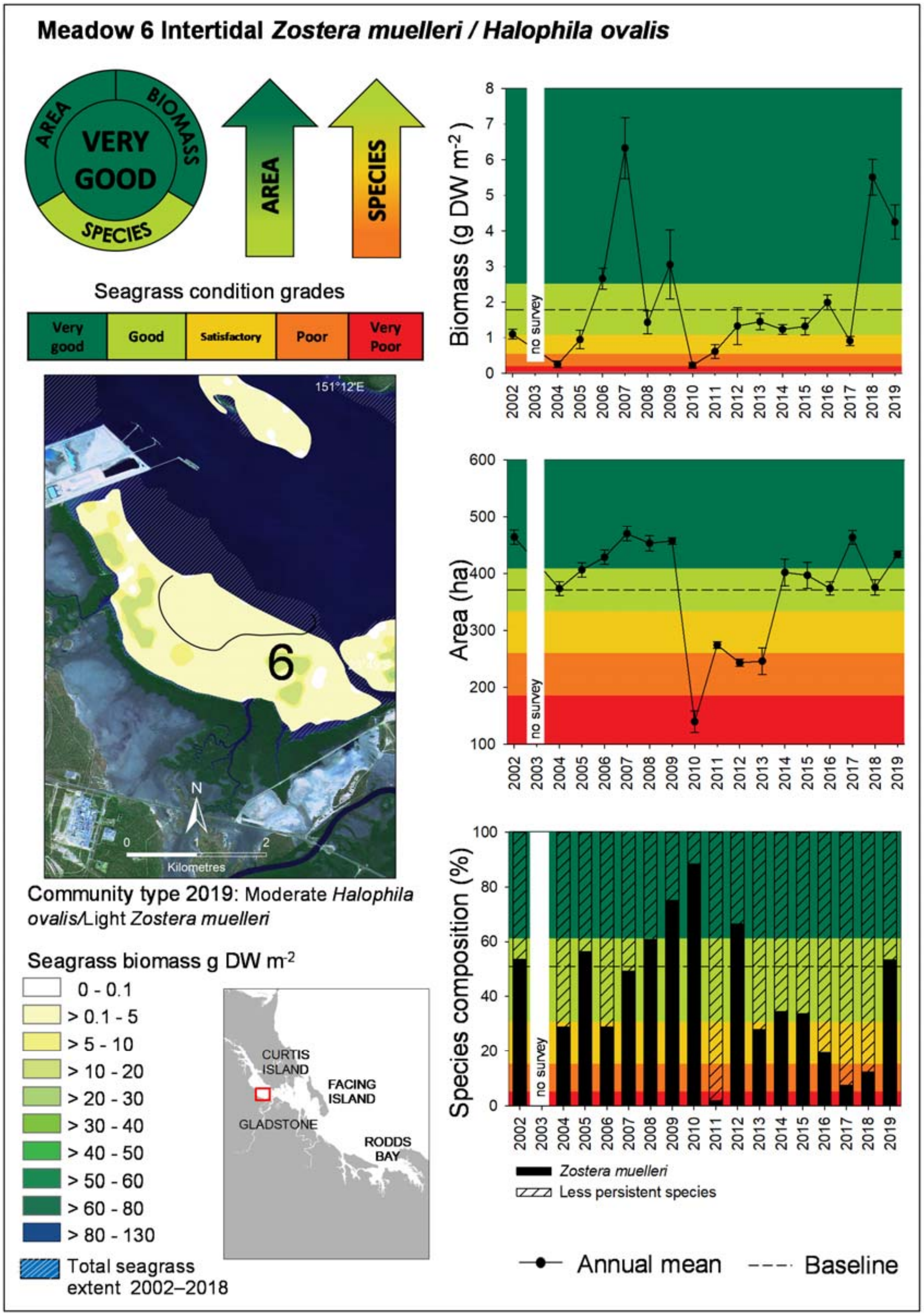

Figure 18. Changes in meadow area, biomass and species composition for seagrass at Meadow 6, South Fisherman's Landing (Western Basin Zone), 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate).

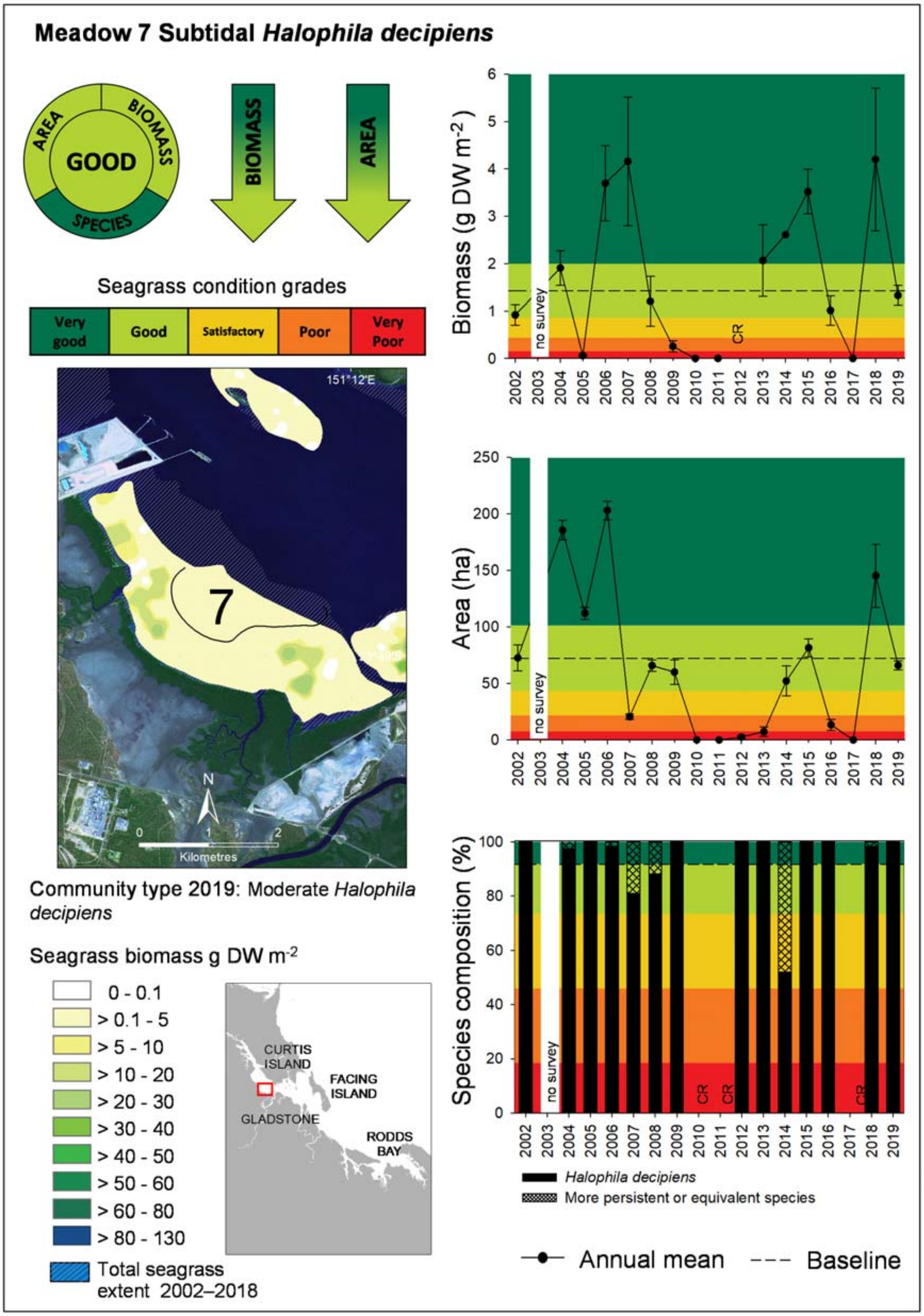

Figure 19. Changes in meadow area, biomass and species composition for seagrass at Meadow 7, South Fisherman's Landing (Western Basin Zone), 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate).

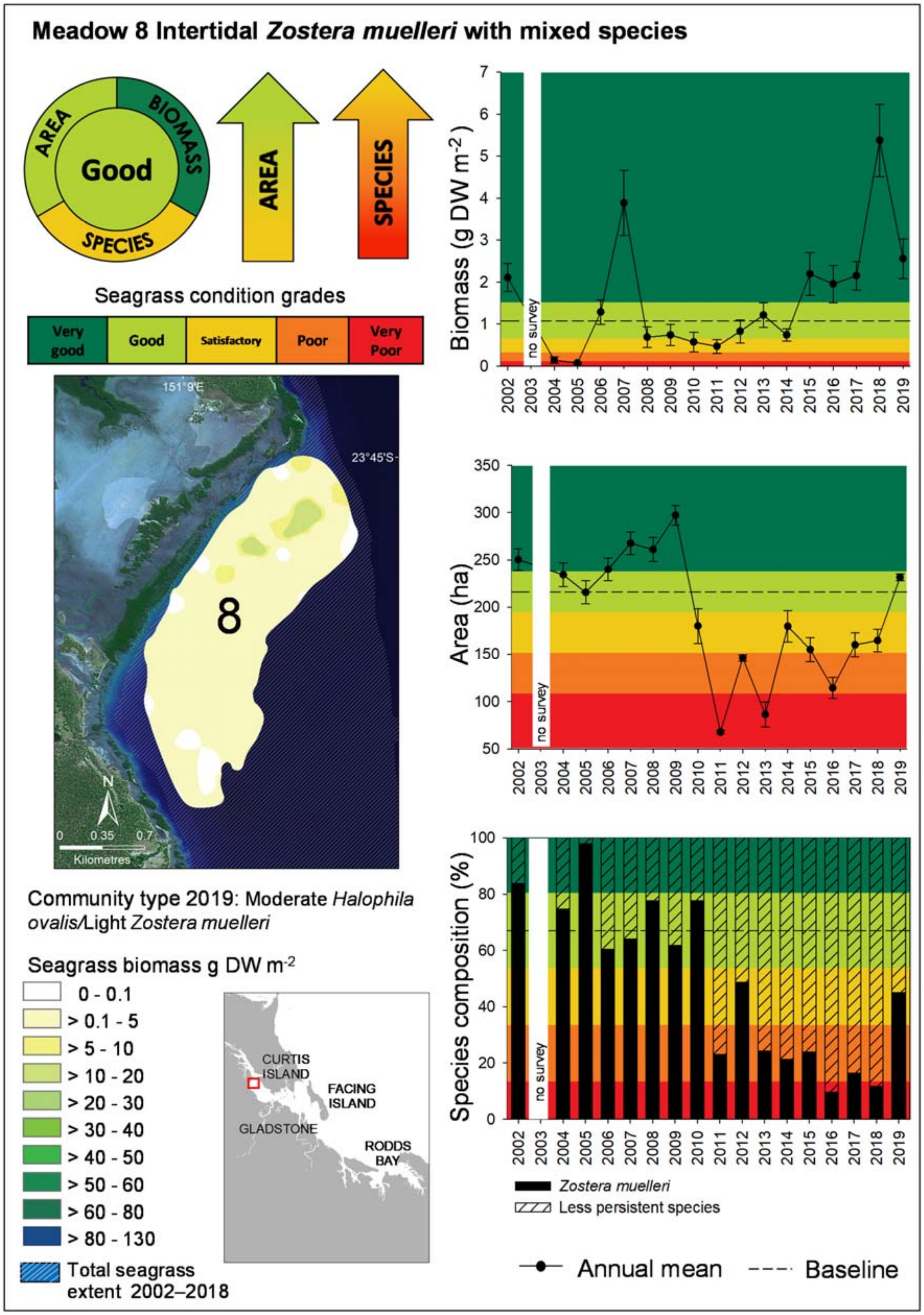

Figure 20. Changes in meadow area, biomass and species composition for seagrass at Meadow 8, North Fisherman's Landing (Western Basin Zone), 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate).

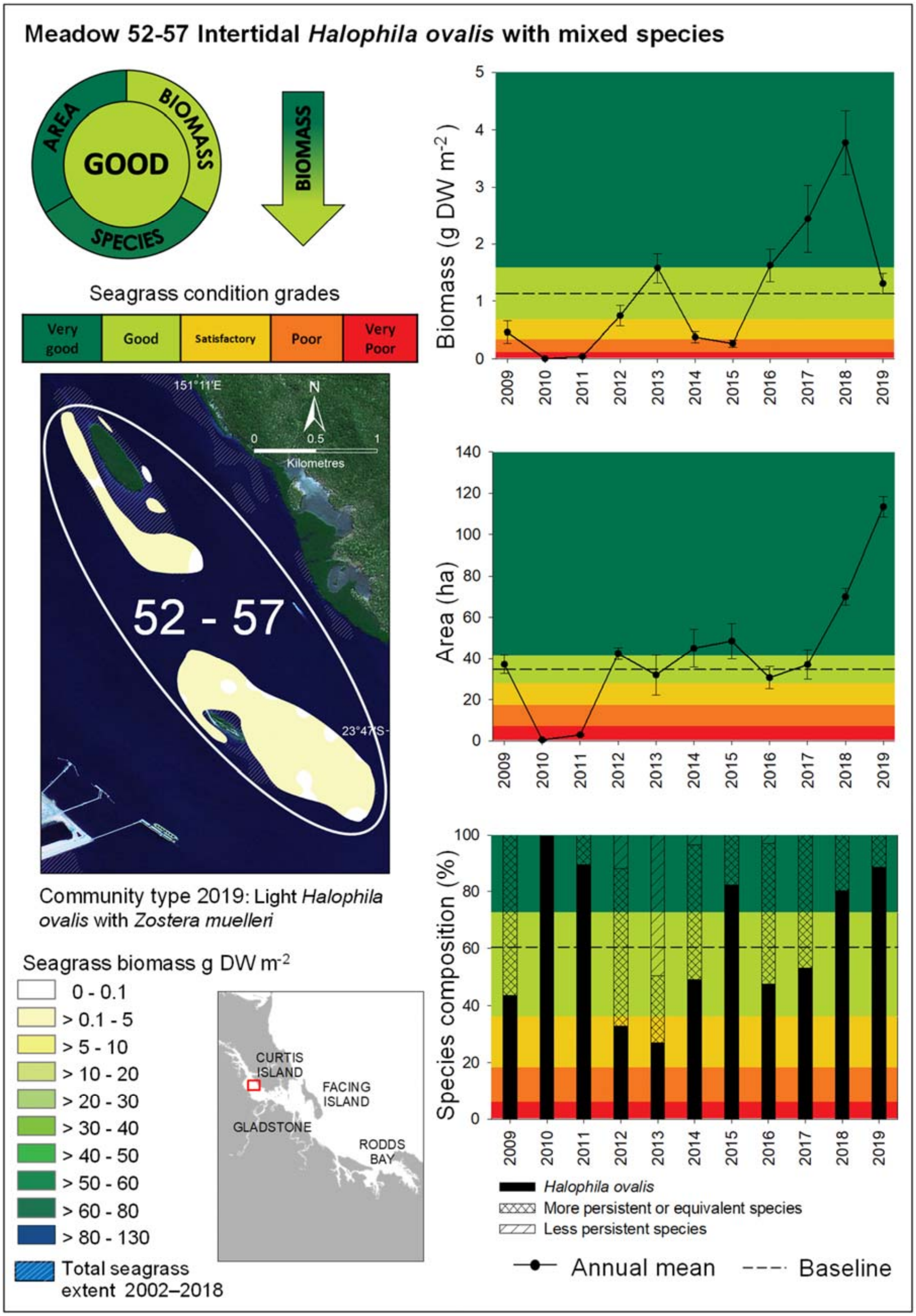

Figure 21. Changes in meadow area, biomass and species composition for seagrass at Meadows 52-57, Passage Islands (Western Basin Zone), 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.2.4 Inner Harbour

Seagrasses in the Inner Harbour Zone covered an area of 321 ± 20 ha, increasing 121 ha since 2018. There was a general expansion in meadows, particularly to the east of Compigne Island (Meadows 80 and 85), in the west of the zone (Meadows 61 and 157) and at South Trees (Meadow 58), but there was also some contraction west of Compigne Island (Meadow 136) and the loss of meadows in the center of the zone (Figure 23). Meadows formed isolated or aggregated patches of either light *Z. muelleri* or light/moderate *H. ovalis*. Meadow biomass was low ranging from diminutive patches of *H. ovalis* to 2.66 ± 0.45 g DW m^{-2} in the *Z. muelleri* meadow to the east of Compigne Island (Meadow 85; Figure 22; Appendix 3).

Long-Term Monitoring Meadows

The single monitoring meadow in the Inner Harbour improved to good condition after four years of very poor condition (Meadow 58; Figure 23; Appendix 3). The score improved from an increase in biomass to just below baseline levels after extremely low values for the previous two years (Figure 23). Meadow area also increased to near record levels after continued decline since it peaked in 2014 (Figure 23). The primary meadow species according to the ten year baseline expectation, *Z. muelleri* continued to increase and now represents 50% of the seagrass biomass, improving the species score to good (Figure 23; Appendix 4). The improvement in all three metrics in Meadow 58 indicates continued recovery.

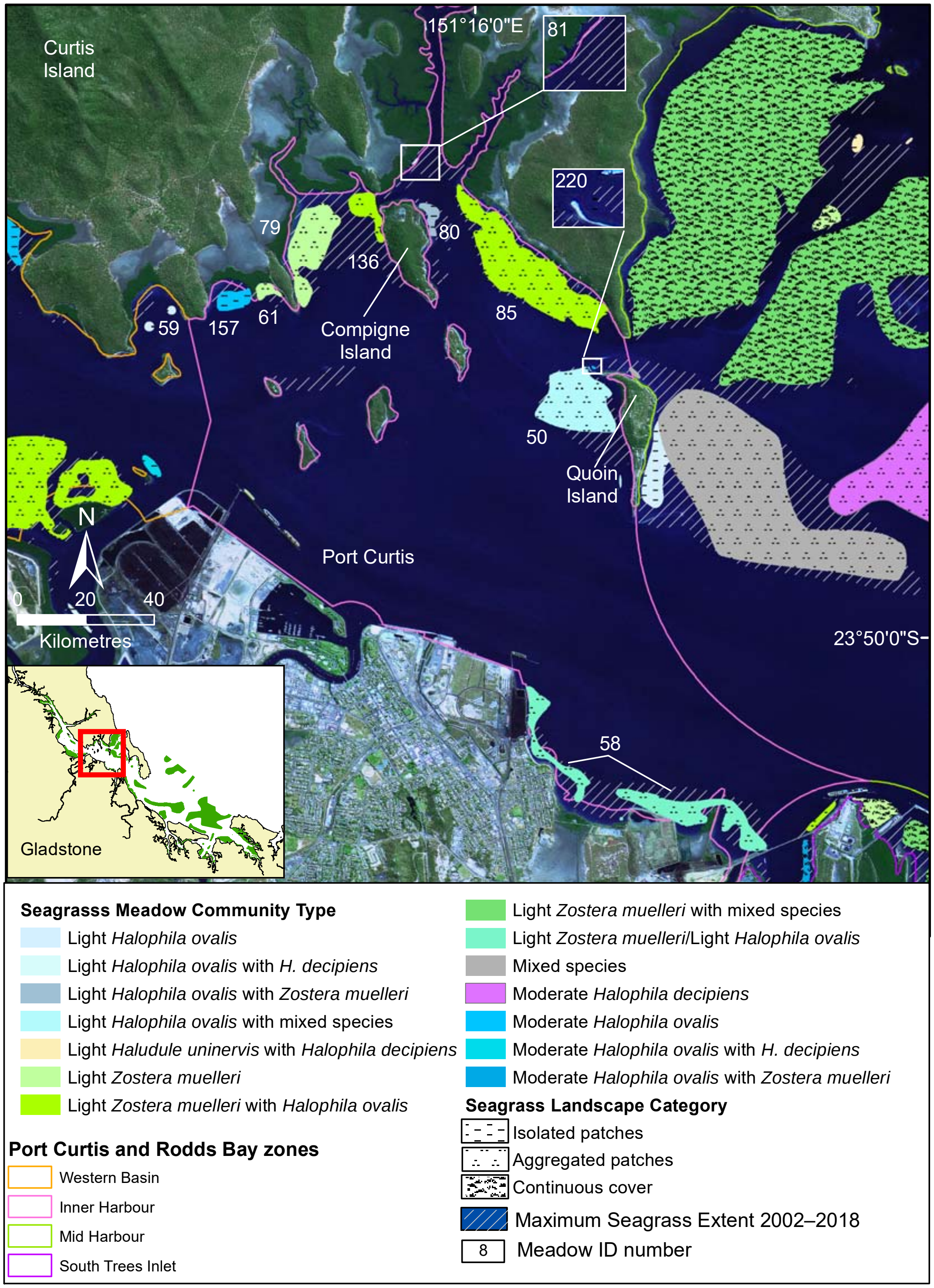

Figure 22. Seagrass distribution and community types in the Inner Harbour Zone, 2019.

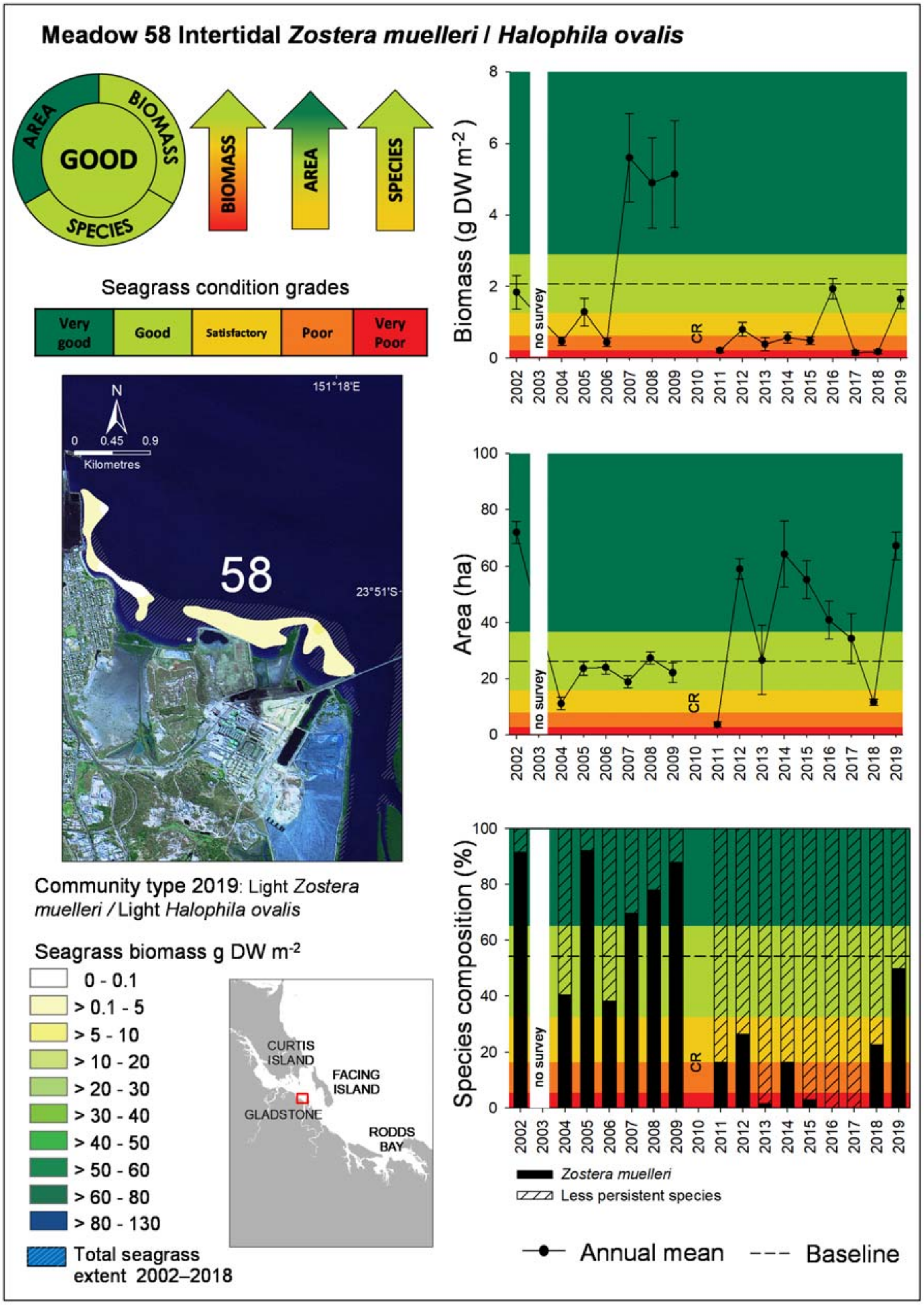

Figure 23. Changes in meadow area, biomass and species composition for seagrass at Meadow 58, Inner Harbour Zone, November 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate). CR = calculation restriction due to the absence of seagrass.

3.2.5 Mid Harbour

Seagrasses in the Mid Harbour Zone formed 20 individual meadows and covered an area of 2,254 ± 76 ha. The area of individual meadows ranged from small patches (~0.05 ha) along Facing Island to one of the largest seagrass meadow surveyed (~685 ha) on the intertidal mud bank near Curtis Island (Meadows 65 and 43 respectively; Figure 24; Appendix 3). All five seagrass species found in Gladstone Harbour were present in the Mid Harbour ranging from isolated patches of *H. ovalis* (Meadow 49) and *H. decipiens* (Meadow 140) to large continuous dense *Halodule uninervis* (Meadow 78/79) adjacent to Boyne Island (Figure 24; Appendix 3).

Long-Term Monitoring Meadows

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

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 17 year monitoring dataset. In 2019, the meadow's overall poor score is unchanged from the previous year despite an increase in meadow area. Biomass remains in poor condition after some increases over the previous two years. The biggest loss of seagrass biomass in 2016 was in the central-south region of the meadow, and biomass in this area of the meadow remained low in 2019 (Figure 25). Area for the meadow again increased in 2019 for the second consecutive year leading to a very good area score. The low proportion of the dominant *Z. muelleri* biomass continued in 2019 and has led to less persistent *H. uninervis* and *H. ovalis* contributing more than a third of meadow biomass (Figure 25; Appendix 4).

Meadow 48:

Meadow 48 is a subtidal meadow on the eastern side of Quoin Island. Overall meadow condition was satisfactory due to a combination of very good area but poor species composition (Figure 26). The meadow was dominated by *H. spinulosa* and *H. ovalis* in place of the more persistent species *H. uninervis* (Figure 26; Appendix 4). Meadow area increased from good to very good in 2019, and at ~348 ha was well above the baseline (Figure 26). Biomass condition decreased to good following the largest biomass monitored in a decade in 2018.

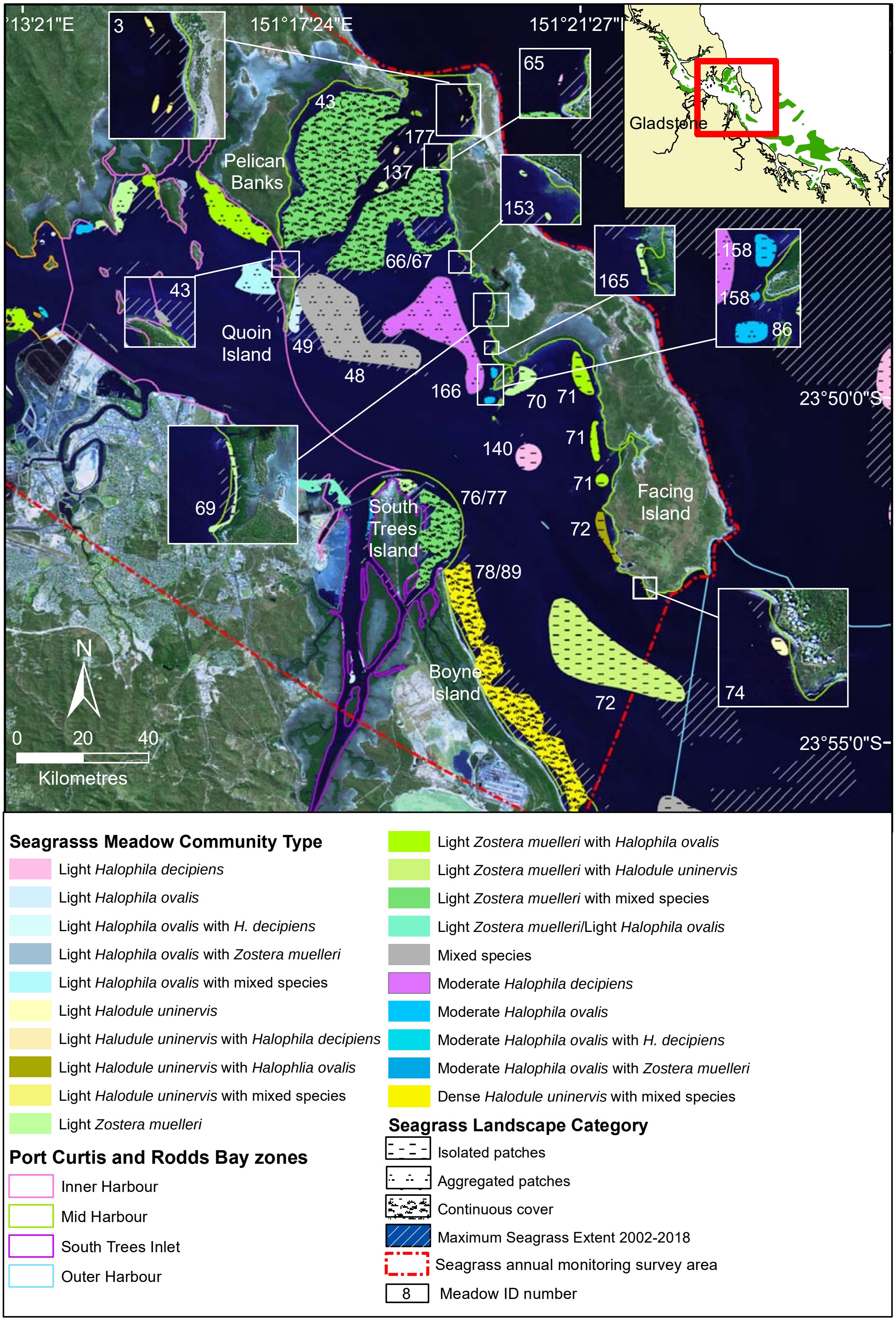

Figure 24. Seagrass distribution and community types in the Mid Harbour Zone, 2019.

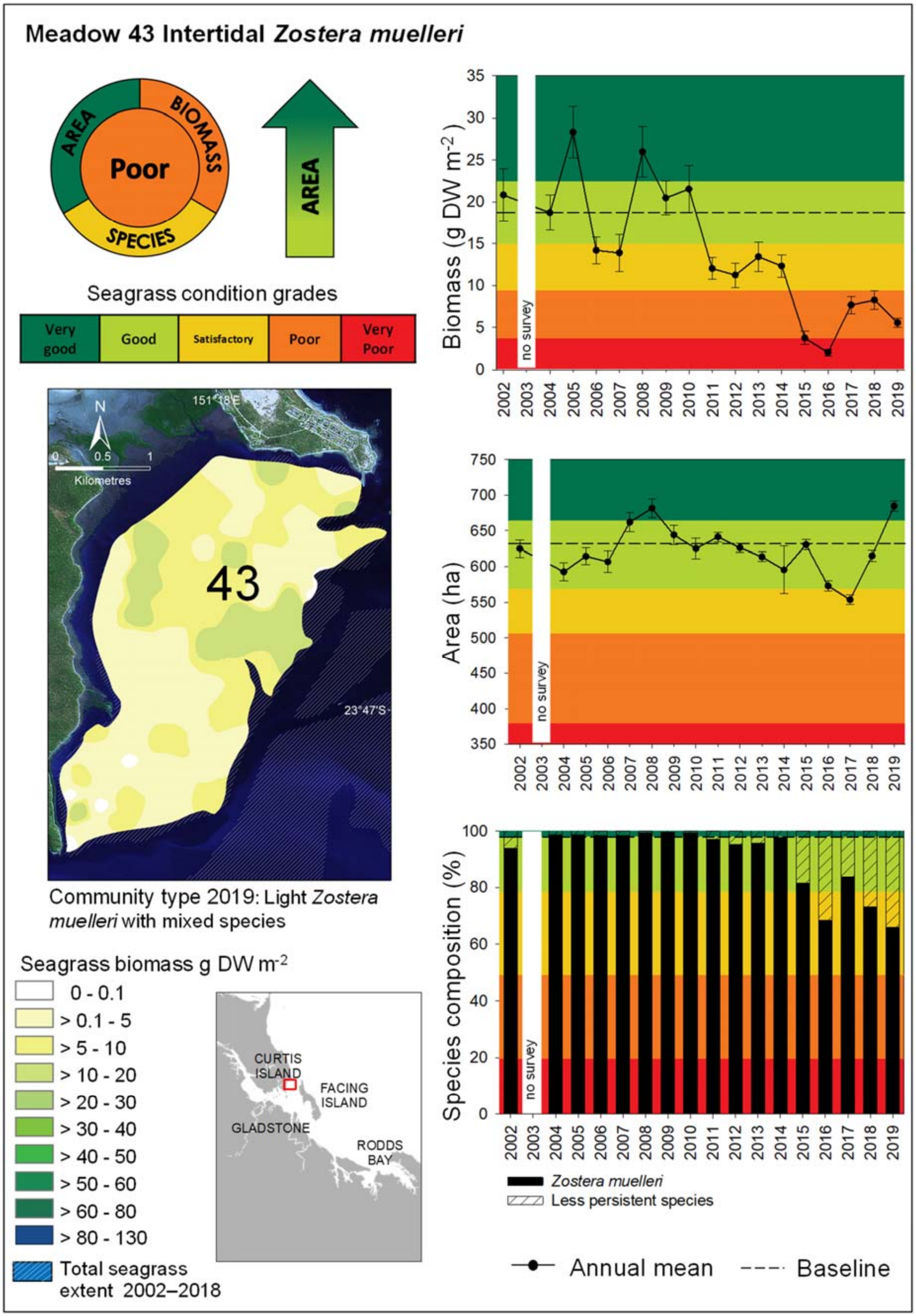

Figure 25. Changes in meadow area, biomass and species composition for seagrass at Meadow 43, Pelican Banks (Mid Harbour Zone), 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

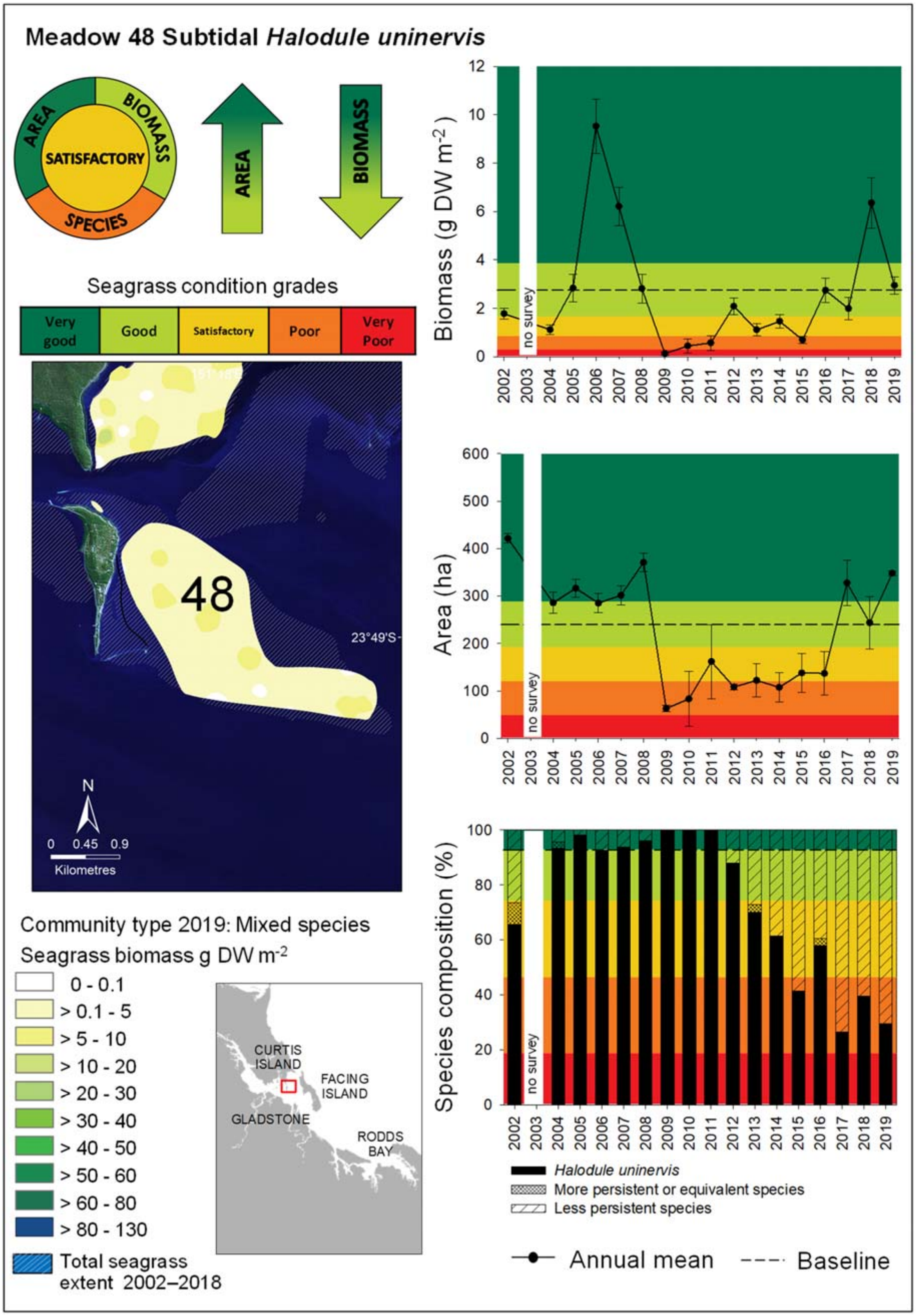

Figure 26. Changes in meadow area, biomass and species composition for seagrass at Meadow 48, Quoin Island (Mid Harbour Zone), November 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.2.6 South Trees Inlet

The South Trees Inlet Zone consisted of eleven meadows and covered an area of approximately 182 ± 9 ha, similar to the previous four years. The area of individual meadows ranged from small isolated patches of *H. ovalis* with minimal biomass along the banks of the inlet to large, continuous cover of intertidal *Z. muelleri* meadows (~152 ha, 9.24 ± 1.60 g DW m^{-2}) to the south of the wharf (Meadows 76-77; Figure 27; Appendix 3).

Long-Term Monitoring Meadows

Meadow 60, the only monitoring meadow in this zone, is located between the two wharves at South Trees Inlet (Figure 28). The intertidal meadow maintained very good scores for all three indicators for a third year in a row, a sustained recovery from the declines that began in 2009/2010 (Figure 28; Appendix 3). Biomass in 2019 reached record levels, more than 20% higher than in 2008. The meadow was continuous in 2019 but there was a pattern of decreasing biomass from the waterline to the mangrove fringe (Figure 28).

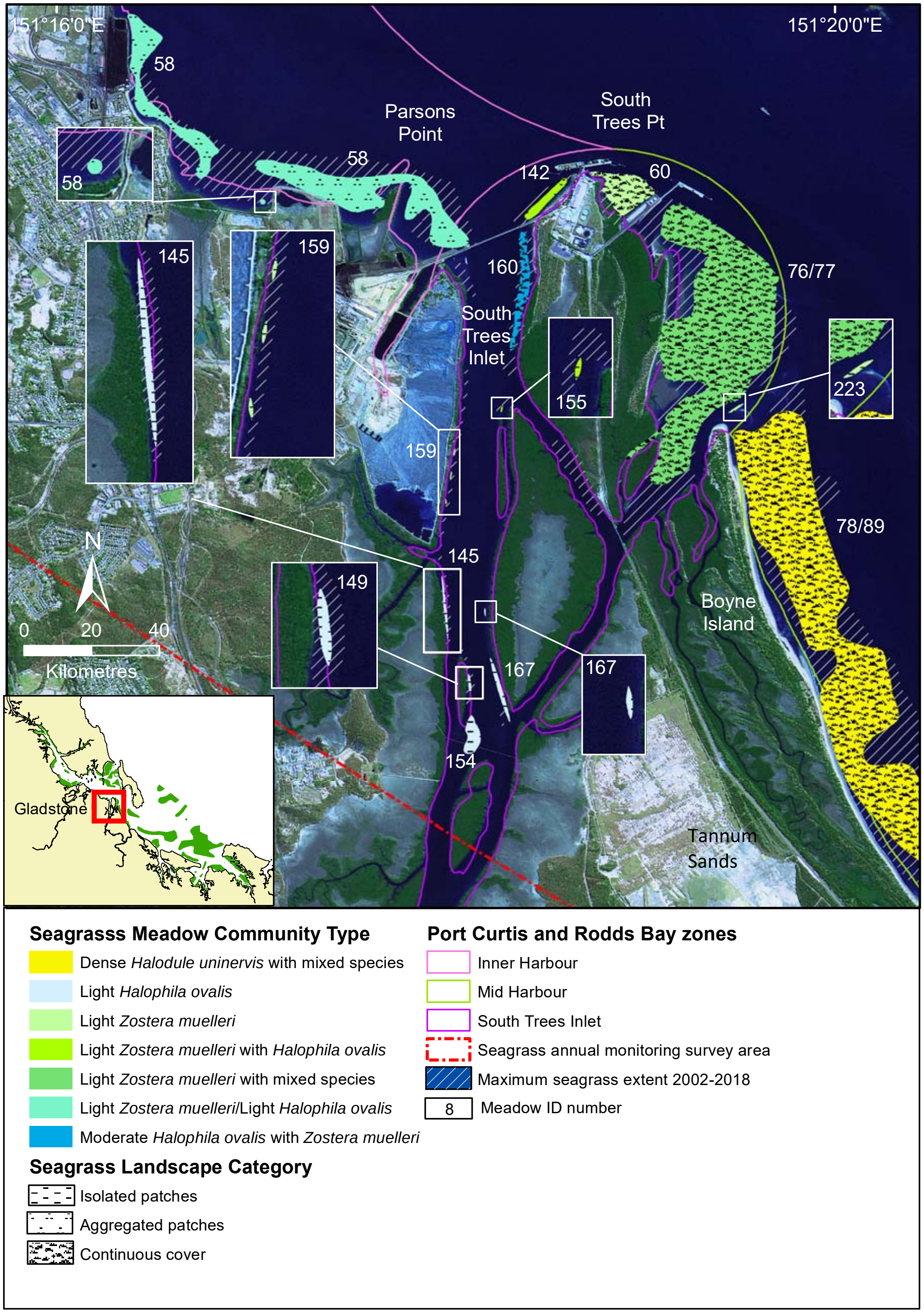

Figure 27. Seagrass distribution and community types at South Trees Inlet Zone, November 2019.

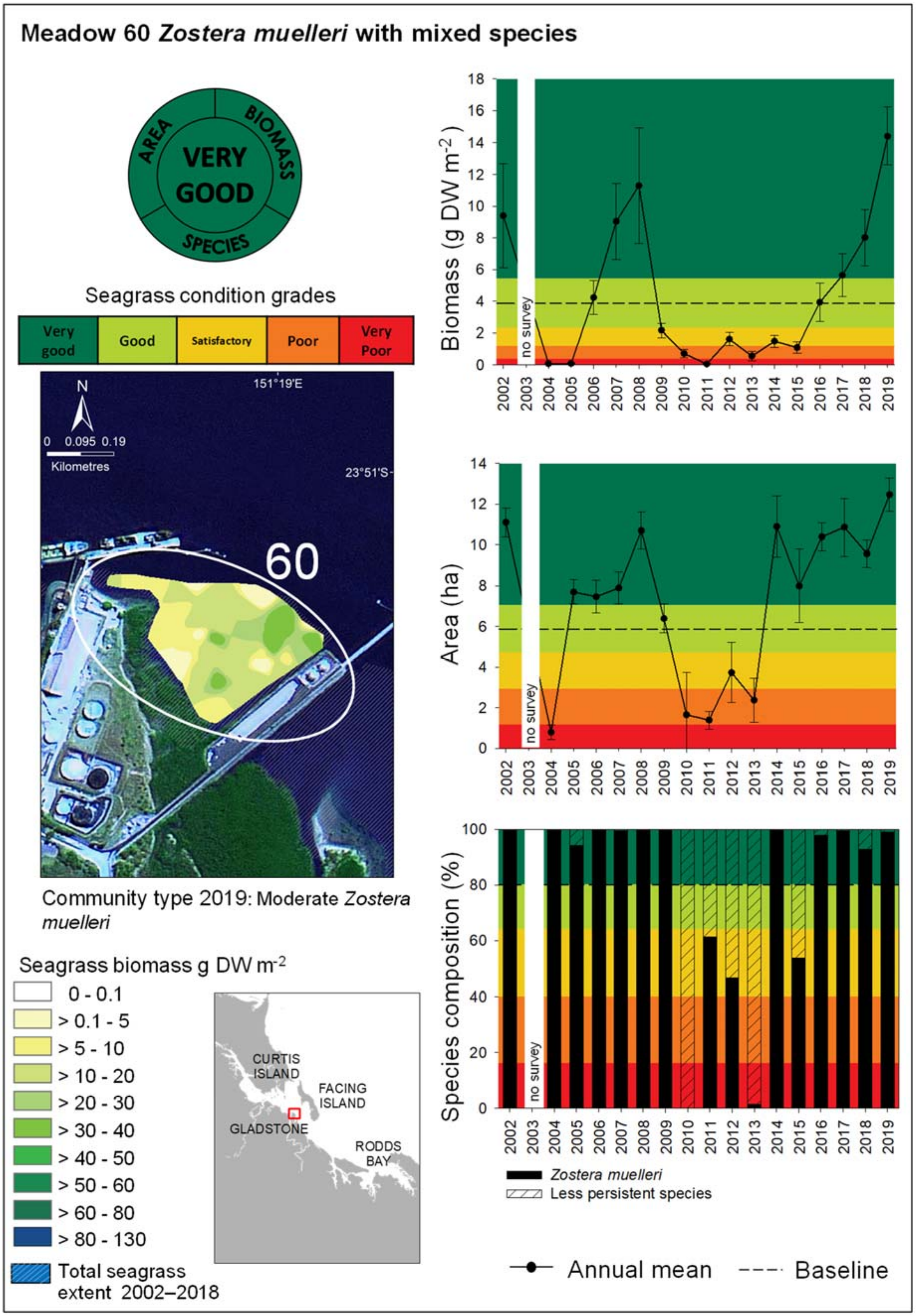

Figure 28. Changes in meadow area, biomass and species composition for seagrass at Meadow 60, South Trees Inlet Zone, November 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.2.7 Outer Harbour

The Outer Harbour is predominantly coastal, stretching from Facing Island to Rodds Bay. Seagrass in this area consists of intertidal *H. uninervis* beds along the coast and offshore deep-water *H. decipiens* meadows at depths up to 20m. Deep-water meadows in the Outer Harbour were the largest across all zones (~900 – 4,700 ha) but biomass in these meadows was very low (<0.1 g DW m^{-2}, Meadows 132, 133, 135, Figure 29, Appendix C). The area and location of deep-water *H. decipiens* meadows have varied since the previous survey in 2014, increasing in area by 1,960 ha to 9,430 ha. Deep-water seagrass meadow area has varied considerably across monitoring years when they were assessed and can change substantially over a year (Carter et al 2015a). Large *H. decipiens* meadows were present adjacent to the Eastern Bank Sea Disposal Site (EBSDS) and crossing into small areas of the EBSDS (Meadows 134, 135). Biomass in these meadows was low 0.01 g DW m^{-2} but covered a substantial area (410 and 965 ha respectively).

There are no long-term annual monitoring meadows in this zone but offshore seagrasses including those in and adjacent to the EBSDS are assessed every 5 years along with all seagrasses within the port limits.

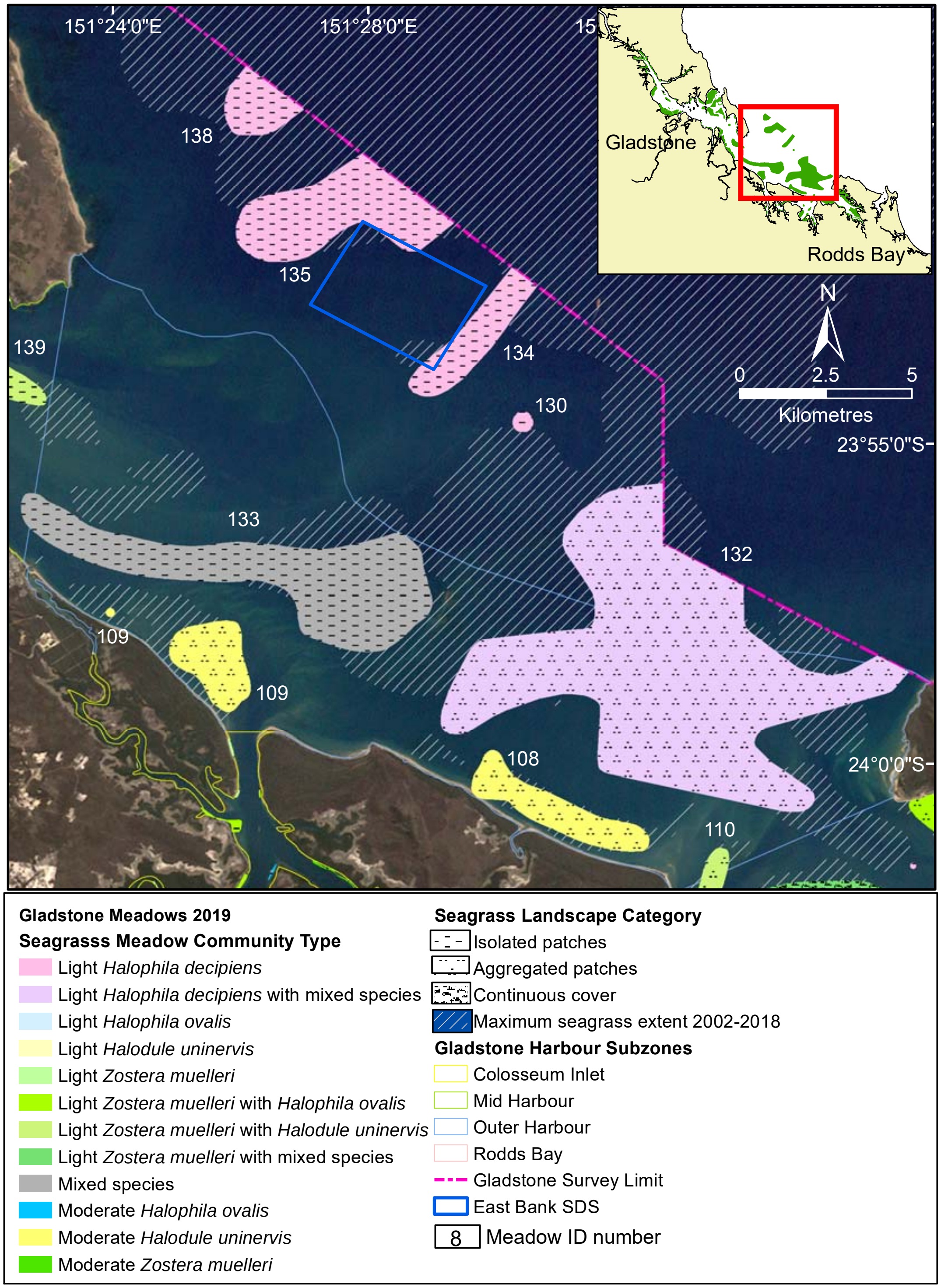

Figure 29. Seagrass distribution and community types in the Outer Harbour Zone, November 2019.

2.2.9 Colosseum Inlet

This was the first time Colosseum Inlet seagrasses have been mapped since 2009. Total seagrass in the inlet covered 199 ± 49 ha made up of 26 meadows predominantly running along the intertidal banks (Figure 30, Appendix C). Meadows ranged from small isolated meadows less than 1 ha (Meadows 90, 206, 222) to large, continuous high biomass *Z. muelleri* meadows greater than 40 ha (Meadows 92). Biomass in Colosseum Inlet was the highest of all the zones surveyed with meadow means reaching greater than 30 g DW m^{-2} (Meadow 203) and consistently above 20 g DW m^{-2} (Figure 30, Appendix C).

There are no long-term annual monitoring meadows in Colosseum Inlet.

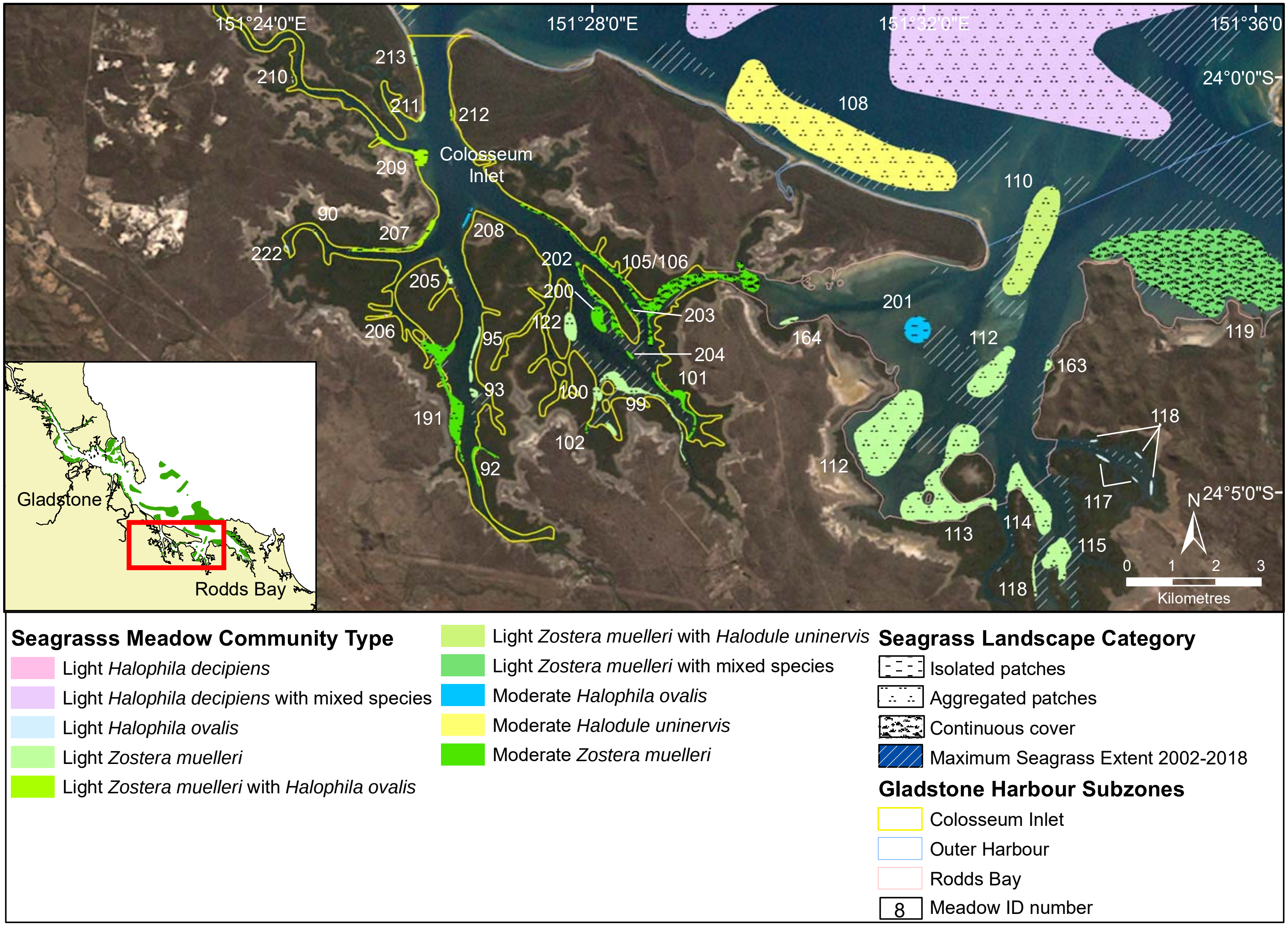

Figure 30. Seagrass distribution and community types in Colosseum Inlet Zone, November 2019.

3.2.8 Rodds Bay

All seagrass in Rodds Bay was assessed in 2019, the first time since 2014. Meadows were predominately dominated by *Z. muelleri* and covered a total area of ~2,579 ha, the highest recorded in any previous survey. The largest meadow covering 744.47 ± 40.04 ha, of aggregated *Z. muelleri* with *H. ovalis* stretched along the northern shoreline of Rodds Bay (Meadow 121). Most meadows in Rodds Bay were aggregated or isolated patches with the exception of a large continuous meadow of *Z. muelleri* on the southern edge of the bay linking the two arms (Meadow 119, Figures 30, 31). Seagrass biomass in Rodds Bay ranged from very low *H. ovalis* and *H. decipiens* (Meadows 117, 118, 218) to *Z. muelleri* meadows > 20 g DW m^{-2} (Meadows 94, 115, Figure 30, 31, Appendix 3). These biomasses were some of the highest recorded across the entire Port Curtis and Rodds Bay region.

Since the inception of the Port Curtis and Rodds Bay monitoring program, three seagrass meadows have been assessed in Rodds Bay to measure seagrass health in an area removed from port activities. In 2019, Rodds Bay seagrasses improved substantially, all meadows were in very good condition. Rodds Bay meadows crashed in 2009 and have stayed suppressed apart from a brief recovery in 2014 before returning to a poor or very poor condition based on most scores until 2018 when some improvements were recorded. Total seagrass area of monitored meadows in 2019 covered ~436 ha, a 17% increase from 2018.

Long-Term Monitoring Meadows

There are three intertidal monitoring meadows in the Rodds Bay Zone – Meadows 94, 96 and 104. The meadows were made up of aggregated seagrass patches, an improvement for meadows 94 and 104 which were isolated patches in 2018.

Meadow 94:
Meadow 94 is the smallest monitoring meadow in Rodds Bay and showed improvement from satisfactory to very good condition in 2019 (Figure 30; Appendix 3). This is the first time the meadow had a score above poor since 2008. The meadow increased in size by 50% from 2018 to be above the baseline for the first time since 2014. Biomass was the second highest recorded since monitoring began at 20.31 ± 3.45 g DW m^{-2} making it one of the highest biomass meadows surveyed (Figure 30). The entire meadow consisted of only *Z. muelleri* for the first time since 2016 (Figure 30; Appendix 4).

Meadow 96:
Overall condition of Meadow 96 went from good to very good in 2019 with improvements in biomass and species composition (Figure 33; Appendix 3). Area were the highest since monitoring began covering 394.95 ± 6.58 ha. Biomass increased from 6.84 ± 1.55 g DW m^{-2} in 2018 to 16.30 ± 1.53 g DW m^{-2}, the third highest ever recorded for this meadow. This is the first time biomass has been above baseline values since 2009 and signifies recovery following consistently very low biomass values (< 2 g DW m^{-2}) between 2010 and 2017 (Figure 31; Appendix 3). For only the second time species composition was exclusively *Z. muelleri* which improved the species composition score to very good (Figure 33; Appendix 4).

Meadow 104:
Overall condition of Meadow 104 improved from poor to very good condition in 2019 with shifts in all three metrics. Biomass improved from 1.99 ± 0.64 g DW m^{-2} in 2018 after 10 years of poor or very poor condition to 11.70 ± 1.95 g DW m^{-2} in 2019, the highest biomass since 2008. After previous years of fragmentation the meadow grew to form a single meadow improving area from poor to very good and above baseline levels. Species composition also improved to be 100% *Z. muelleri* (Figure 33; Appendix 4).

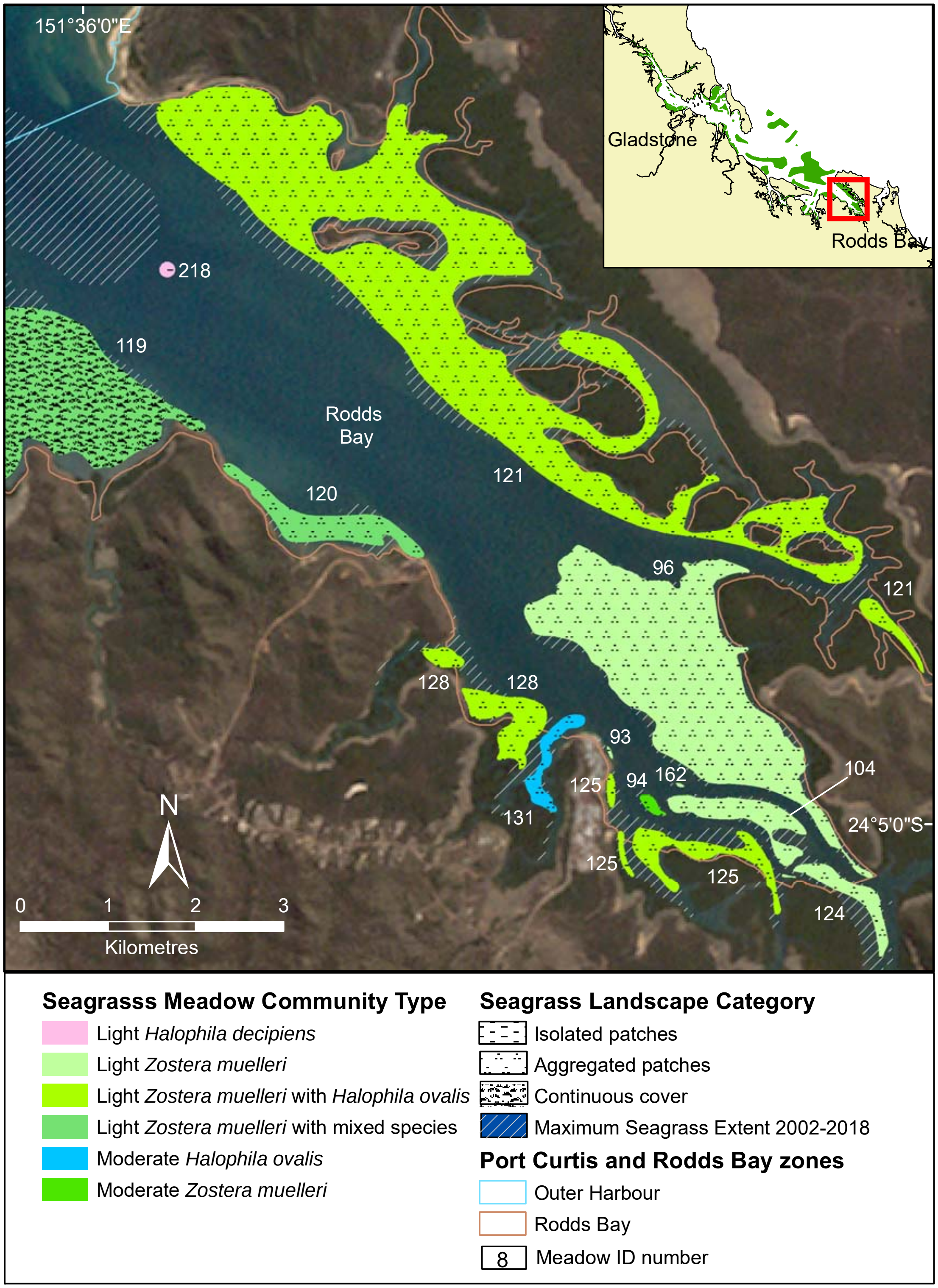

Figure 31. Seagrass distribution and community types in the Rodds Bay Zone, November 2019.

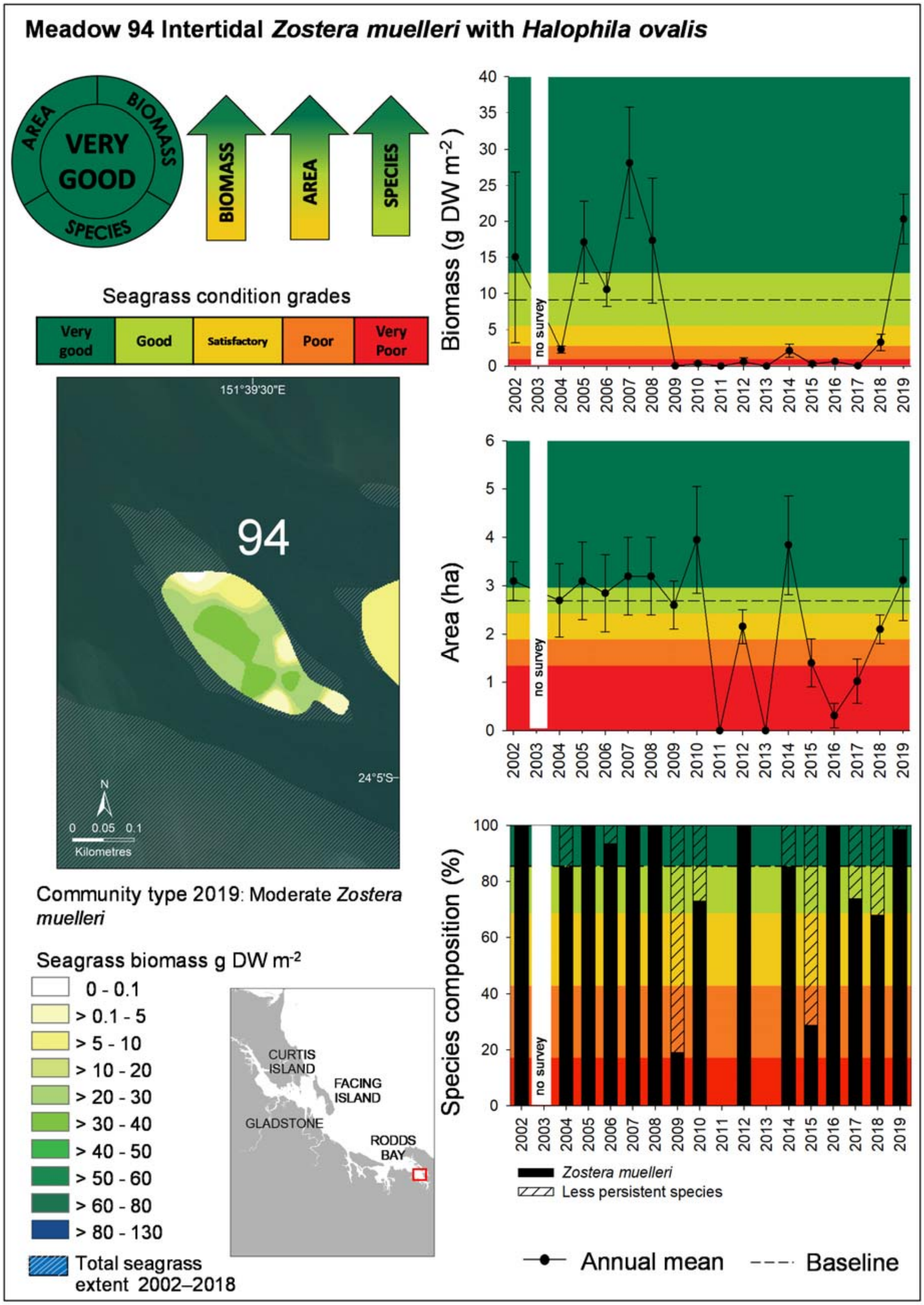

Figure 32. Changes in meadow area, biomass and species composition for seagrass at Meadow 94, Rodds Bay Zone, November 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate).

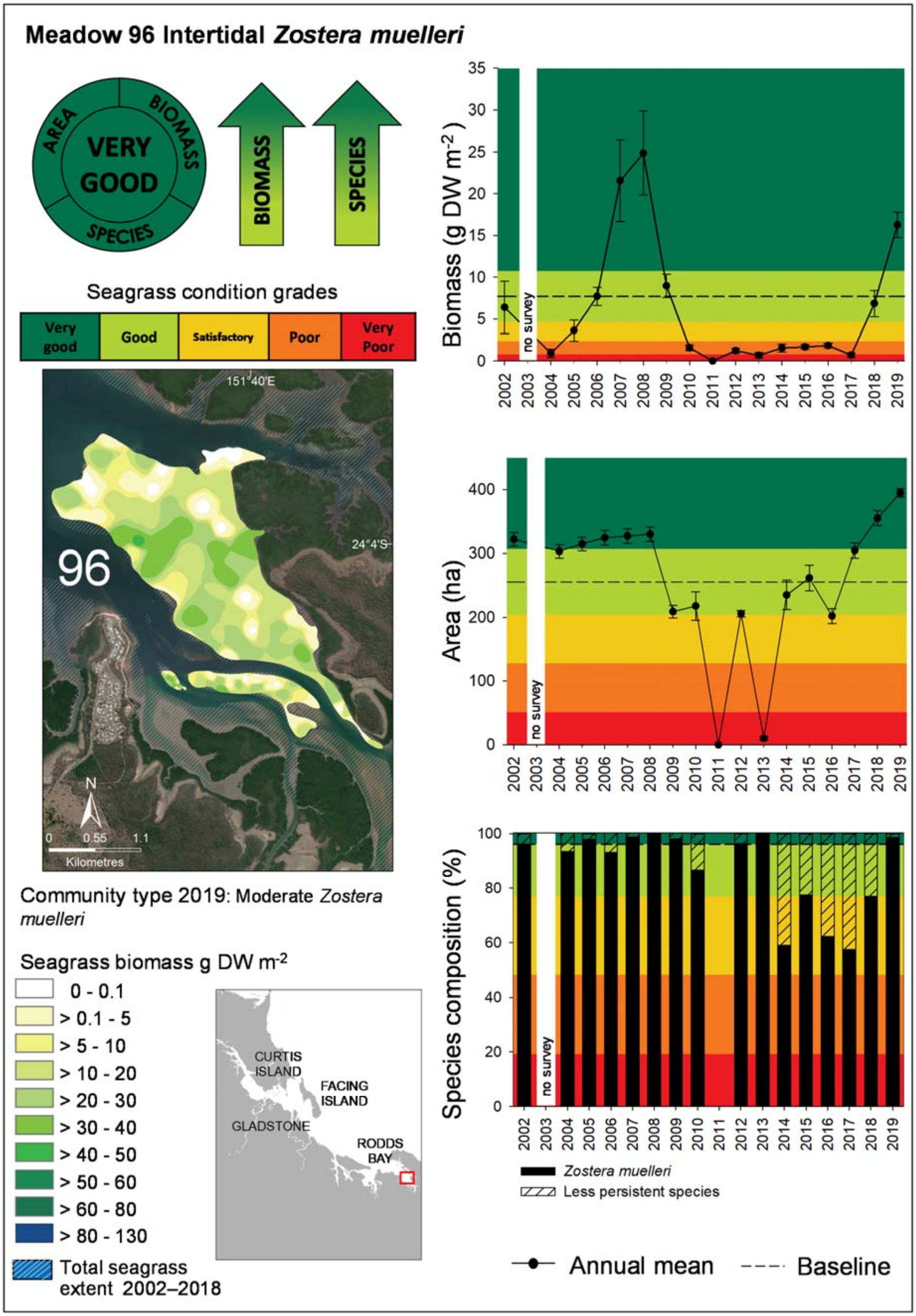

Figure 33. Changes in meadow area, biomass and species composition for seagrass at Meadow 96, Rodds Bay Zone, November 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate).

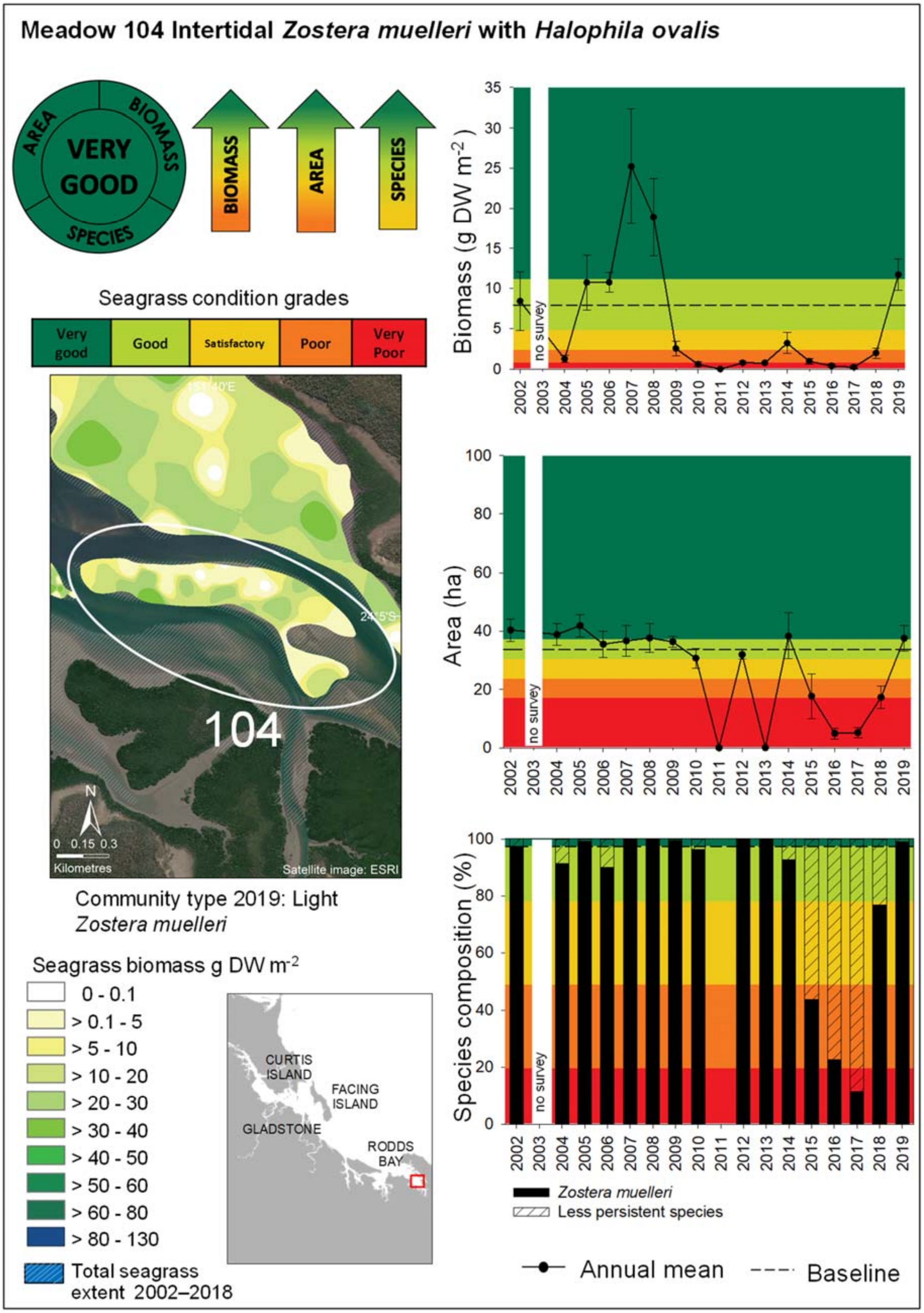

Figure 34. Changes in meadow area, biomass and species composition for seagrass at Meadow 104, Rodds Bay Zone, November 2002–2019 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.3 Comparison to previous whole of port assessments

The 2019 whole of port survey was the first since 2014. In total, there have been five occasions between 2002 and 2019 when seagrasses in the greater Port Curtis and Rodds Bay area have been surveyed. Between surveys there has been some variation in the total extent covered but all have assessed a common area that covers the port limits as well as an adjacent area of Rodds Bay (Figure 10). Colosseum Inlet has been included in three of these five surveys, 2002, 2009 and this survey in 2019. Comparisons among years were restricted to common areas mapped in each study (Figure 35). The total area of seagrass mapped in these common areas in 2019 was higher than any previous survey, ~16,900 ha (including 200 ha in Colosseum Inlet), more than 4,000 ha higher than the previous whole of port survey in 2014 (12,700 ha) and more than 2,000 ha higher than the previous highest in the 2002 baseline survey (~13, 500 ha).

Gains in seagrass occurred throughout the survey area. There was a large increase in seagrass within the Port Curtis region (Figure 36). Much of the area of seagrass loss through The Narrows and Western Basin seen in 2013 and 2014 surveys has returned to 2009 levels and there has been an increase in area to the east of Facing Island compared to 2009 (Figure 36). Almost half (~2,000 ha) of the increased seagrass area since 2014 occurred in deep-water meadows which increased by 26% to cover ~9,400 ha (Figure 37). This included areas of seagrass that occurred immediately adjacent to the spoil ground with meadows extending to be within the boundaries of the spoil ground in 2019 (Figure 37).

Seagrass in Rodds Bay was decimated in 2010 losing ~1,000 ha from 2009 to 2013 to leave just 150 ha in 2013. There was some recovery in 2014 but now the meadow has recovered to beyond the 2009 area to be 14,200 ha. The meadow on the north side of Rodds Bay has aggregated to form a single patch for the first time since 2009 and meadows at Turkey Beach and the mouth of Rodds Bay have returned (Figure 38).

The gains in seagrass occurred both in the shallow coastal meadows and offshore deep-water meadows, with both at record highs in 2019 (Figure 35).

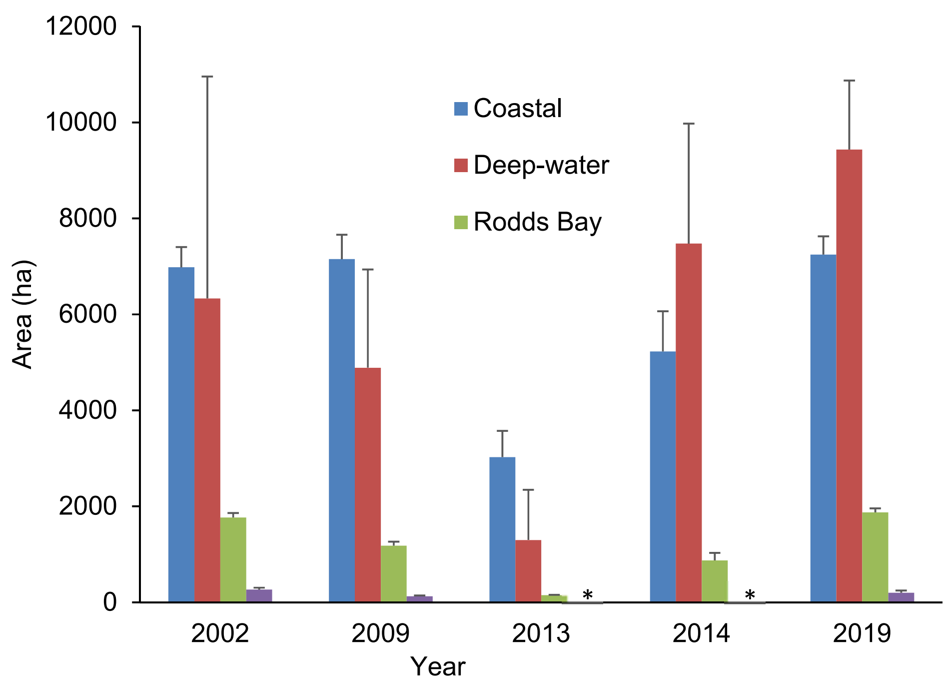

Figure 35. Comparison of area of seagrass meadows between all whole of port surveys (2002; 2009; 2013; 2014; 2019) in the Port Curtis Coastal, Deep-water, Rodds Bay and Colosseum Inlet regions. *Colosseum Inlet not surveyed in 2013 or 2014.

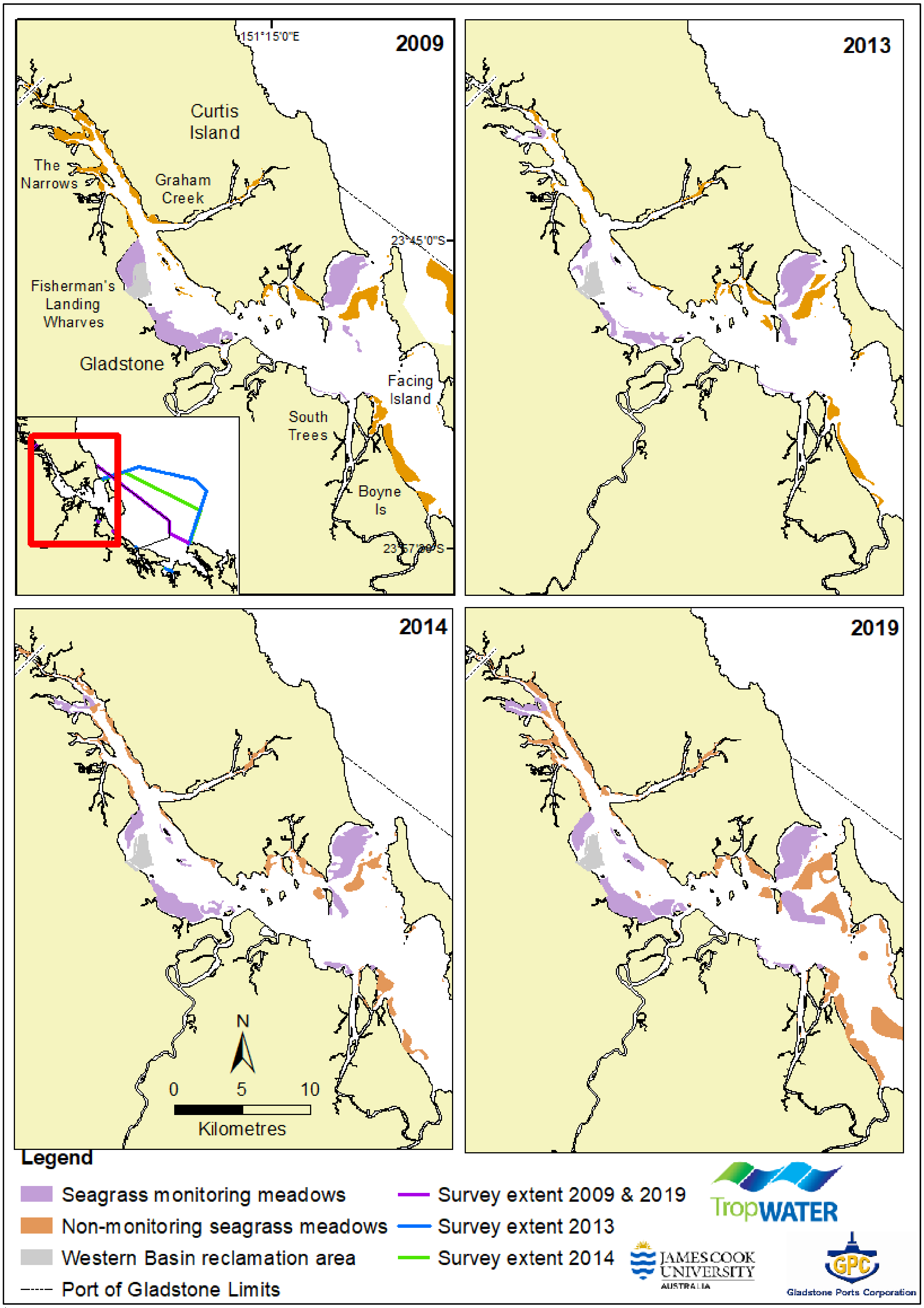

Figure 36. Seagrass distribution in The Narrows, Graham Creek, Western Basin, Inner Harbour and Mid Harbour regions of Port Curtis and Rodds Bay, 2009, 2013, 2014, 2019.

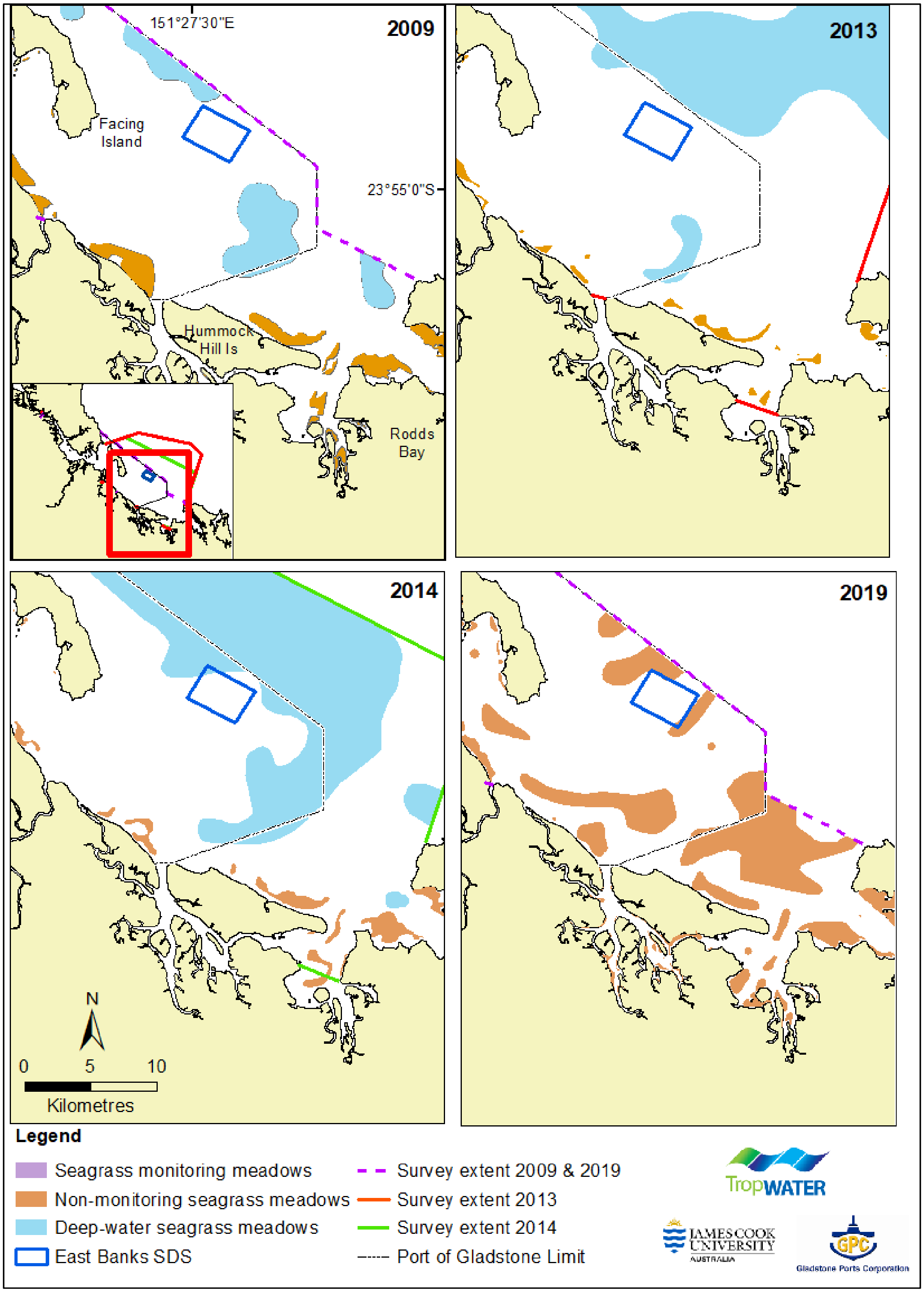

Figure 37. Seagrass distribution in Outer Harbour regions of Port Curtis and Rodds Bay, 2009, 2013, 2014, 2019.

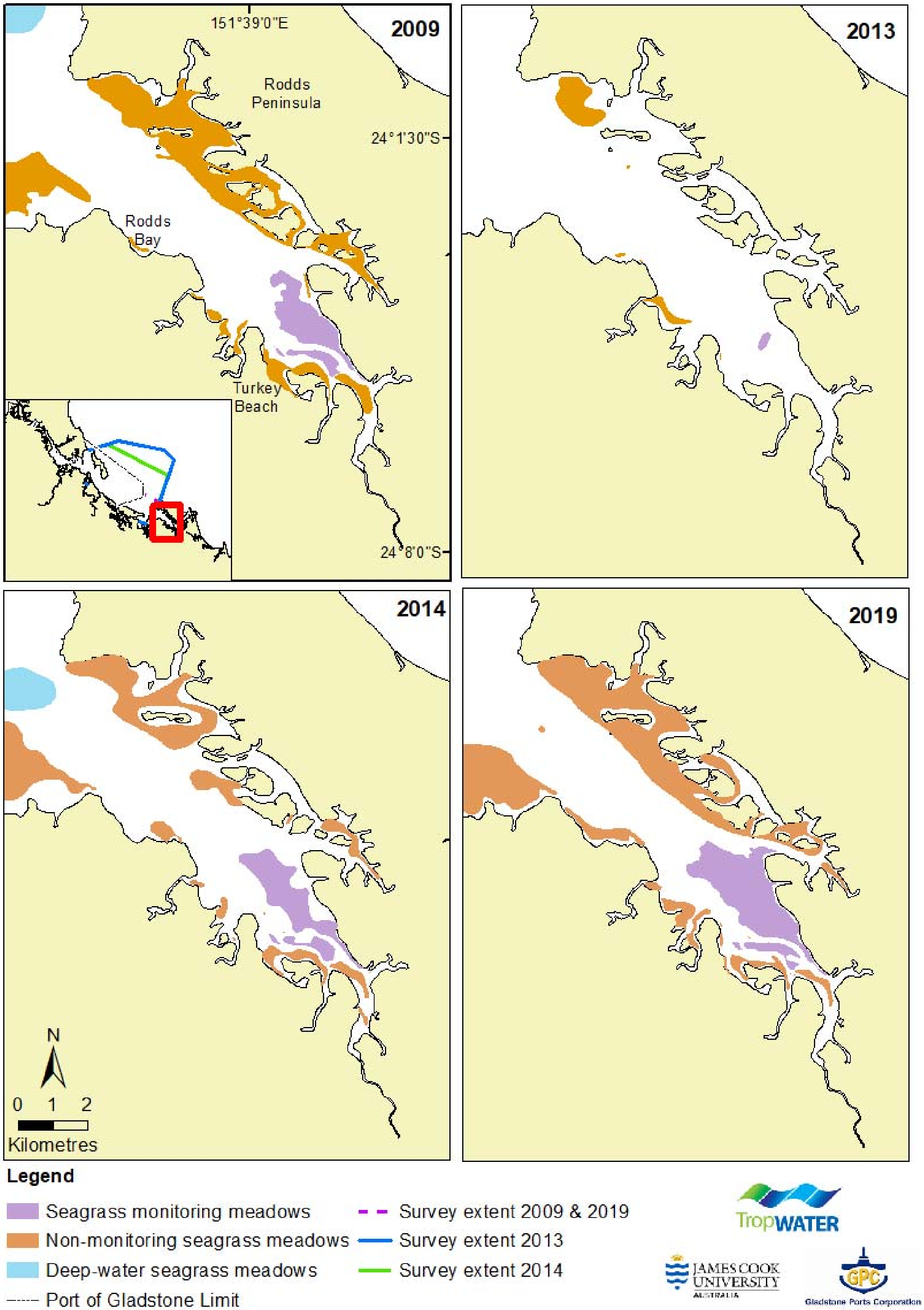

Figure 38. Seagrass distribution in Rodds Bay 2009, 2013, 2014, 2019.

3.4 Gladstone environmental conditions

3.4.1 Rainfall, riverflow, and tidal exposure

Total annual rainfall in the 12 months preceding the November 2019 survey was well below average and the third lowest since seagrass monitoring began in 2002 (Figure 39a). The only substantial rainfall events occurred in January 2019, in line with expected wet season conditions, and in October 2019, just prior to the annual seagrass monitoring survey (Figure 39b). Both were above the long-term monthly average. River flow from the Calliope River was very low throughout the entire 12 months including the wet season with virtually no flow since February 2018 (Figure 40). Annual total daytime exposure of seagrass meadows was below average (Figure 41).

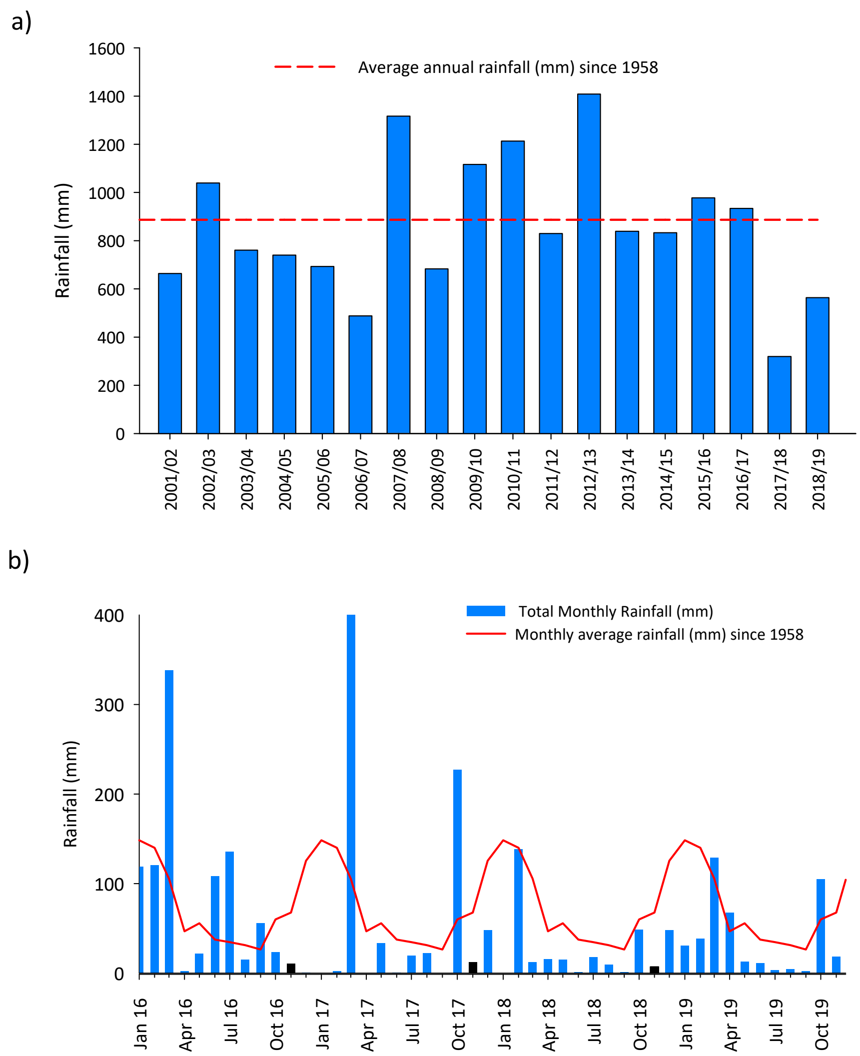

Figure 39. a) Gladstone annual rainfall (mm) and b) monthly rainfall (mm) totals; January 2016–November 2019. Black bars indicate October/November rainfall when seagrass was sampled (spring peak growth period).

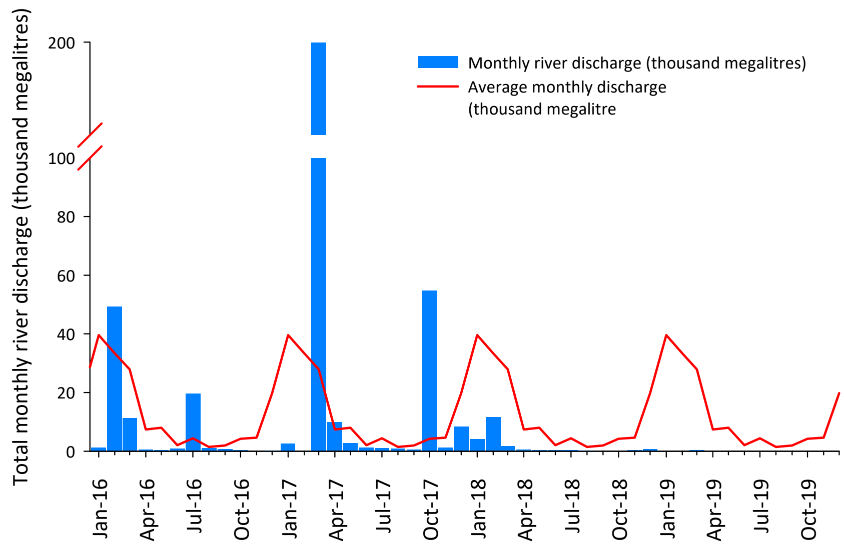

Figure 40. Monthly total river flow for the Calliope River (thousand megalitres); January 2015–November 2019.

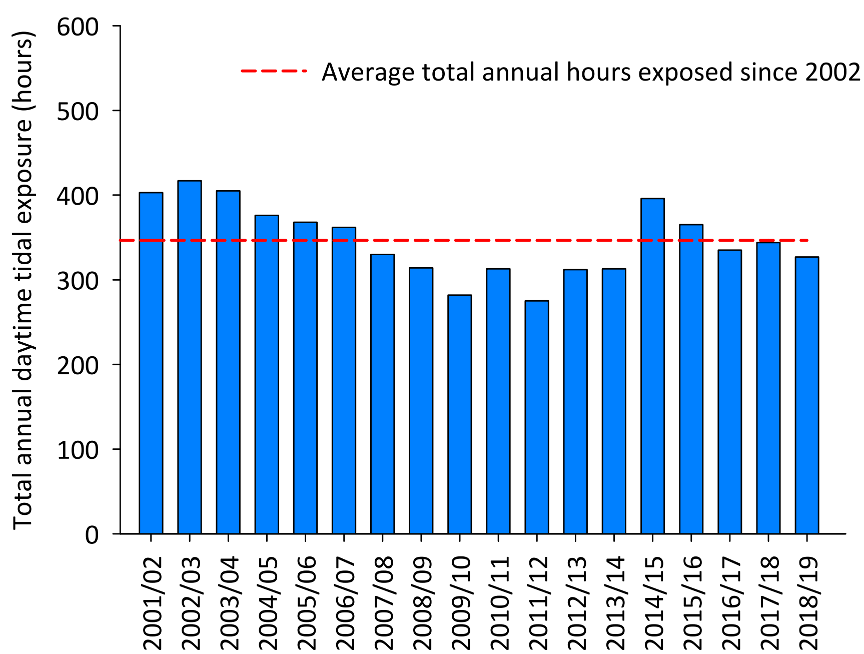

Figure 41. Total annual daytime hours exposed 2001/02 to 2018/19 (0600 – 1800; <1.0 m below mean sea level).

4 DISCUSSION

In 2019 seagrasses in Port Curtis and Rodds Bay were in the best condition of the past decade and one of the best conditions ever recorded in the 18 years that monitoring has been conducted. The majority of individual annual monitoring meadows were in a good to very good condition for seagrass biomass, area and species composition and for the first time since 2008 all three Rodds Bay monitoring meadows were in very good condition. Combined, this resulted in overall seagrass condition being rated as good for the first time since 2009. Changes in the annual monitoring meadows were reflected in the broader scale survey of the entire port limits and Rodds Bay area, where the highest ever area of seagrass was recorded, 26% greater than the last time the entire region was surveyed in 2014.

Improvement in seagrass condition over the past two years can be attributed to environmental conditions that promote seagrass growth. Analysis of the long-term patterns of seagrass condition from the 18 years of annual monitoring reveal a strong relationship with river flow and to rainfall in the region. Flow from the Calliope River in 2019 was the lowest since 2010 following the second lowest flow in 2018. There was below average rainfall in both years. These conditions coincide with seagrass recovery, high biomass and the establishment of the most persistent seagrass species in the area, *Z. muelleri* at some meadows where historic lows were recorded between 2010 and 2017. The relationship between seagrass growth and river output and rainfall is the result of benthic light increases with fewer significant rainfall and flood events. Slightly below average number of tidal exposure hours in 2019 also protected intertidal seagrasses from any extreme desiccation and thermal stress (Unsworth et al. 2012). Trends in seagrass recovery reinforce that mild environmental conditions in 2019 were the biggest driver of improved seagrass condition. If drier conditions continue in 2020, we would expect these gains to be sustained for the next monitoring period.

The health of seagrass meadows was generally reflected throughout the various zones of Port Curtis and Rodds Bay and across different seagrass habitat types. Improvements were seen in The Narrows, Western Basin, Inner Harbour and Rodds Bay zones. Biomass, area and species composition in many of these meadows returned to levels prior to major seagrass losses in 2009 for the first time. Monitoring meadows in the Western Basin and South Trees had the highest biomass and area since monitoring began in 2002. The recovery of meadows throughout the harbour and in the out of port reference area in Rodds Bay indicate changes in meadow condition are related to overall environmental variation rather than anthropogenic or port activity.

There were two meadows that decreased in condition score from 2018 to 2019, Meadows 7 and 52-57, but both of these were coming off record high levels the previous year and still remained in good condition in 2019. Meadow 7 recorded decadal high biomass and area in 2018 and Meadows 52-57 the highest ever biomass and area. These meadows consisted of predominately ephemeral species *H. decipiens* and *H. ovalis* that commonly vary substantially over short time scales (Hovey at al. 2015; York et al. 2015).

The only exception to the pattern of recoved seagrass meadows was for the the largest and historically highest biomass area of seagrass in Port Curtis (Pelican Banks). While area of this seagrass meadow continued to improve in 2019, biomass remained low and the species composition contained a higher prevelance of colonising species than would be expected for the baseline condition of this meadow. There were no obvious differences in environmental conditions or changed human activities in this area compared to the rest of Port Curtis that could lead to the lack of biomass recovery here. In fact, 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). One of the most likely explanations could be high levels of herbivory from dugong and green turtles. The Pelican Banks meadow has a high level of herbivory from dugong and turtle, with dugong feeding trails observed within the meadow during every seagrass monitoring survey and during a detailed study of dugong feeding in recent years (Rasheed et al. 2017). Green turtles also regularly feed on the meadow (direct observations and Hamann et al. 2016; Limpus et al. 2017). A major research program has been underway in Port Curtis to measure the effects of grazing pressure on seagrass meadows with results showing that they can have a major impact on seagrass biomass and structure on the Pelican Banks meadow as well as elsewhere in Port Curtis (Scott et al. in prep). While it is unclear if there has been an increased focus of grazing pressure in this meadow in recent times, major meadow losses have occurred in other locations arounf the world as a direct result of turtle herbivory (Christianen et al. 2014).

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. 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. 2018, in prep).

In 2019 offshore deep-water seagrasses in Port Curtis were assessed for the first time since 2014. This offshore region, which includes the EBSDS, contains deep-water Halophila species that are known to form highly variable and ephemeral meadows in Gladstone and elsewhere in the Great Barrier Reef coast of Queensland (Chartrand et al. 2018a; York et al 2015). In particular the species that dominates this deep-water area, *H. decipiens,* is a highly ephemeral coloniser that is a short lived annual, relying on seed banks for persistence (Hovey et al. 2015; York et al. 2015). These deep-water Halophila species generally exist at the very limits of their light requirements so are particularly susceptible to short-term impacts to the light environment due to turbidity as well as natural inter-annual changes to climate and weather (Chartrand et al. 2018b; Hovey et al. 2015). While they are quick to decline they are also generally fast to recover exploiting short windows of favorable light to germinate and spread. This makes monitoring and management of these species particularly difficult. In 2019 the area covered by these deep-water meadows was the highest ever recorded suggesting that deep-water seagrass in Port Curtis and Rodds Bay are healthy. The fact that seagrass was found adjacent to and within the EBSDS in 2019 indicates that the periodic disposal of spoil material has not had any long-term impact on adjacent seagrasses.

Seagrass meadows in the out of port reference area at Rodds Bay had large declines in 2009 and 2010, culminating in the complete loss of all three monitoring meadows in 2011-2013. The recovery of these meadows since then has lagged behind many of the other seagrass areas in the monitoring program. After some increases in area and biomass in 2018 all monitoring meadows showed improvement to pre 2010 condition in 2019. All three meadows had biomass peaks that were amongst the highest recorded since monitoring began in 2002. Species composition has returned to be dominated by *Z. muelleri. Zostera muelleri* is a large persistent seagrass species that can grow at rates of 7-8 mm per day (Kerr and Strother, 1989). The dominance of *Z. muelleri*, coupled with favorable growing conditions led to very large increases (130-560%) in biomass to levels not seen since before 2009. After complete loss of the standing crop occurs, such as in Rodds Bay in 2011, substantial delays in recovery are likely as initial recolonisation will be reliant on germination of seeds either from the seed bank or via dispersal from other meadows (Rasheed 1999; 2004). This initial re-establishment of seagrass meadows may take an extended period, 9 years in the case of Rodds Bay. However, once the meadow re-establishment begins (i.e. Rodds Bay meadows 2017-2018), meadow biomass and overall condition can return quickly.

4.1 Comparisons with Queensland-wide monitoring program

The improvement in seagrass meadow condition in Port Curtis and Rodds Bay was consistent with seagrass trends along Queensland's east coast between Cairns and Port Curtis. Widespread losses of seagrasses occurred along the east coast leading up to 2009 and 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). Since then, recovery has differed by location, varying according to local climate events as well as the severity of the initial decline. For example, in Mourilyan Harbour where there were multiple years of complete meadow loss, seagrass remains in very poor condition with little prospect of seagrass recovery without some form of restoration (Wells et al. 2019a). At the other end of the spectrum, Townsville meadows were quick to recover (within 3 years) as initial impacts were less severe and followed by several years of mild weather (Bryant et al. 2019).

While there has been a general trend of recovery over recent years, localised climate events have had a major impact on seagrass outcomes in 2019 around the state. During 2019, severe localised flooding occurred in the Townsville region, which led to a decline in seagrass meadows (McKenna et al. 2020). While further to the north, in Cairns, seagrasses had increased to the best condition in a decade after experiencing comparatively milder climate in 2019 (Reason et al. 2020). Elsewhere on the east coast, initial recovery of seagrasses at Bowen/Abbot Point and Mackay/Hay Point suffered a setback in 2017 due to rainfall and flooding associated with TC Debbie (Chartrand et al. 2018b). However, drier conditions and lower river flows in the subsequent two years has led to seagrasses increasing (Chartrand et al. 2019).

Outside of the east coast, Queensland seagrasses were not impacted by the weather events leading up to 2011 and have fared better over recent times. These regions generally experienced a lower frequency or severity of extreme weather events, rainfall and flooding than along Queensland's east coast south of Cooktown. Seagrass condition at monitoring locations in Thursday Island (Torres Strait) (Wells et al. 2019b) and Weipa (Rasheed et al. 2020) were in satisfactory to good condition in 2019. However, in Karumba in the southern Gulf of Carpentaria, where flooding of the local rivers led to a persistent turbid plume over the seagrass meadows, they declined to their poorest state in more than 25 years (Shepherd et al. 2020).

In this context the Port Curtis and Rodds Bay seagrasses were one of the better outcomes for seagrass condition in Queensland in 2019.

4.2 Implications for port management

Results of this latest annual survey, have found seagrasses to be in a good condition compared with the 18 year monitoring history. With the exception of Pelican Banks, all seagrass monitoring meadows were at or above baseline condition and the majority have recovered to their pre 2010 condition. In 2019 offshore seagrasses in deeper areas of the port including adjacent to the spoil disposal ground also covered a record area. The seagrass dynamics observed in the program were consistent with the major climate drivers of seagrass change and the continued use of the meadows by dugongs and green turtles are signs of a functional seagrass ecosytem. As recognised indicators of overall marine environmental health (Dennison et al. 1993), the good condition of seagrasses in 2019 point toward a healthy marine environment for Port Curtis and Rodds Bay.

Improvements in species composition and biomass and the record spatial footprint of seagrasses have increased resilience of meadows in Port Curtis and Rodds Bay to future impacts. These meadows are likely to have maintained and replenished their seedbanks, further increasing their resilience to impacts and capacity for recovery (Reason et al 2017b), although currently seed banks are not monitored as part of the program. The high levels of resilience mean seagrasses were well placed to cope with natural and anthropogenic pressures in 2020 including planned maintenance and capital dredging activities.

The overwhelming factor controlling seagrass outcomes in Gladstone and elsewhere in Queensland is maintaining a light environment that is sufficient to support seagrass growth. 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).

Despite repeated disturbances from climate, floods, cyclones and anthropogenic activities over the last nine years, seagrass stayed within its historical area although they have struggled to recover their biomass and species composition until the last two years. Improvements in biomass and the return of more persistent species to meadows, suggest seagrasses will be more resilient to future pressures or impacts than over the previous 9 years. 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 2020 should favourable environmental conditions prevail.

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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). In some cases less than 10 years of data were available, e.g. meadows 21 and 52–57 which have only been surveyed since 2009, or species composition data were unavailable for years where no seagrass was present. In this instance the baseline was calculated over the longest available time period. Once the monitoring program has collected over 10 years of data, the 10 year long-term average will be used in future assessments. This 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 

Decrease below threshold from previous year 

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. For meadows 21 and 52-57 this upper limit will be recalculated each year until the 10 year baseline period is complete.

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).

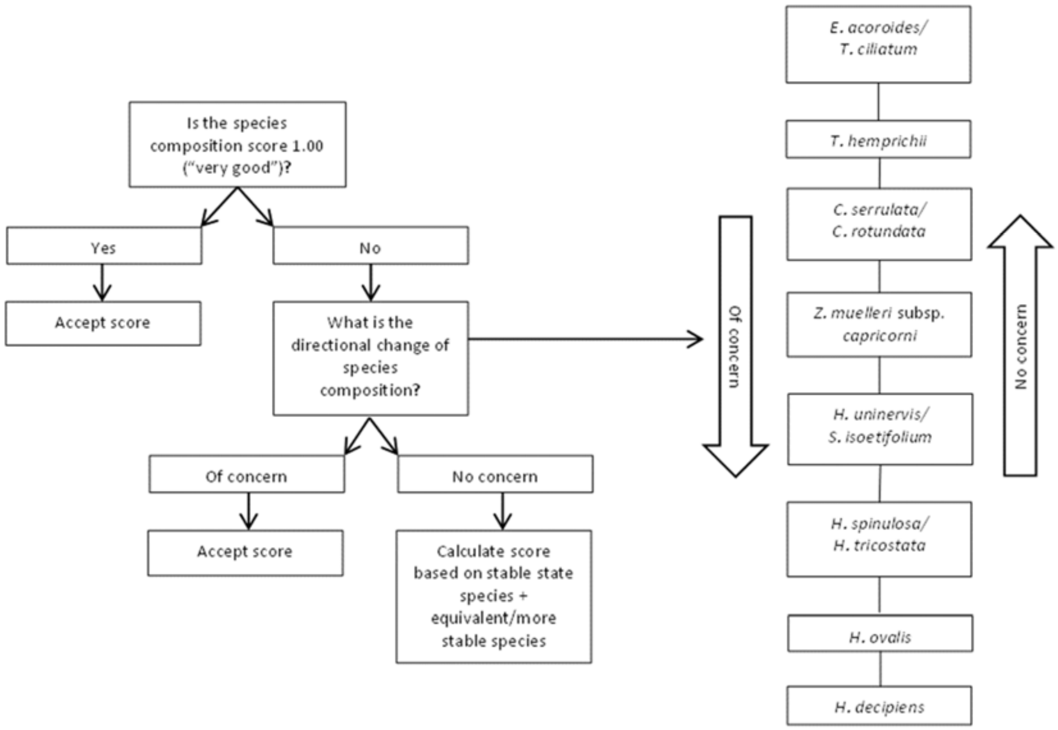


Figure 10. (a) Decision tree and (b) directional change assessment for grading and scoring seagrass species composition.

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 3 indicator scores was modified so that in the circumstances where species composition is the lowest of the 3 indicators, it contributes 50% of the score, with the other 50% coming from the lower of the 2 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 3 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 in 2019.

1. Determine the grade for the 2019 (current) area value (i.e. satisfactory).

2. Calculate the difference in area (A_{diff}) between the 2018 area value (A_{2017}) and the area value of the lower threshold boundary for the satisfactory grade ($A_{satisfactory}$):

$$\mathrm{A_{diff}} = \mathrm{A_{2018}} - \mathrm{A_{satisfactory}}$$

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_{2018} takes up:

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

5. Determine the area score for 2018 ($Score_{2016}$) by scaling A_{prop} against the score range (SR) for the satisfactory grade ($SR_{satisfactory}$), i.e. 0.15 units:

$$\mathrm{Score_{2016}} = \mathrm{LB_{satisfactory}} + \left(\mathrm{A_{prop}} \times \mathrm{SR_{satisfactory}}\right)$$

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

Meadow ID	Biomass ± SE (g DW m^{-2})	Area ± R (ha)	Community Type	Landscape Category	Species Present
The Narrows Zone					
1	6.14 ± 3.08	8.33 ± 2.32	Light *Z. muelleri*	Isolated patches	*Z. muelleri*
10 & 17	12.15 ± 3.29	16.90 ± 2.85	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri*
13	0.27 ± 0.17	27.39 ± 9.14	Light *H. decipiens* with *H. spinulosa*	Isolated patches	*H. decipiens, H. spinulosa*
19	8.25 ± 3.49	79.14 ± 6.71	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
21	6.04 ± 1.41	196.16 ± 8.64	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis, H. spinulosa*
22	0.64 ± 0.64	21.96 ± 1.14	Moderate *H. decipiens*	Aggregated patches	*H. decipiens, H. ovalis, H. spinulosa*
23	3.09 ± 1.05	118.29 ± 6.74	Light *Z. muelleri*	Continuous cover	*Z. muelleri, Z. ovalis, H. spinulosa, H. decipiens*
25	0.55 ± 0.55	1.80 ± 0.52	Light *H. ovalis*	Isolated patches	*H. ovalis, H. decipiens, H. spinulosa*
26	1.08	0.49 ± 0.30	Light *Z. muelleri*	Isolated patches	*Z. muelleri, H. ovalis*
28	4.19 ± 1.26	26.21 ± 3.65	Light *Z. muelleri* with *H. ovalis*	Isolated patches	*Z. muelleri, H. ovalis*
29	5.51 ± 1.15	57.40 ± 8.11	Light *Z. muelleri* with mixed species	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*
33	4.31 ± 1.23	153.60 ± 14.99	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*
219	n.a.	3.18 ± 1.90	Light *H. decipiens*	Aggregated patches	*H. decipiens*

Mean above-ground biomass (g DW m^{-2}) + standard error and area (ha) ± reliability estimate (R) for seagrass meadows in Port Curtis and Rodds Bay, 2018. n.a. – biomass not available due to grab sampling

Meadow ID	Biomass ± SE (g DW m^{-2})	Area ± R (ha)	Community Type	Landscape Category	Species Present
Graham Creek Zone					
2	2.18 ± 0.74	6.00 ± 1.13	Moderate *H. ovalis* with *Z. muelleri*	Isolated patches	*H. ovalis, Z. muelleri*
34	0.66 ± 0.16	7.20 ± 1.36	Light *H. ovalis*	Isolated patches	*H. ovalis*
36	1.00 ± 0.33	3.74 ± 1.35	Light *Z. muelleri* with *H. ovalis*	Isolated patches	*Z. muelleri, H. ovalis*
37 & 41	2.73 ± 1.14	75.97 ± 5.62	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*
38	0.41	0.16 ± 0.08	Light *H. decipiens*	Isolated patches	*H. decipiens*
141	0.46 ± 0.46	1.83 ± 0.31	Light *H. ovalis*	Aggregated patches	*H. ovalis*
168	0.35 ± 0.15	8.13 ± 2.49	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*
171	1.05 ± 0.44	1.74 ± 1.14	Light *Z. muelleri*	Aggregated patches	*Z. muelleri*
175	n.a.	0.14 ± 0.09	Light *H. ovalis*	Isolated patches	*H. ovalis*
217	1.10 ± 1.04	1.57 ± 0.96	Light *Z. muelleri*	Aggregated patches	*Z. muelleri*
221	n.a.	0.25 ± 0.22	Light *H. ovalis*	Isolated patches	*H. ovalis*
Western Basin Zone					
4	5.51 ± 1.22	38.40 ± 1.96	Light *Z. muelleri* with *H. ovalis*	Aggregated patches	*Z. muelleri, H. ovalis*
5	5.74 ± 1.01	153.17 ± 2.96	Light *Z. muelleri* with *H. ovalis*	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*
6	4.24 ± 0.49	433.70 ± 6.12	Moderate *H. ovalis*/Light *Z. muelleri*	Continuous cover	*Z. muelleri, H. ovalis*
7	1.50 ± 0.21	65.96 ± 4.08	Moderate *H. decipiens*	Isolated patches	*H. decipiens*
8	2.56 ± 0.47	231.59 ± 3.67	Moderate *H. ovalis*/Light *Z. muelleri*	Aggregated patches	*H. ovalis, Z. muelleri, H. decipiens*
9	0.27 ± 0.18	2.39 ± 1.03	Light *H. ovalis* with *H. decipiens*	Isolated patches	*H. ovalis, H. decipiens*
11	3.44 ± 0.40	3.71 ± 0.41	Moderate *H. ovalis* with *H. decipiens*	Isolated patches	*H. ovalis, H. decipiens*
16	1.94 ± 0.48	25.54 ± 2.91	Moderate *H. ovalis*	Isolated patches	*H. ovalis*
42	1.82 ± 0.54	18.39 ± 3.76	Moderate *H. ovalis* with *Z. muelleri*	Isolated patches	*H. ovalis, Z. muelleri*
44	1.86 ± 0.67	3.58 ± 1.33	Moderate *H. ovalis*	Isolated patches	*H. ovalis*
52 & 57	1.41 ± 0.18	113.42 ± 4.96	Light *H. ovalis* with *Z. muelleri*	Isolated patches	*H. ovalis, Z. muelleri*
51	0.85	0.10 ± 0.10	Light *H. ovalis*	Isolated patches	*H. ovalis*
59	0.53 ± 0.53	2.35 ± 0.83	Light *H. ovalis*	Isolated patches	*H. ovalis*
215	0.64 ± 0.32	13.63 ± 3.25	Light *H. decipiens*	Aggregated patches	*H. decipiens*
216	n.a.	1.46 ± 0.98	Light *H. ovalis*	Isolated patches	*H. ovalis*

Meadow ID	Biomass ± SE (g DW m^{-2})	Area ± R (ha)	Community Type	Landscape Category	Species Present
Inner Harbour Zone					
50	1.73 ± 0.32	61.52 ± 1.78	Light *H. ovalis* with mixed species	Aggregated patches	*H. ovalis, Z. muelleri, H. spinulosa*
61	1.52 ± 0.86	4.37 ± 0.48	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
74	3.13	0.43 ± 0.28	Light *H. uninervis*	Isolated patches	*H. uninervis*
79	2.03 ± 0.50	45.91 ± 1.80	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
80	1.10 ± 0.24	5.57 ± 1.25	Light *H. ovalis* with *Z. muelleri*	Isolated patches	*Z. muelleri, H. ovalis*
81	0.53 ± 0.53	0.51 ± 0.29	Light *H. ovalis*	Isolated patches	*H. ovalis*
85	2.66 ± 0.45	112.15 ± 6.34	Light *Z. muelleri* with *H. ovalis*	Aggregated patches	*Z. muelleri, H. ovalis*
136	2.49 ± 1.33	13.02 ± 1.93	Light *Z. muelleri* with *H. ovalis*	Aggregated patches	*Z. muelleri, H. ovalis*
157	1.47 ± 0.28	9.81 ± 1.27	Moderate *H. ovalis*	Isolated patches	*H. ovalis*
220	2.28	0.20 ± 0.09	Moderate *H. ovalis*	Isolated patches	*H. ovalis*
58	1.68 ± 0.27	67.15 ± 4.78	Light *Z. muelleri*/Light *H. ovalis*	Aggregated patches	*Z. muelleri, H. ovalis*

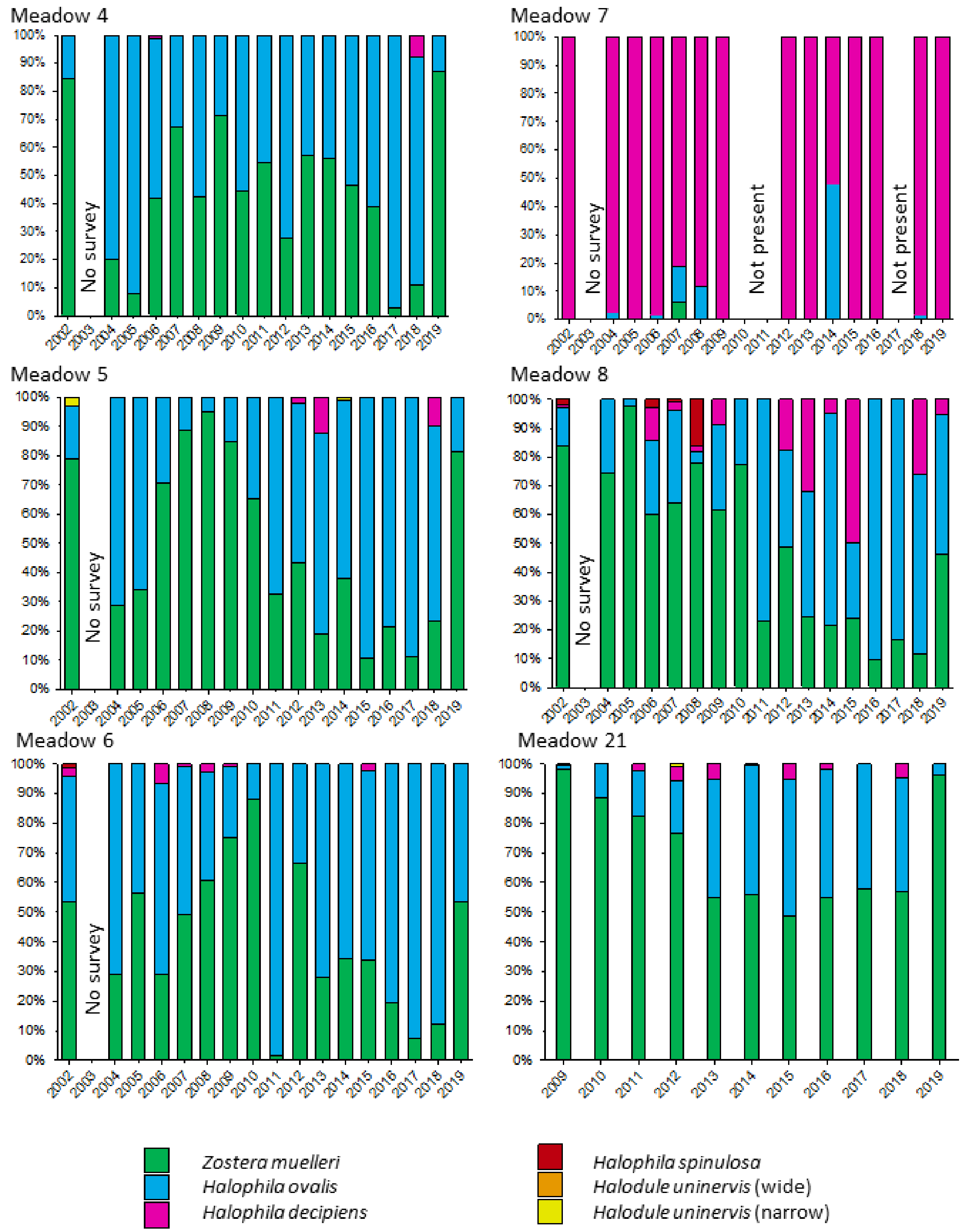
Meadow ID	Biomass ± SE (g DW m^{-2})	Area ± R (ha)	Community Type	Landscape Category	Species Present
Mid Harbour Zone					
3	1.76 ± 0.61	1.62 ± 0.58	Light *H. uninervis* with mixed species	Isolated patches	*H. uninervis, H. ovalis, H. decipiens*
49	0.54 ± 0.34	21.51 ± 1.34	Light *H. ovalis*	Isolated patches	*H. ovalis*
65	0.82	0.25 ± 0.27	Light *H. decipiens*	Isolated patches	*H. decipiens*
66 & 67	4.82 ± 0.69	369.53 ± 6.52	Moderate *Z. muelleri* with mixed species	Continuous cover	*Z. muelleri, H. uninervis, H. ovalis, H. spinulosa*
69	8.88 ± 2.29	2.49 ± 1.90	Light *Z. muelleri*	Isolated patches	*Z. muelleri*
70	1.68 ± 1.39	29.41 ± 2.55	Light *Z. muelleri*	Isolated patches	*Z. muelleri, H. ovalis*
71	1.72 ± 0.78	62.53 ± 6.31	Light *Z. muelleri* with *H. ovalis*	Isolated patches	*Z. muelleri, H. ovalis*
72	1.15 ± 0.58	23.52 ± 3.20	Light *H. uninervis* with *H. ovalis*	Isolated patches	*H. uninervis, H. ovalis*
78 & 89	5.58 ± 0.60	387.64 ± 17.33	Dense *H. uninervis* with mixed species	Continuous cover	*H. uninervis, Z. muelleri, H. ovalis, H. decipiens*
86	1.43	4.44 ± 1.68	Moderate *H. ovalis*	Aggregated patches	*H. ovalis, H. decipiens*
137	7.21 ± 0.74	7.24 ± 0.55	Light *Z. muelleri*	Continuous cover	*Z. muelleri*
140	0.01	36.21 ± 17.79	Light *H. decipiens*	Isolated patches	*H. decipiens*
153	15.93 ± 4.37	0.27 ± 0.15	Light *Z. muelleri*	Isolated patches	*Z. muelleri*
158	2.05 ± 0.52	4.13 ± 0.40	Moderate *H. ovalis*	Isolated patches	*H. ovalis*
165	9.64 ± 6.15	0.92 ± 0.79	Light *Z. muelleri*	Isolated patches	*Z. muelleri*
166	2.49 ± 0.75	266.84 ± 1.84	Moderate *H. decipiens*	Aggregated patches	*H. decipiens*
177	0.91 ± 0.53	2.97 ± 0.94	Light *H. uninervis* with *H. decipiens*	Isolated patches	*H. uninervis, H. decipiens*
223	0.40	0.28 ± 0.17	Light *Z. muelleri*	Isolated patches	*Z. muelleri*
43	5.55 ± 0.50	684.59 ± 7.05	Light *Z. muelleri* with mixed species	Continuous cover	*Z. muelleri, H. uninervis, H. ovalis*
48	2.94 ± 0.35	348.12 ± 4.82	Mixed species	Aggregated patches	*H. uninervis, H. ovalis, H. spinulosa*

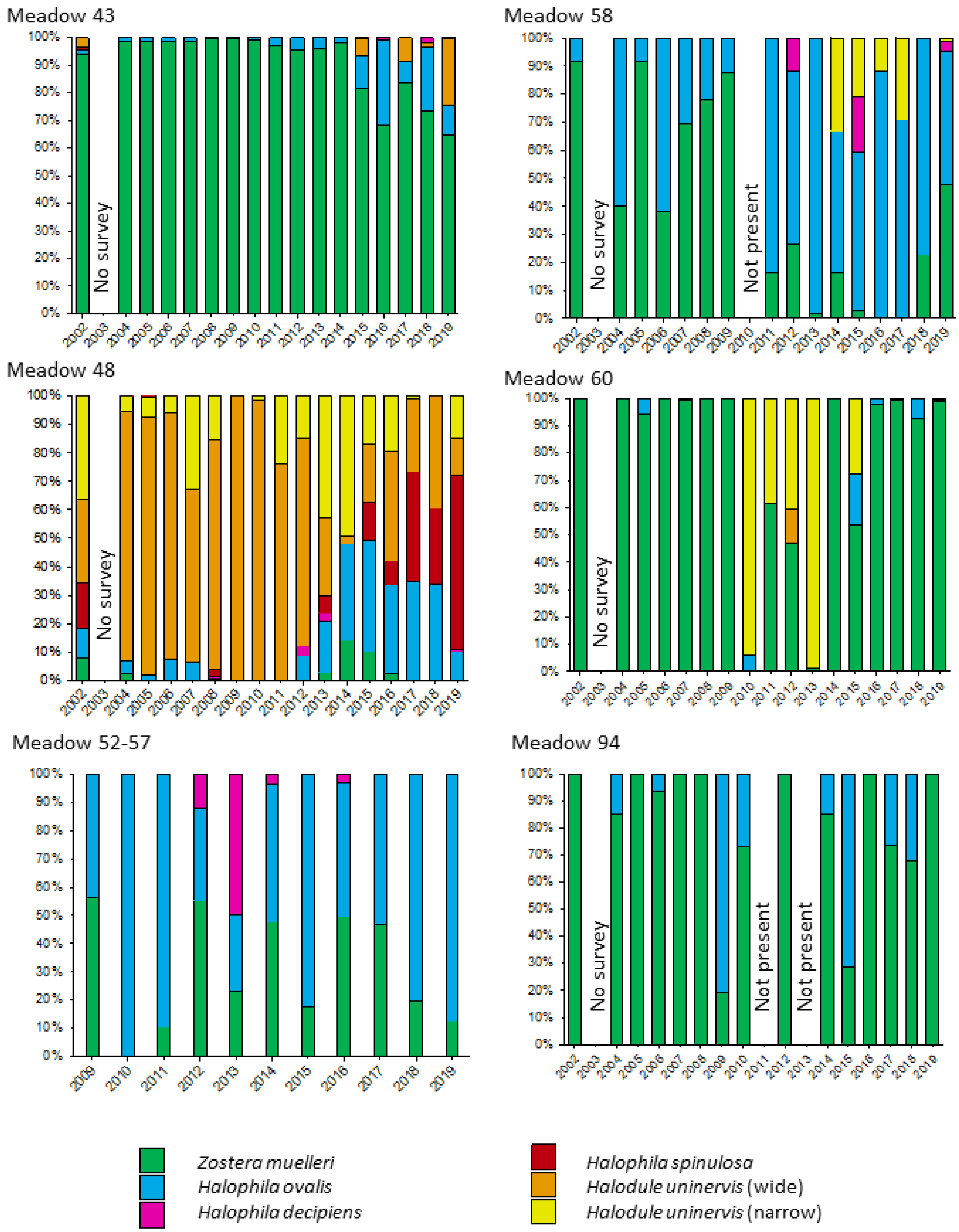
Meadow ID	Biomass ± SE (g DW m^{-2})	Area ± R (ha)	Community Type	Landscape Category	Species Present
South Trees Inlet Zone					
60	14.41 ± 1.81	12.47 ± 0.81	Moderate *Z. muelleri*	Continuous cover	*Z. muelleri, H. ovalis, H. decipiens*
76 & 77	9.24 ± 1.60	151.31 ± 4.10	Moderate Z. muelleri with mixed species	Continuous cover	*Z. muelleri, H. uninervis, H. ovalis, H. spinulosa*
142	2.37 ± 0.34	3.27 ± 1.13	Light *Z. muelleri* with *H. ovalis*	Aggregated patches	*Z. muelleri, H. ovalis*
145	0.42 ± 0.20	1.08 ± 0.63	Light *H. ovalis*	Isolated patches	*H. ovalis*
149	0.53 ± 0.07	0.37 ± 0.20	Light *H. ovalis*	Isolated patches	*H. ovalis*
154	0.72 ± 0.46	3.54 ± 0.88	Light *H. ovalis*	Isolated patches	*H. ovalis*
155	2.14	0.08 ± 0.08	Light *Z. muelleri* with *H. ovalis*	Isolated patches	*Z. muelleri, H. ovalis*
159	2.11 ± 1.06	0.24 ± 0.10	Light *Z. muelleri*	Isolated patches	*Z. muelleri*
160	1.86 ± 0.62	7.74 ± 0.47	Moderate *H. ovalis* with *Z. muelleri*	Continuous cover	*H. ovalis, Z. muelleri*
167	0.82 ± 0.24	1.98 ± 0.29	Light *H. ovalis*	Isolated patches	*H. ovalis*
173	0.02	0.06 ± 0.03	Light *H. ovalis*	Isolated patches	*H. ovalis*
Outer Harbour Zone					
108	2.39 ± 0.90	449.47 ± 60.34	Moderate *H. uninervis*	Aggregated patches	*H. uninervis, H. ovalis*
109	3.73 ± 0.95	380.57 ± 17.17	Moderate *H. uninervis*	Aggregated patches	*H. uninervis*
130	0.01	26.10 ± 15.37	Light *H. decipiens*	Isolated patches	*H. decipiens*
132	0.07 ± 0.05	4,712.44 ± 422.81	Light *H. decipiens* with mixed species	Aggregated patches	*H. decipiens, H. ovalis, Z. muelleri, H. uninervis*
133	0.01 ± 0.01	1,795.00 ± 268.17	Mixed species	Isolated patches	*H. uninervis, H. decipiens, Z. muelleri, H. ovalis*
134	0.01 ± 0.01	410.64 ± 106.77	Light *H. decipiens*	Isolated patches	*H. decipiens*
135	0.01 ± 0.01	965.37 ± 306.08	Light *H. decipiens*	Isolated patches	*H. decipiens*
138	0.15	263.46 ± 138.51	Light *H. decipiens*	Isolated patches	*H. decipiens*
139	0.01 ± 0.01	415.47 ± 98.52	Light *Z. muelleri* with *H. uninervis*	Isolated patches	*Z. muelleri, H. uninervis, H. spinulosa*

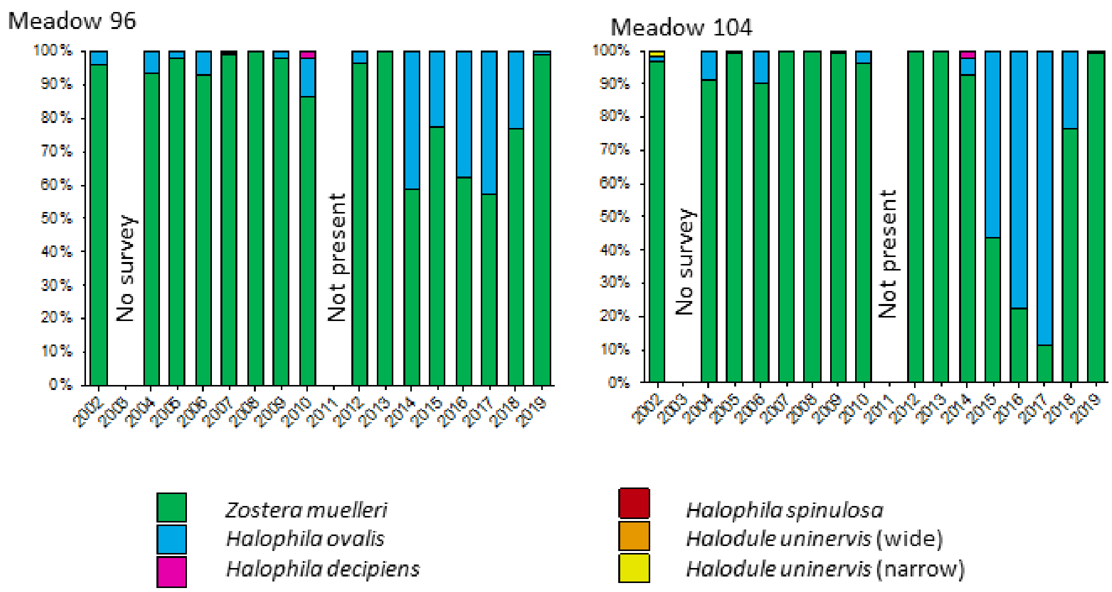
Meadow ID	Biomass ± SE (g DW m^{-2})	Area ± R (ha)	Community Type	Landscape Category	Species Present
Colosseum Inlet Zone					
90	10.89	0.70 ± 0.54	Light *Z. muelleri*	Isolated patches	*Z. muelleri*
91	24.68 ± 3.44	48.62 ± 6.73	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
92	29.61 ± 6.21	6.37 ± 2.95	Dense *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
93	15.93 ± 2.15	3.17 ± 1.02	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
95	14.04	7.20 ± 2.65	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri*
98	0.68	2.90 ± 0.78	Light *Z. muelleri*	Aggregated patches	*Z. muelleri*
99	17.98 ± 6.48	23.02 ± 6.26	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
100	8.49 ± 1.38	5.66 ± 1.51	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
101	21.66 ± 5.60	13.57 ± 4.13	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
102	23.88	1.00 ± 0.63	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri*
122	27.35 ± 8.40	13.27 ± 1.53	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
200	10.96	12.19 ± 1.49	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri*
202	18.78 ± 9.00	16.40 ± 4.11	Dense *Z. muelleri*	Continuous cover	*Z. muelleri, H. ovalis*
203	30.32	2.60 ± 1.39	Dense *Z. muelleri*	Continuous cover	*Z. muelleri*
204	22.62	1.35 ± 0.60	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri*
205	n.a.	2.58 ± 0.99	Light *Z. muelleri*	Isolated patches	*Z. muelleri*
206	0.49	0.33 ± 0.23	Light *H. decipiens*	Isolated patches	*H. decipiens*
207	0.85 ± 0.37	13.80 ± 4.19	Light *Z. muelleri* with *H. ovalis*	Isolated patches	*Z. muelleri, H. ovalis*
208	2.71	2.28 ± 1.09	Moderate *H. ovalis*	Isolated patches	*H. ovalis*
209	0.60 ± 0.43	14.74 ± 2.96	Light *Z. muelleri* with *H. ovalis*	Isolated patches	*Z. muelleri, H. ovalis*
210	0.15	0.40 ± 0.19	Light *Z. muelleri*	Isolated patches	*Z. muelleri*
211	0.23	1.23 ± 0.60	Light *Z. muelleri*	Isolated patches	*Z. muelleri*
212	2.05	1.28 ± 0.67	Light *Z. muelleri* with *H. ovalis*	Isolated patches	*Z. muelleri, H. ovalis*
213	0.94 ± 0.94	3.45 ± 1.27	Light *Z. muelleri*	Isolated patches	*H. uninervis, H. ovalis*
214	n.a.	0.35 ± 0.35	Light *H. ovalis*	Isolated patches	*H. ovalis*
222	0.39	0.91 ± 0.54	Light *H. ovalis*	Isolated patches	*H. ovalis*

Meadow ID	Biomass ± SE (g DW m^{-2})	Area ± R (ha)	Community Type	Landscape Category	Species Present
Rodds Bay Zone					
94	20.31 ± 3.45	3.12 ± 0.84	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
96	16.29 ± 1.53	394.95 ± 6.58	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
104	11.70 ± 1.96	37.61 ± 4.39	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
105 & 106	18.07 ± 4.17	89.49 ± 7.36	Moderate *Z. muelleri*	Continuous cover	*Z. muelleri, H. ovalis*
110	11.55 ± 3.15	133.39 ± 11.59	Light *Z. muelleri* with *H. uninervis*	Aggregated patches	*Z. muelleri, H. uninervis, H. ovalis*
112	10.43 ± 3.30	217.65 ± 16.94	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
113	14.49 ± 4.39	136.82 ± 18.76	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri*
114	8.09 ± 5.11	51.49 ± 4.13	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
115	21.36 ± 3.03	32.26 ± 2.63	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
116	6.44 ± 6.44	4.71 ± 1.98	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
117	0.41 ± 0.12	2.17 ± 1.15	Light *H. ovalis*	Isolated patches	*H. ovalis*
118	0.37 ± 0.37	3.16 ± 1.62	Light *H. ovalis*	Isolated patches	*H. ovalis*
119	7.27 ± 1.33	515.39 ± 5.81	Moderate *Z. muelleri* with mixed species	Continuous cover	*Z. muelleri, H. ovalis, H. uninervis*
120	3.83 ± 1.74	53.51 ± 5.33	Light *Z. muelleri* with mixed species	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*
121	5.71 ± 1.22	744.47 ± 40.04	Light *Z. muelleri* with *H. ovalis*	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*
124	7.02 ± 4.57	21.56 ± 1.63	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
125	5.42 ± 1.42	41.28 ± 7.86	Light *Z. muelleri* with *H. ovalis*	Aggregated patches	*Z. muelleri, H. ovalis*
128	7.85 ± 2.39	44.76 ± 4.61	Light *Z. muelleri* with *H. ovalis*	Aggregated patches	*Z. muelleri, H. ovalis*
131	2.69 ± 0.38	17.33 ± 3.09	Moderate *H. ovalis*	Aggregated patches	*H. ovalis, Z. muelleri*
162	n.a.	0.30 ± 0.25	Light *Z. muelleri*	Isolated patches	*Z. muelleri, H. ovalis*
163	5.97 ± 5.97	2.87 ± 1.50	Moderate *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*
164	6.74	3.45 ± 0.93	Light *Z. muelleri*	Isolated patches	*Z. muelleri, H. ovalis*
201	2.29	25.35 ± 9.72	Moderate *H. ovalis*	Isolated patches	*H. ovalis*
218	0.02	2.34 ± 1.21	Light *H. decipiens*	Isolated patches	*H. decipiens*

Appendix 4. Detailed species composition for long term monitoring meadows, 2002–2019




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


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