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JAMES COOK UNIVERSITY
AUSTRALIA

# Seagrasses in Port Curtis and Rodds Bay 2018
# Annual long-term monitoring

Chartrand KM, Wells JN, Carter AB, and Rasheed MA

Report No. 19/02
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# A Report for Gladstone Ports Corporation

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# KEY FINDINGS

Seagrass Condition 2018

**Satisfactory**

1. Seagrasses in Port Curtis and Rodds Bay were surveyed as part of annual monitoring from the 4th–10th November 2018. Seagrass improved substantially over the previous year to be in an overall satisfactory condition in 2018.

2. Program-wide improvements in seagrass occurred due to significant increases in meadow condition in The Narrows, Western Basin, and Rodds Bay Zones and maintenance of seagrass condition in the South Trees, Inner, and Mid Harbour meadows.

3. Seagrasses in Rodds Bay underwent the most substantial shift with the largest recovery since major losses in this zone in 2009.

4. Closer to the port, the subtidal monitoring meadow in the Western Basin Zone returned with a substantial footprint, and highest biomass for this meadow since monitoring began, helping to bolster the Port's collective seagrass grade.

5. Pelican Banks, the largest and historically most stable seagrass meadow in Port Curtis, remained in a poor condition due to continued low biomass despite improvements in area.

6. Flow from local rivers and rainfall have had a strong influence on seagrass condition throughout the 17 year history of the monitoring program. Declines in Port Curtis and Rodds Bay seagrass condition are strongly correlated with increases in total annual river flow and rainfall.

7. The gain in total seagrass extent in 2018 and recovery in some meadows was likely due to a lack of major rainfall and flooding events in 2018.

8. There was no relationship between proximity of port and anthropogenic activities and change or improvement within meadows indicating regional environmental conditions rather than anthropogenic activity were the driver of observed seagrass changes in 2018.

9. Previous analysis of seagrass change between pre, post and during the Western Basin Dredging and Disposal Project (2009-2016), found similar results with major rainfall, river flow events and associated available light impacting seagrass.

10. A range of other factors such as sediment dynamics and grazing pressure, not monitored in the program, are also potential drivers of seagrass change for some meadows.

11. The improved state of seagrasses in 2018 is a promising sign. Should conditions remain favourable during 2019 we would expect to see further increases in seagrasses. Seagrass resilience in Port Curtis and Rodds Bay is likely to have improved in 2018 due to the increase in seagrass biomass and area, however, some meadows may still remain vulnerable as they are yet to fully recover.

# 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 the Gladstone region. In addition all seagrass has been assessed across intertidal and shallow subtidal waters in the Port Curtis monitoring area (Figure 2) between 2009 and 2018, while Rodds Bay assessments are limited to the three monitoring meadows (Figures 1, 2).

Seagrass condition in 2018 was satisfactory among the 14 monitoring meadows, an improvement following several years of poor condition. The total area of seagrass mapped in the Port Curtis monitoring area continued to increase above the long-term average for the second year (Figure 1). Ten monitoring meadows were in very good to satisfactory condition, and only four remained in poor or very poor condition (Figures 3, 4 and section 3.4 for more details). South Trees, Inner, and Mid Harbour monitoring meadow condition remained the same. Western Basin and The Narrows meadows either improved or remained unchanged, with several meadows improving more than one grade (Figures 3, 4). Condition of Rodds Bay meadows improved substantially in 2018 following a decade of poor to very poor condition (Figure 4).

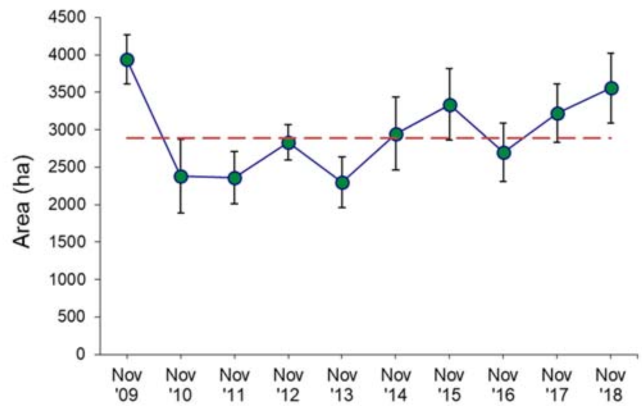


**Figure 1.** Annual variation in total seagrass area, Port Curtis, and mean area (red dashed line), 2009–2017.

Concerns were raised in 2016 regarding the very poor condition of seagrass at Pelican Banks. This meadow contains the largest area and historically densest seagrass in the region, and had experienced significant reductions in biomass and the proportion of the foundation species. Meadow condition improved from very poor to poor in 2017, and in 2018 biomass and area continued to improve. Given this meadow's importance as a key seagrass resource in Port Curtis, a continued recovery trajectory remains key to marine environmental health in the region. Evidence from research into the impacts of herbivory on Gladstone seagrasses indicate that high levels of feeding from dugongs and green turtles may explain, at least in part, the lower biomass of seagrasses on Pelican Banks.

Resilience of seagrasses in Port Curtis and Rodds Bay to further natural or anthropogenic impacts is likely to have improved due to the increase in seagrass biomass and area recorded in 2018. Future recovery may continue if climate and weather conditions remain favourable for seagrass growth, particularly as the increased biomass and spatial footprint found in many areas in 2018 is likely to provide a beneficial base from which recovery can continue.

The recovery of seagrasses in Port Curtis and Rodds Bay generally reflects trends in other seagrass areas monitored as part of the network of seagrass monitoring between Cairns and Port Curtis. For full details of the Queensland ports seagrass monitoring program see www.jcu.edu.au/ portseagrassqld.

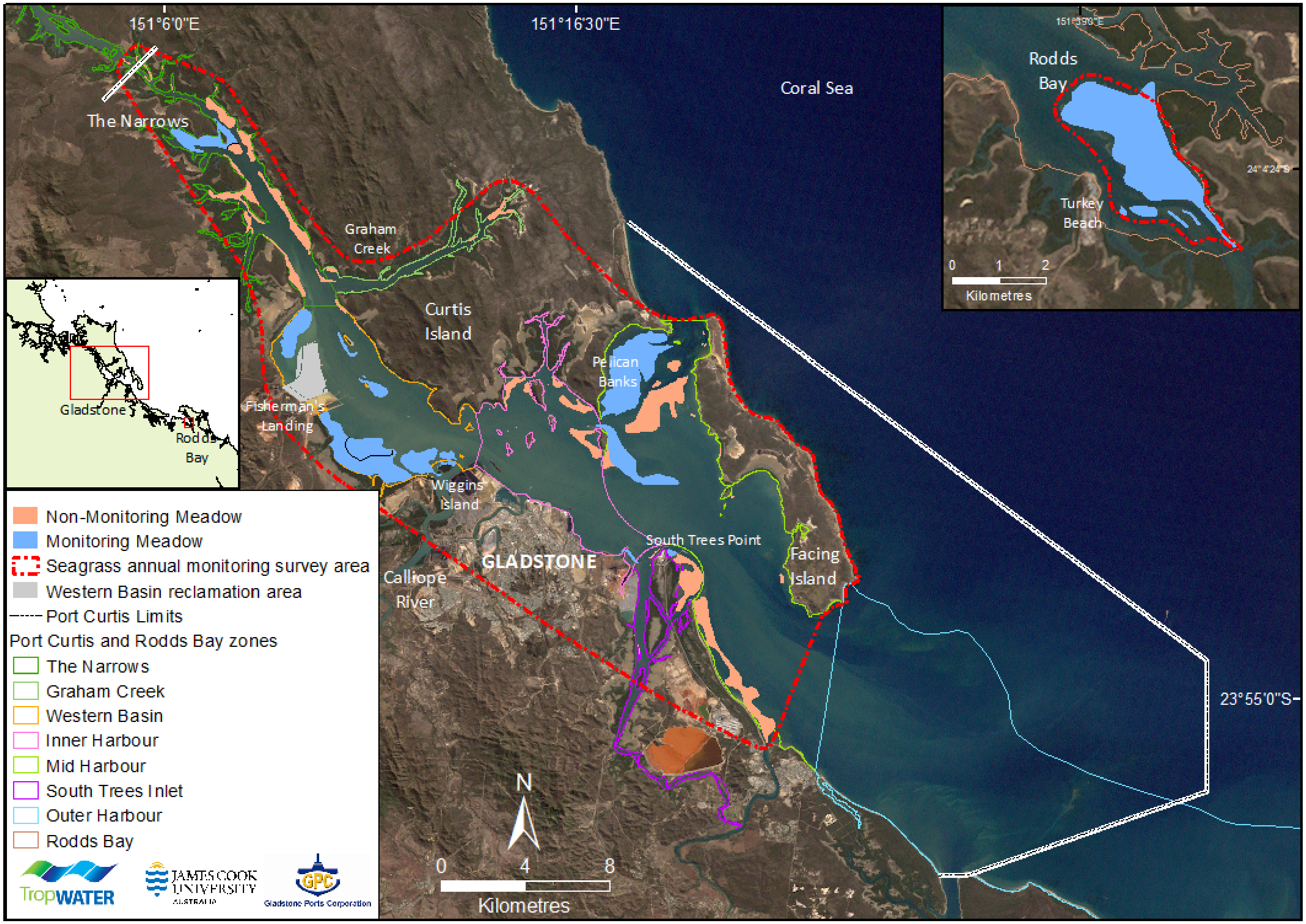


**Figure 2.** Seagrass distribution within the Port Curtis and Rodds Bay annual monitoring areas, November 2018.

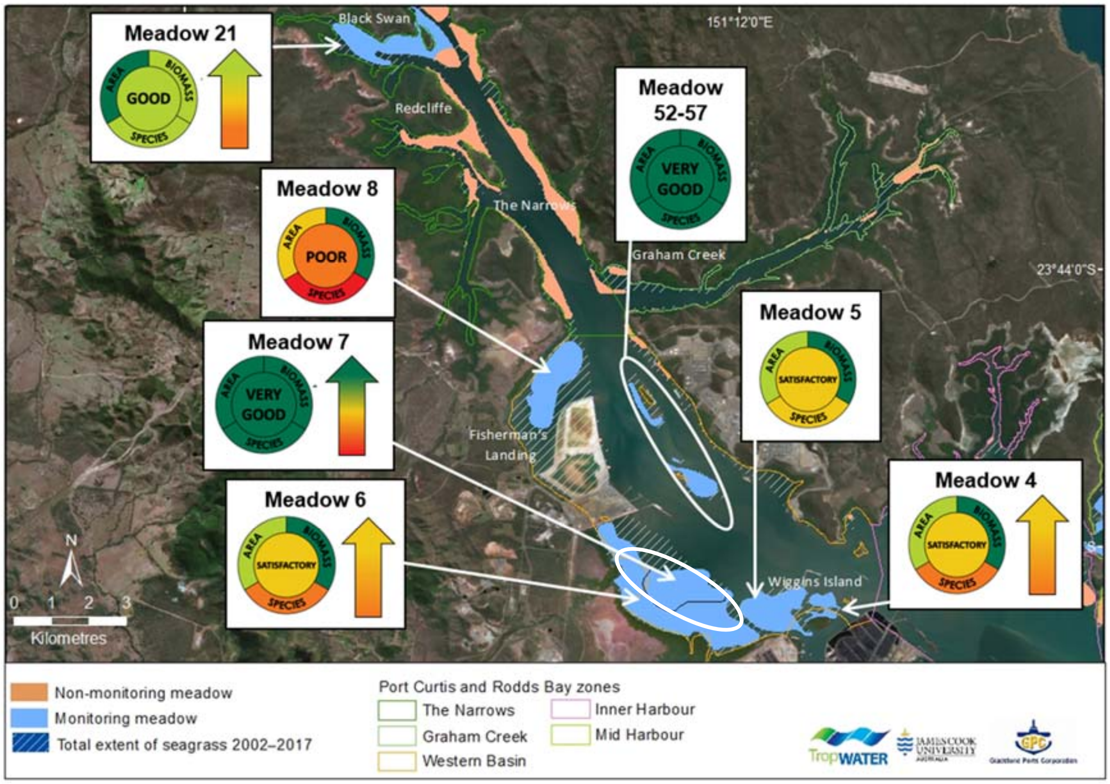


**Figure 3.** Seagrass distribution and meadow condition in The Narrows and Western Basin Zones (Port Curtis), November 2018. Arrows indicate an overall grade change from 2017.

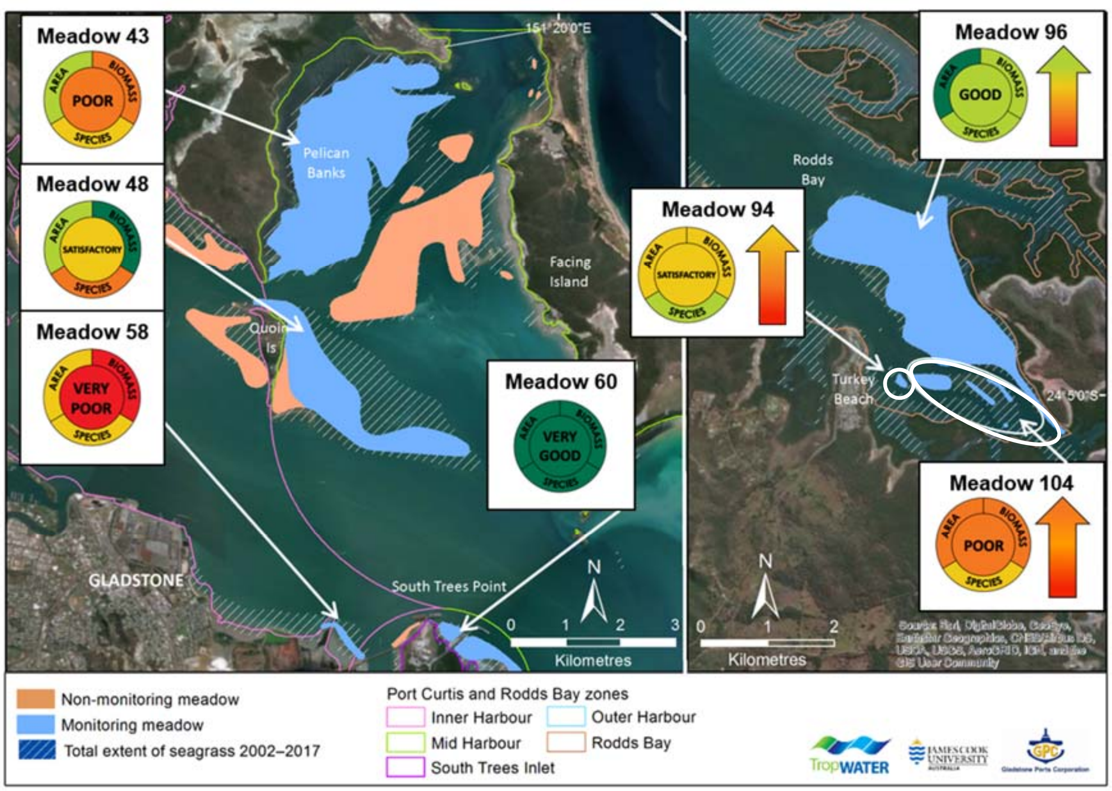


**Figure 4.** Seagrass distribution and meadow condition in the Inner Harbour, Mid Harbour, and South Trees Inlet Zones (Port Curtis), and Rodds Bay, November 2018. Arrows indicate an overall grade change from 2017.

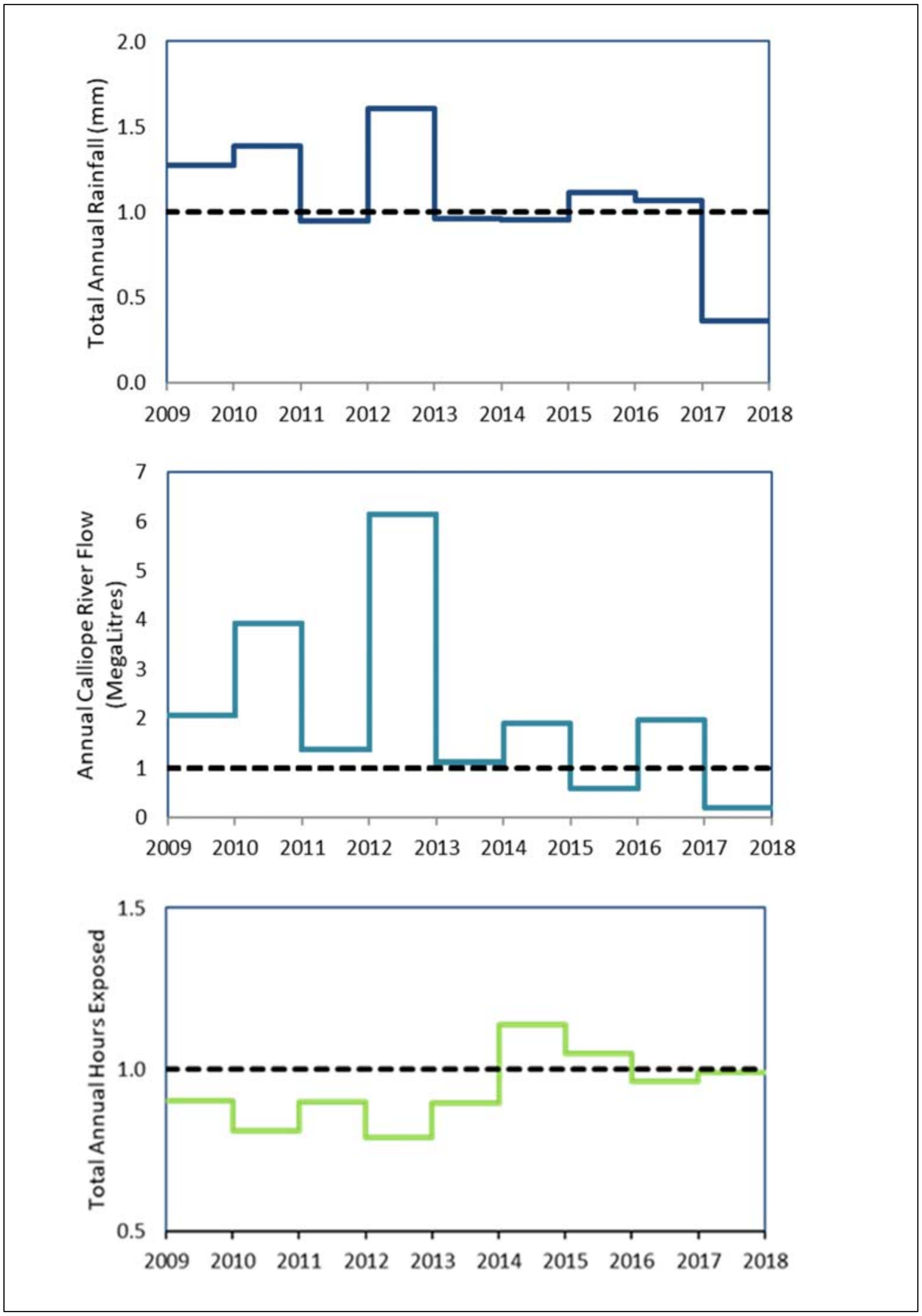


**Figure 5.** Climate trends in Port Curtis, 2009 to 2018. Annual average (solid coloured line) expressed as a relative change where 1.0 equals the long-term average (dashed line). Long-term averages calculated for rainfall (1958-2018), river flow (1974-2018), hours daytime tidal exposure hours (2002-2018). 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 |
| GIS | Geographic Information System |
| GPC | Gladstone Ports Corporation |
| 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 & Aquatic Ecosystem Research (TropWATER) (formerly part of the Department Agriculture and Fisheries) in partnership with the various Queensland port authorities. Each location is funded separately, but the common methods 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 to ensure effective management of seagrass habitat. This information is often central to planning and implementing port development and maintenance programs that 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 also has provided 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 drivers of seagrass change.

For more information on the program and reports from other monitoring locations see www.jcu.edu.au/portseagrassqld.

## 1.2 Gladstone 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), a further indication of the region's importance as a dugong foraging ground.

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 selected initially 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 include:

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 and 2014 (Carter et al. 2015a; Bryant et al. 2014c; Thomas et al. 2010).

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. 2014; Chartrand et al. 2012; Bostrom et al. 2006).

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 stores or seeds to persist following wet season conditions such as flooding, poor water quality, and light reductions (Chartrand et al. 2012). Seagrass biomass and area is at its lowest around June, and peaks between October and November. Annual monitoring is scheduled to coincide with that peak.

# 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 can be found in previous reports (Rasheed et al. 2005; Rasheed et al. 2003). Seagrass was surveyed 4th – 10th November 2018 during the peak seagrass growth period. Standardising surveys to every October-December allows for appropriate comparisons of seagrass condition among years (2002-2018). The survey involved mapping and assessing:

- All intertidal and shallow subtidal seagrasses within the Port Curtis monitoring area.
- The 14 long-term monitoring meadows within Port Curtis and Rodds Bay.

Intertidal meadows were surveyed at low tide using a helicopter. GPS was used to map the position of meadow boundaries and sites were scattered haphazardly within each meadow. Sites were surveyed as the helicopter hovered approximately one metre above the substrate (Figure 7a). Shallow subtidal meadows were sampled by boat using camera drops and van Veen grab (Figure 7b, c). Subtidal sites were positioned at ~100 - 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 meadows was informed by power analysis (Rasheed et al. 2003). Where underwater visibility was poor addition 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.

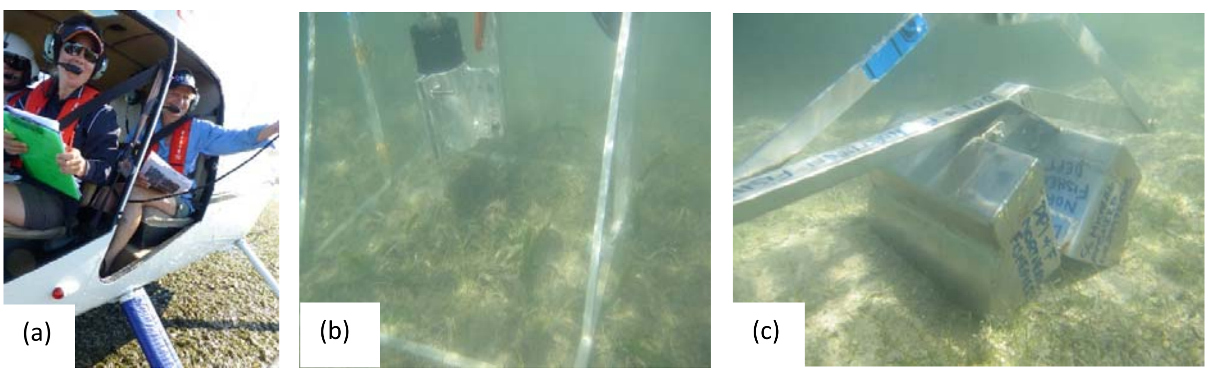



**Figure 7.** Seagrass monitoring methods in 2018. (a) helicopter survey of intertidal seagrass, (b, c) boat-based camera drops and van Veen grab for subtidal seagrass.

## 2.2 Seagrass biomass estimates

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

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

## 2.3 Geographic Information System

All survey data were entered into a Geographic Information System (GIS) using ArcGIS 10.4®. 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 (dbMSL; 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 (DFT) 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 2018, 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 $\leq$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,<br>Intertidal meadows completely exposed or visible at low tide,<br>Relatively high density of mapping and survey sites,<br>Recent aerial photography aided in mapping. |
| 10-20 m | Meadow boundaries determined from helicopter and boat surveys,<br>Intertidal boundaries interpreted from helicopter mapping and survey sites,<br>Recent aerial photography aided in mapping,<br>Subtidal boundaries interpreted from survey sites,<br>Moderately high density of mapping and survey sites. |
| 20-50 m | Meadow boundaries determined from helicopter and boat surveys,<br>Intertidal boundaries interpreted from helicopter sites,<br>Subtidal boundaries interpreted from boat survey sites,<br>Lower density of survey sites for some sections of 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)<br>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* subsp. *capricorni* |
| 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.

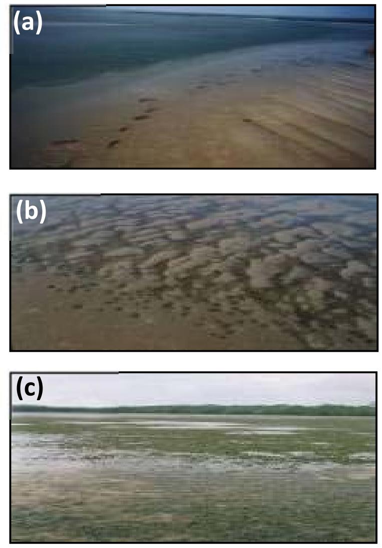



**Figure 8.** Seagrass meadow landscape categories: (a) Isolated seagrass patches, (b) aggregated seagrass patches, (c) continuous seagrass cover.

## 2.4 Environmental data

Environmental data were collated for the 12 months preceding each survey. Tidal data was provided by Maritime Safety Queensland (MSQ) (© The State of Queensland (Department of Transport and Main Roads) 2017, 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; ML) 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 driven by 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.

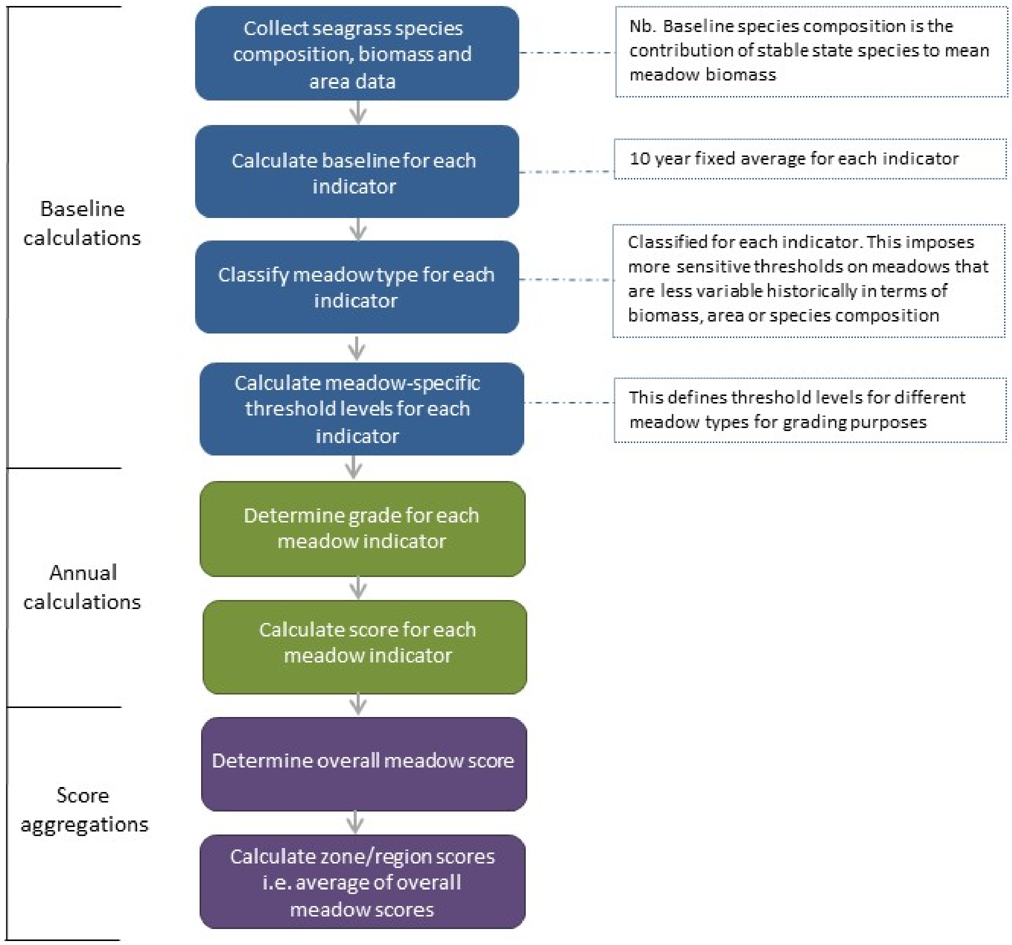



**Figure 9.** Flow chart used to determine monitoring meadow condition.

## 2.6 Analysis of meadow scores and environmental conditions

Overall meadow scores for each monitoring meadow from 2002 – 2018 were tested against total annual rainfall and total annual river flow from the Calliope River. All modelling was performed using R v.3.4.4 with the package 'mgcv' (Wood 2017). A quasibinomial generalised additive mixed effects model (GAMM) was run with the random effect of 'meadow' to account for the repeated nature of the annual scoring dataset. Due to strong collinearity between river flow and rainfall, only one parameter could be run at a time, however results were similar. Overall, residual plots were checked and the best fit model was selected.

# 3 RESULTS

## 3.1 Seagrasses in Port Curtis and Rodds Bay

A total of 1,507 sites were surveyed in the Port Curtis and Rodds Bay annual monitoring survey area in 2018 (Figure 10). Five seagrass species from three families were observed during the survey (Figure 11). For a full list of species found in the Gladstone region see Thomas et al. 2010. A total seagrass area of 3,558 ± 466 ha was mapped in the Port Curtis survey limits, approximately 700 ha above the long-term average (Figure 1). Seagrass area within the Rodds Bay survey area was 374 ± 16 ha. Dugong feeding trails (DFTs) were observed throughout the Port Curtis and Rodds Bay survey areas, with the exception of Graham Creek.

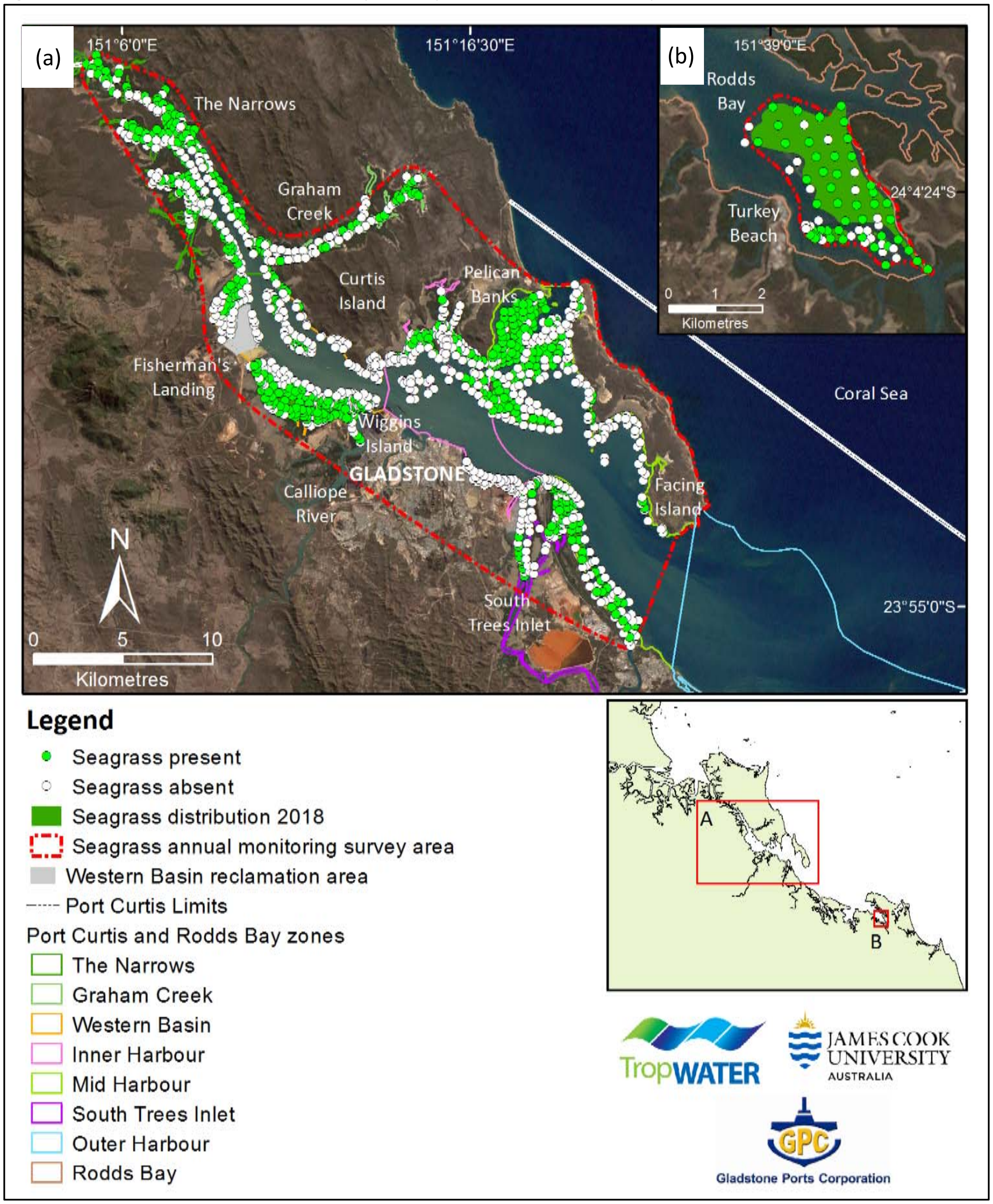



**Figure 10. S**eagrass presence/absence at sites surveyed within (a) Port Curtis and (b) Rodds Bay survey areas, 2018.

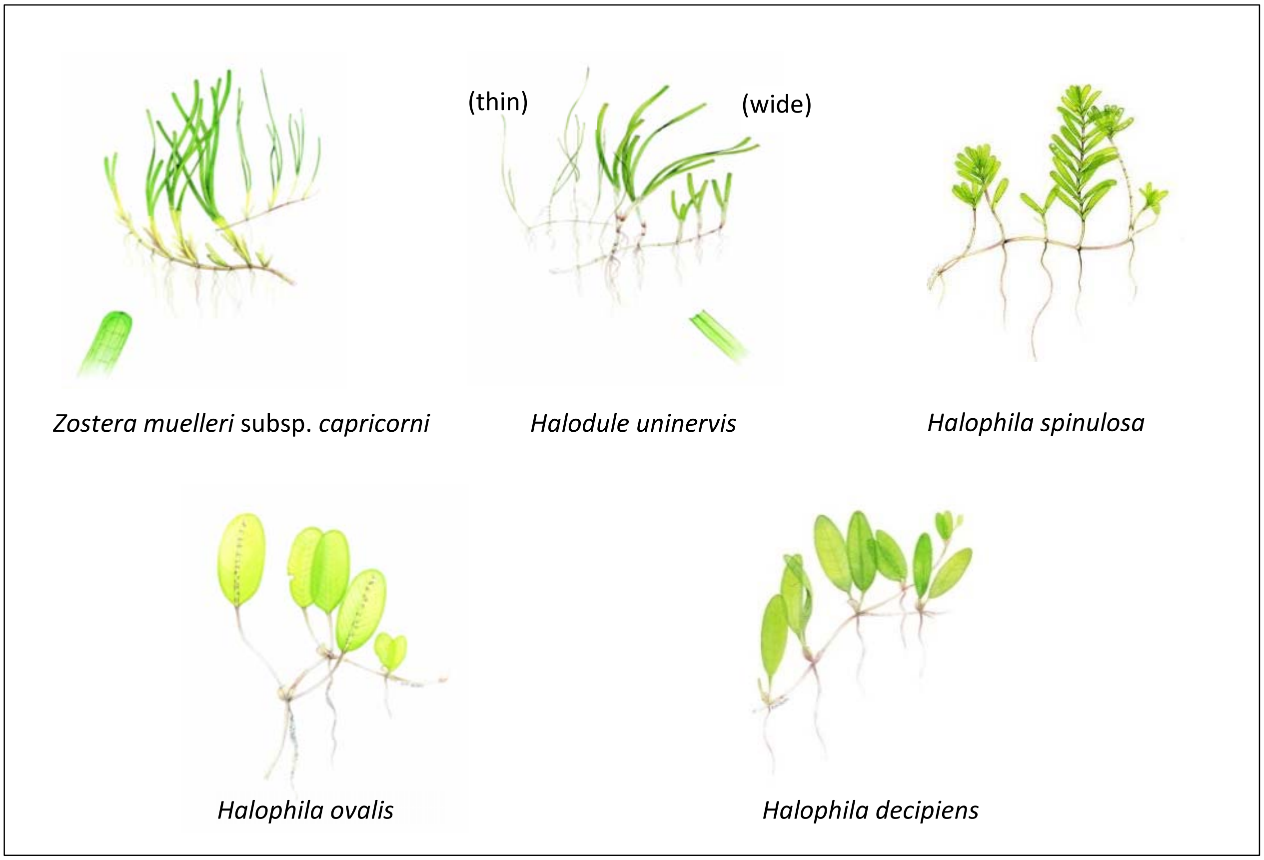



**Figure 11.** Seagrass species present in Port Curtis and Rodds Bay, 2018.

## 3.2 Seagrass condition for individual meadows and zones

The overall condition score for Port Curtis and Rodds Bay seagrass was satisfactory, an improvement following three years of consistently poor condition. Individual monitoring meadow condition either improved or remained stable from 2017. Many meadows improved by more than one grade. For example, Meadow 21 in The Narrows improved from poor to good condition. Species composition remained the dominant indicator driving overall meadow condition for Port Curtis meadows, with biomass and area generally in good to very good condition (Table 4). Overall meadow condition improved from very poor for all three Rodds Bay monitoring meadows compared with 2017. The largest meadow (Meadow 96) returned to good condition for the first time in a decade, and biomass and area condition improved in all three meadows (Table 4).

The Port Curtis and Rodds Bay region has been partitioned into zones (see Figure 2) for the purposes of assessing water quality and for developing a regional report card. In the below sections we have presented the results for the 2018 seagrass monitoring for each of the zones where we have seagrass information.

**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 | 0.82 | 0.43 | 0.63 |
| 5 | 0.91 | 0.74 | 0.54 | 0.64 |
| 6 | 0.95 | 0.76 | 0.43 | 0.60 |
| 7 | 0.94 | 0.91 | 1.00 | 0.91 |
| 8 | 1.00 | 0.55 | 0.22 | 0.39 |
| 21 | 0.75 | 0.91 | 0.67 | 0.71 |
| 43 | 0.45 | 0.75 | 0.62 | 0.45 |
| 48 | 0.91 | 0.76 | 0.44 | 0.60 |
| 52-57* | 0.97 | 0.98 | 1.00 | 0.97 |
| 58 | 0.21 | 0.57 | 0.56 | 0.21 |
| 60 | 0.89 | 0.93 | 0.95 | 0.89 |
| 94 | 0.53 | 0.56 | 0.65 | 0.53 |
| 96 | 0.72 | 1.00 | 0.65 | 0.69 |
| 104 | 0.44 | 0.27 | 0.64 | 0.27 |
| **Overall score for Gladstone seagrass monitoring meadows** | | | | **0.60** |

* 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 240 ha from 2017, with 13 meadows covering 641 ± 113 ha. The largest meadows were on exposed banks at Black Swan Island and Redcliffe (Meadows 21 and 23), and the subtidal *H. ovalis* meadow (Meadow 13) that runs along the eastern side of The Narrows (Figure 12, Appendix 3). Seagrass communities were predominantly isolated or aggregated patches of light *Z. muelleri* subsp. *capricorni* and moderate/dense *H. ovalis*. Meadow biomass ranged from 13.23 ± 6.02 g DW $m^{-2}$ for aggregated patches of *Z. muelleri* subsp. *capricorni* at the northernmost survey area (Meadows 10 and 17) to 2.69 ± 0.69 g DW $m^{-2}$ for aggregated patches of *H. ovalis* on the exposed bank opposite Black Swan Island (Meadow 19) (Figure 12 and Appendix 3).

*Long-Term Monitoring Meadows*

The sole long-term monitoring meadow in The Narrows is at Black Swan Island (Meadow 21; Figure 13). This intertidal meadow was in good condition in 2018, and had a large increase in mean biomass from 1.31 ± 0.35 g DW $m^{-2}$ in 2017 to 5.01 ± 1.22 g DW $m^{-2}$. Meadow area increased for the second year and is now in very good condition with 172 ± 11 ha. Species composition remained good in 2018; the dominant species *Z. muelleri* subsp. *capricorni* comprises 57% of mean meadow biomass relative to the less persistent species *H. ovalis* and *H decipiens* (Figure 13; Appendix 4).

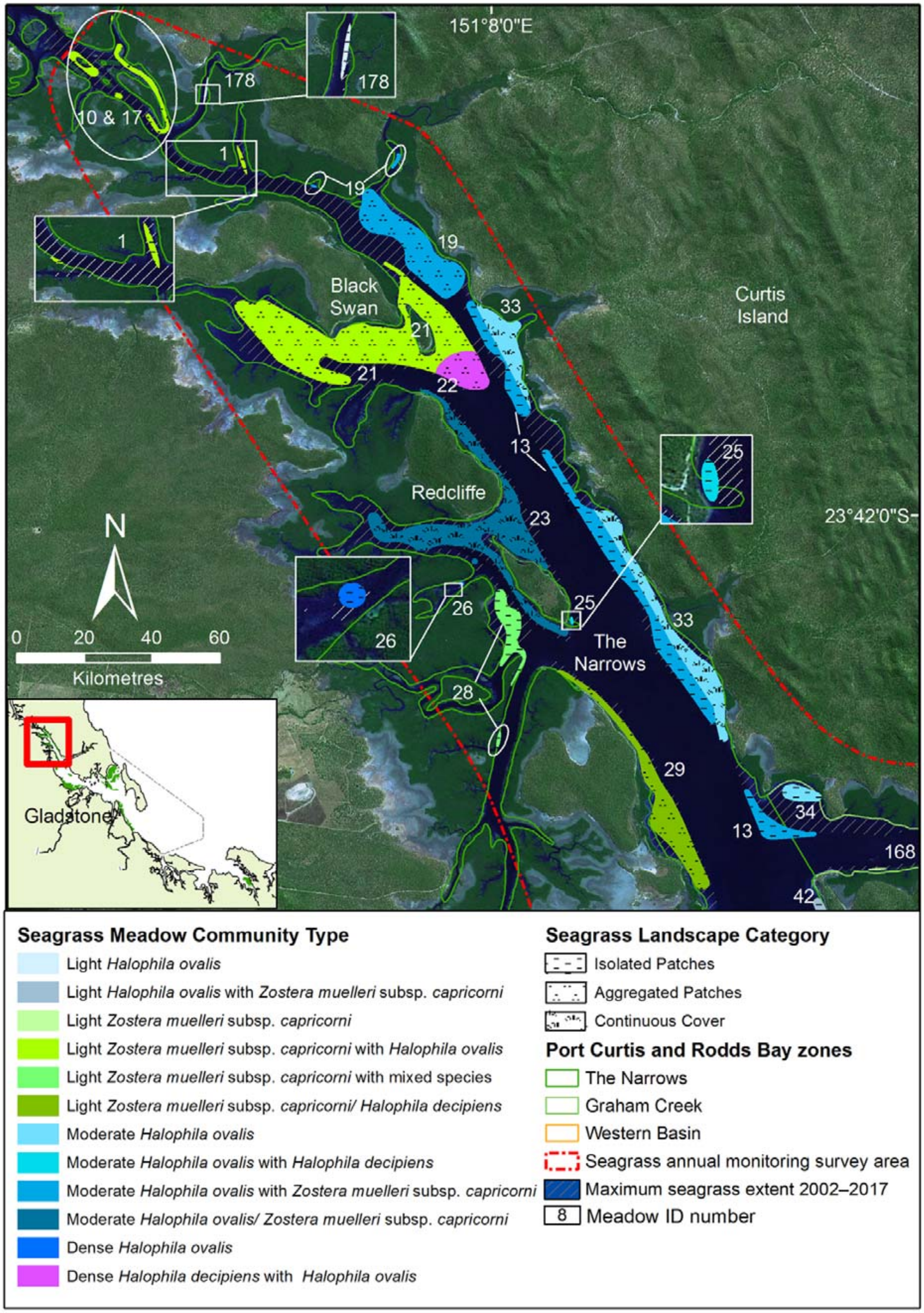



**Figure 12**. Seagrass distribution and community types in The Narrows, 2018.

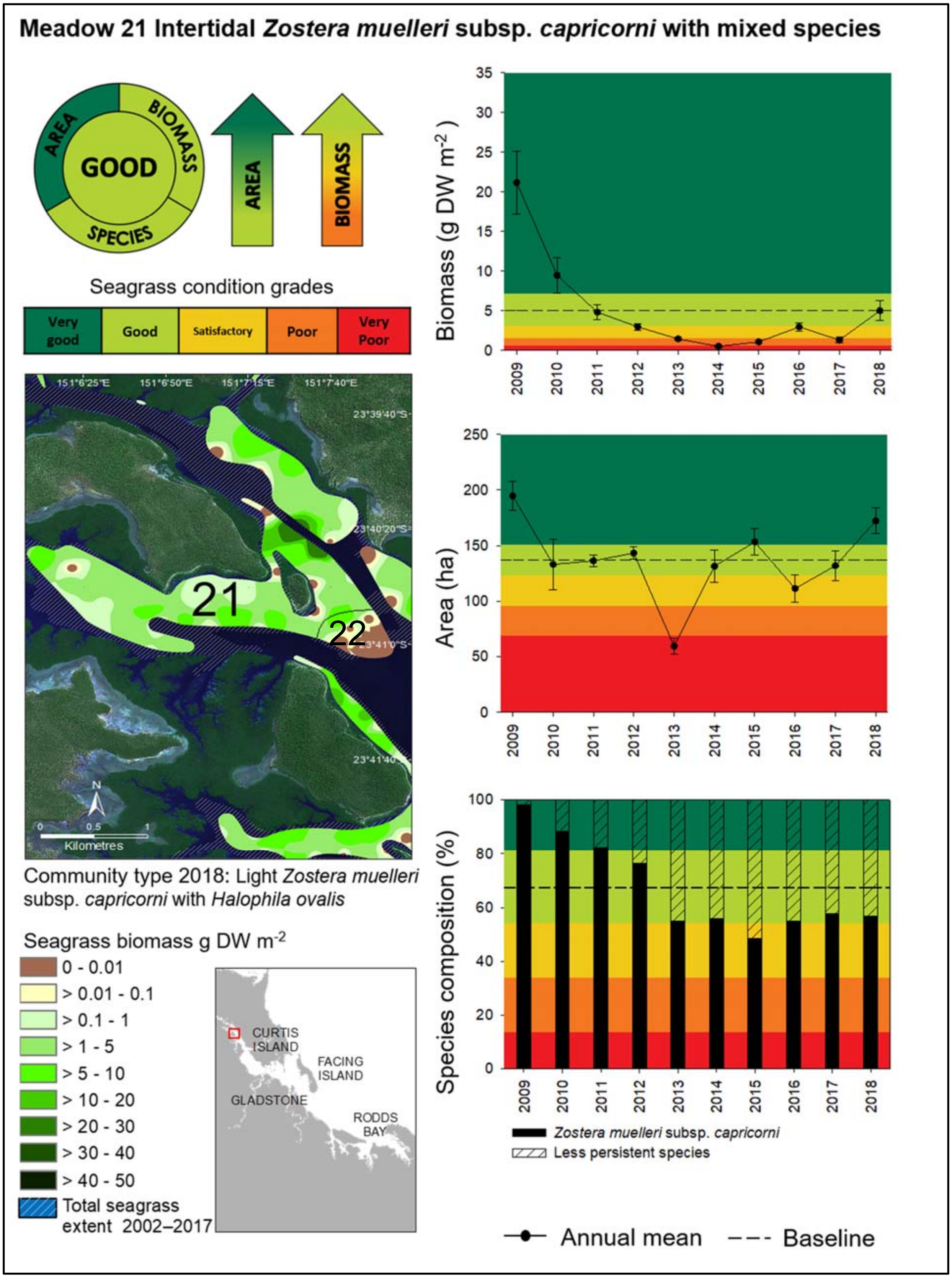



**Figure 13**. Changes in meadow area, biomass and species composition for seagrass at Meadow 21, Black Swan (The Narrows Zone), 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

### *3.2.2 Graham Creek (Upper and Lower)*

Seagrasses in the Graham Creek (Upper and Lower) Zone formed nine individual meadows covering 51 ± 9 ha. The majority of meadows were isolated or aggregated patches of *Z. muelleri* subsp. *capricorni*, *H. ovalis* and *H. decipiens* covering less than 1 ha. The largest meadow covered 32 ± 5 ha at the top of the creek, and also had the highest biomass with 4.52 g DW $m^{-2}$ (Meadow 37 and 41; Figure 14 and Appendix 3). Meadow biomass is typically quite low in this zone.

All but two meadows continue to be dominated by *Halophila* spp. following the decline in dominance by *Z*. *muelleri* subsp. *capricorni* in 2016 (Figure 14 and Appendix 3). While the presence of *H. decipiens* in the Graham Creek meadows has increased from 2017, it remains reduced compared to 2015, as does the overall seagrass distribution in this zone. Graham Creek has no long-term monitoring meadows.

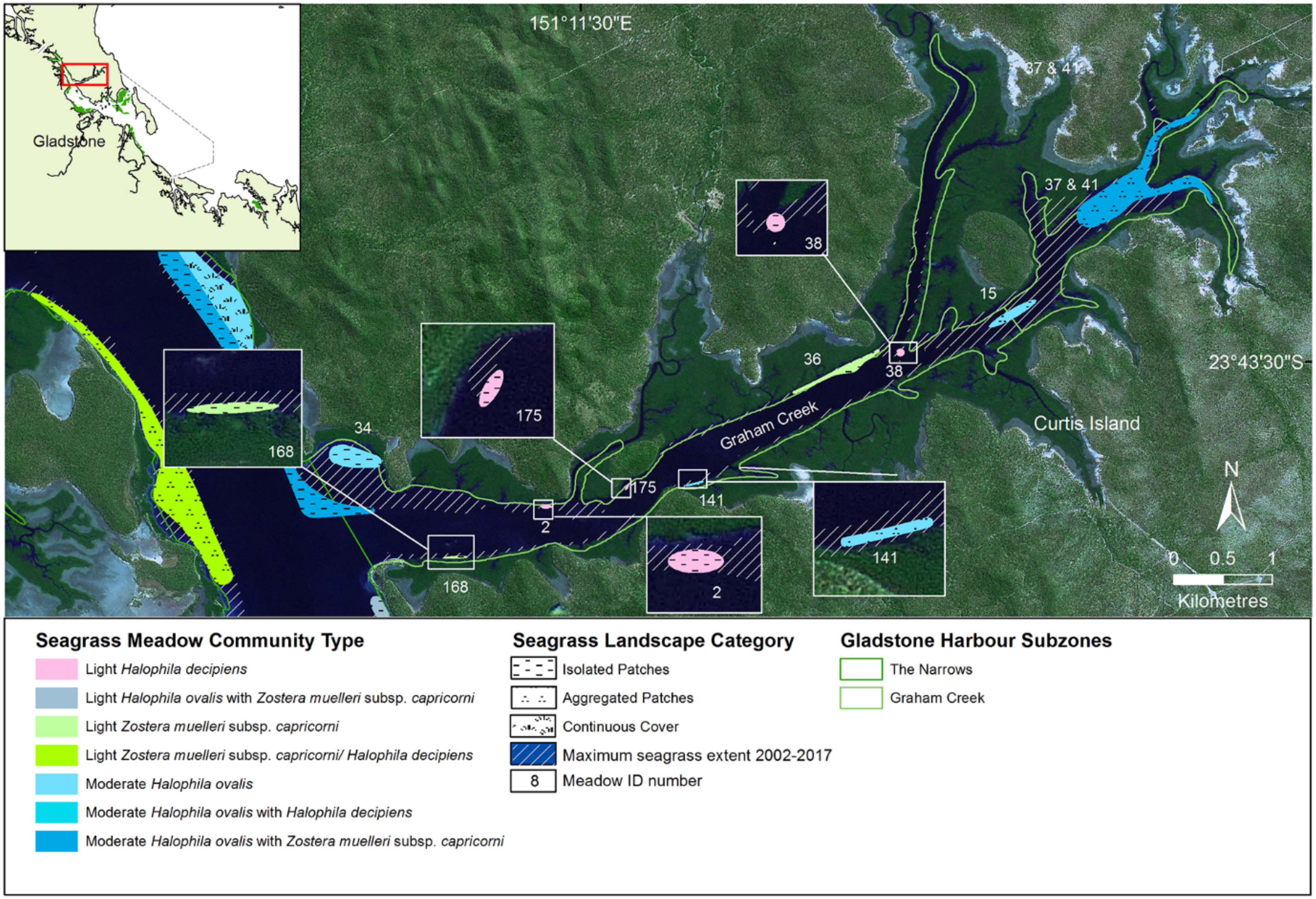



**Figure 14.** Seagrass distribution and community types in Graham Creek Zone, 2018.

### *3.2.3 Western Basin*

Seagrasses in the Western Basin covered 943 ± 73 ha in 2018, similar to the previous year. *Halophila ovalis* continued to dominate most meadows and increased from light to moderate biomass across the Zone (Figure 15; Appendix 3). Meadow biomass ranged from minute *H. decipiens* and *H. ovalis* patches to 6.44 ± 0.75 gDW $m^{-2}$ for a *H. ovalis* dominated meadow at Wiggins Island (Meadow 5; Figure 15). There were no meadows dominated by *Z. muelleri* subsp. *capricorni* in 2018 (Appendix 4).

Some intertidal meadows along the developed Curtis Island shoreline were absent in 2018 while the only substantial subtidal meadow (Meadow 7) returned. For the first time, small patches of subtidal *H. decipiens* were found along the eastern boundary of the Western Basin Reclamation Areas, an area previously dominated by subtidal *H. decipiens* and part of the long-term monitoring program (see Thomas et al. 2010; Meadow 179; Figure 15). The South Fisherman's Landing intertidal meadow (Meadow 6) remained the largest in area at 375 ha and formed continuous cover over the mud bank for the first time since 2015.

*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 an overall satisfactory condition (Figure 16; Appendix 3). The improvement from poor to satisfactory was driven by an increase in the presence of *Z. muelleri* subsp. *capricorni*, the historically persistent species in the meadow (Figure 16; Appendix 3). Overall meadow area was stable and above the long-term average following a continual increase since 2013 while biomass continued to increase for the third consecutive year (Figure 16; Appendix 3).

**Meadow 5:**
The adjacent, intertidal *Z. muelleri* subsp. *capricorni* meadow west of Wiggins Island remains in satisfactory condition in 2018 (Figure 17; Appendix 3). The Meadow 5 score was driven by species composition for the third consecutive year with *H. ovalis* comprising 77% of the meadow; *Z. muelleri* subsp. *capricorni* last dominated the meadow in 2010. Biomass, on the other hand, increased to levels last recorded in 2008 prior to Port Curtis-wide declines from high regional rainfall and flooding. Area remained stable at the baseline level (Figure 17).

**Meadow 6:**
Meadow 6 at South Fisherman's Landing improved to satisfactory condition in 2018 (Figure 18; Appendix 3). Similar to Meadows 4 and 5, the increase in score was again due to a combination of good area, a substantial increase in biomass (very good), but poor species composition.

**Meadow 7:**
The only subtidal monitoring meadow in the Western Basin, Meadow 7, returned following it's' absence in 2017 (Figure 19). The return of this ephemeral, monospecific *H. decipiens* meadow led to a very good overall score. Not only had the meadow re-established, but area and biomass were the largest recorded since 2006 and 2007 respectively (Figure 19; Appendix 3).

**Meadow 8:**
The intertidal Meadow 8 at North Fisherman's Landing remained in poor condition in 2018. Consistent with the other intertidal monitoring meadows in the Western Basin, the meadow was historically dominated by *Z. muelleri* subsp. *capricorni*, yet has remained well-below the baseline level of 67% since 2011 (Figure 20; Appendix 4). Biomass has been in good or very good condition since 2012 and peaked in 2018 at 5.38 ± 0.86 g DW $m^{-2}$. Meadow area remained in satisfactory condition, with the south-western corner of the meadow being most patchy with the least biomass (Figure 20).

**Meadows 52-57:**

Meadows 52-57, are a group of predominantly intertidal meadows surrounding the Passage Islands. In 2018 the overall condition for these meadows remained very good. The baseline condition was updated for Meadow 52-57 to incorporate 2018 data to attain the 10-year baseline timeframe established for assessing scores for all Gladstone monitoring meadows (see Appendix 1). The additional baseline data affected the threshold levels set for each grade, in effect shifting trends in the meadow compared to the previous year but not changing the very good condition for each indicator assigned in both 2017 and 2018 (Figure 21; Appendix 3; Chartrand et al. 2018). Biomass was the highest recorded since monitoring began in 2009 regardless of the small stature of the dominant species *H. ovalis* (Figure 21; Appendix 3).

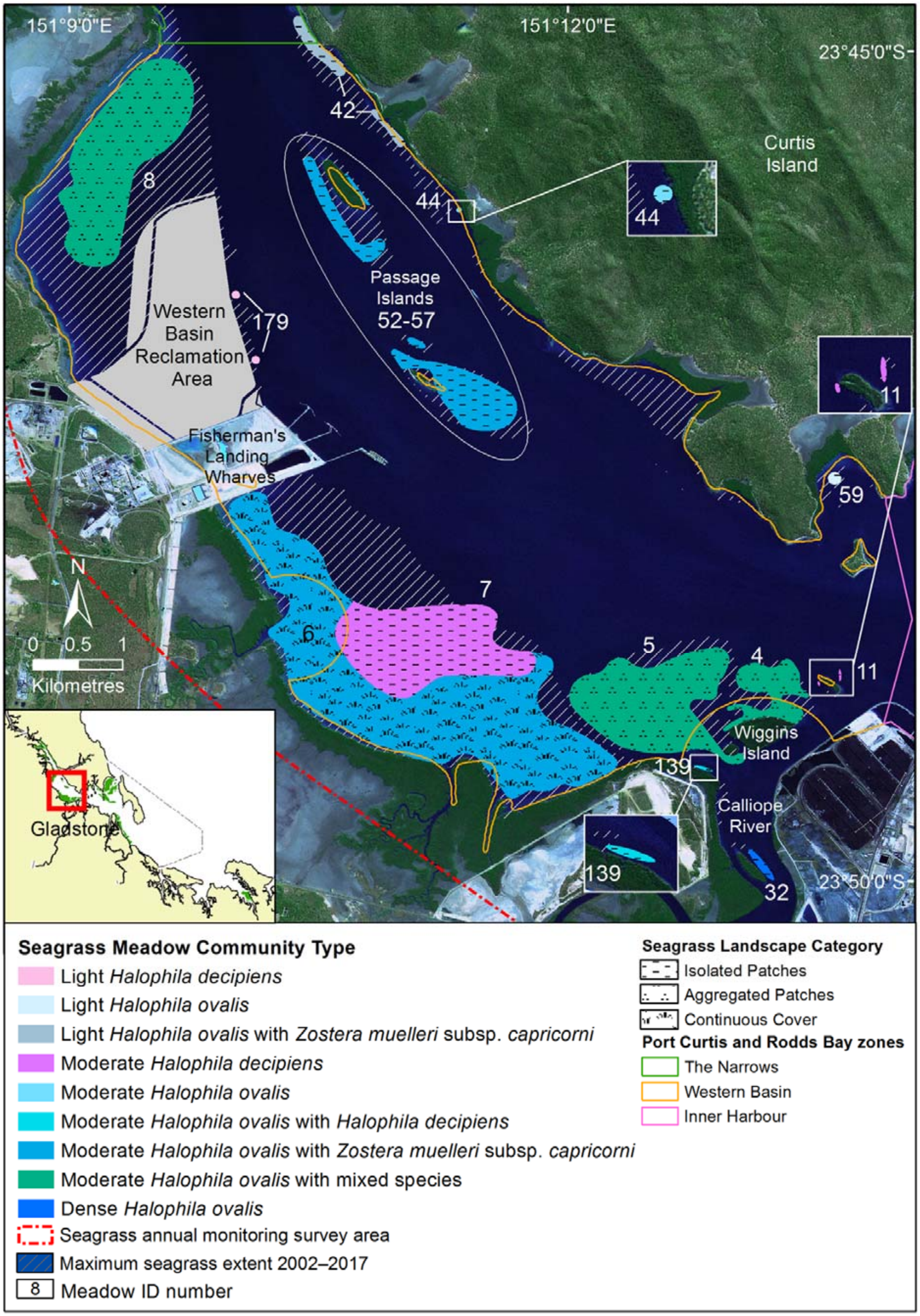



**Figure 15.** Seagrass distribution and community types in the Western Basin Zone, 2018.

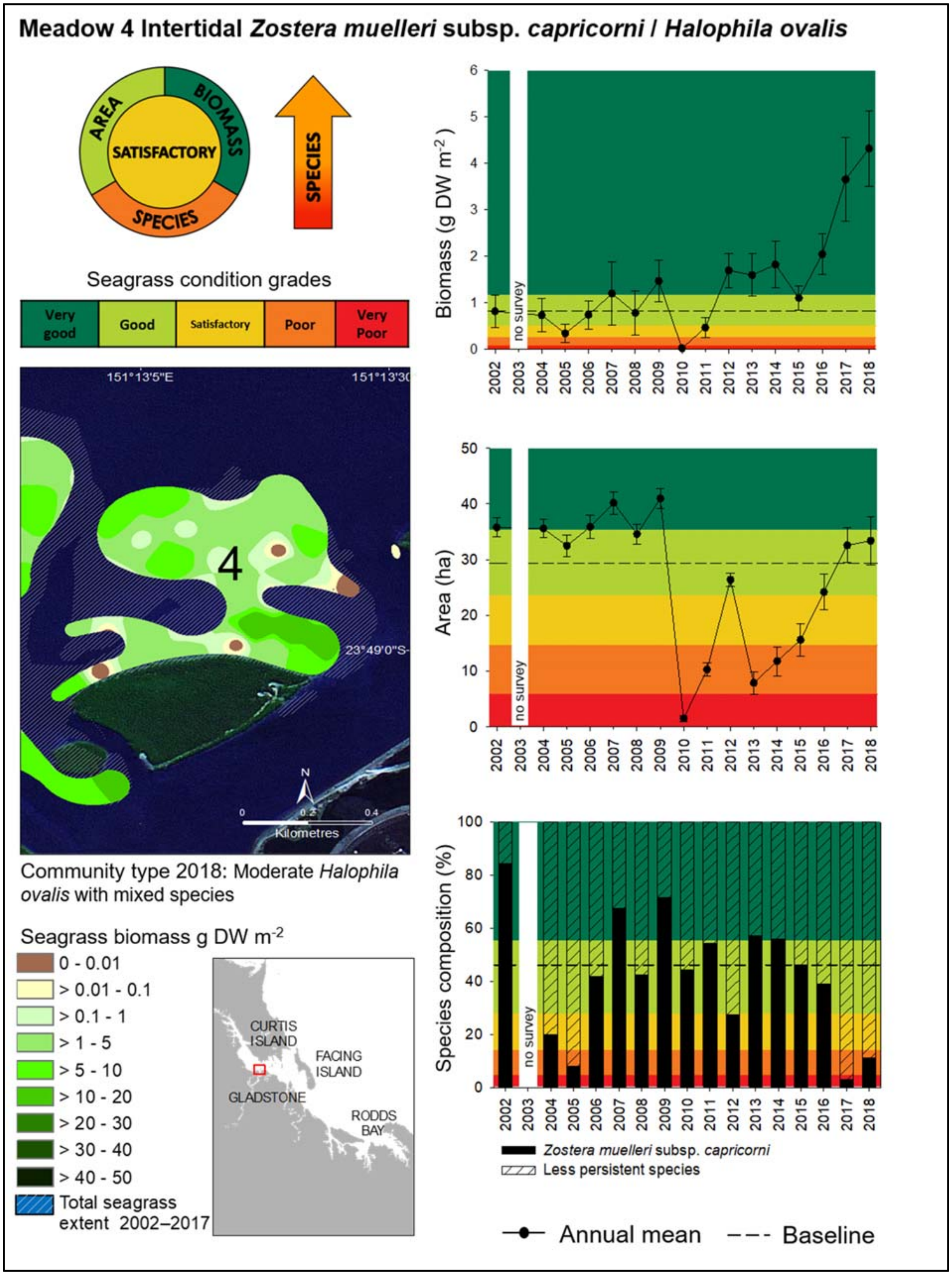



**Figure 16**. Changes in meadow area, biomass and species composition for seagrass at Meadow 4, Wiggins Island (Western Basin Zone), 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

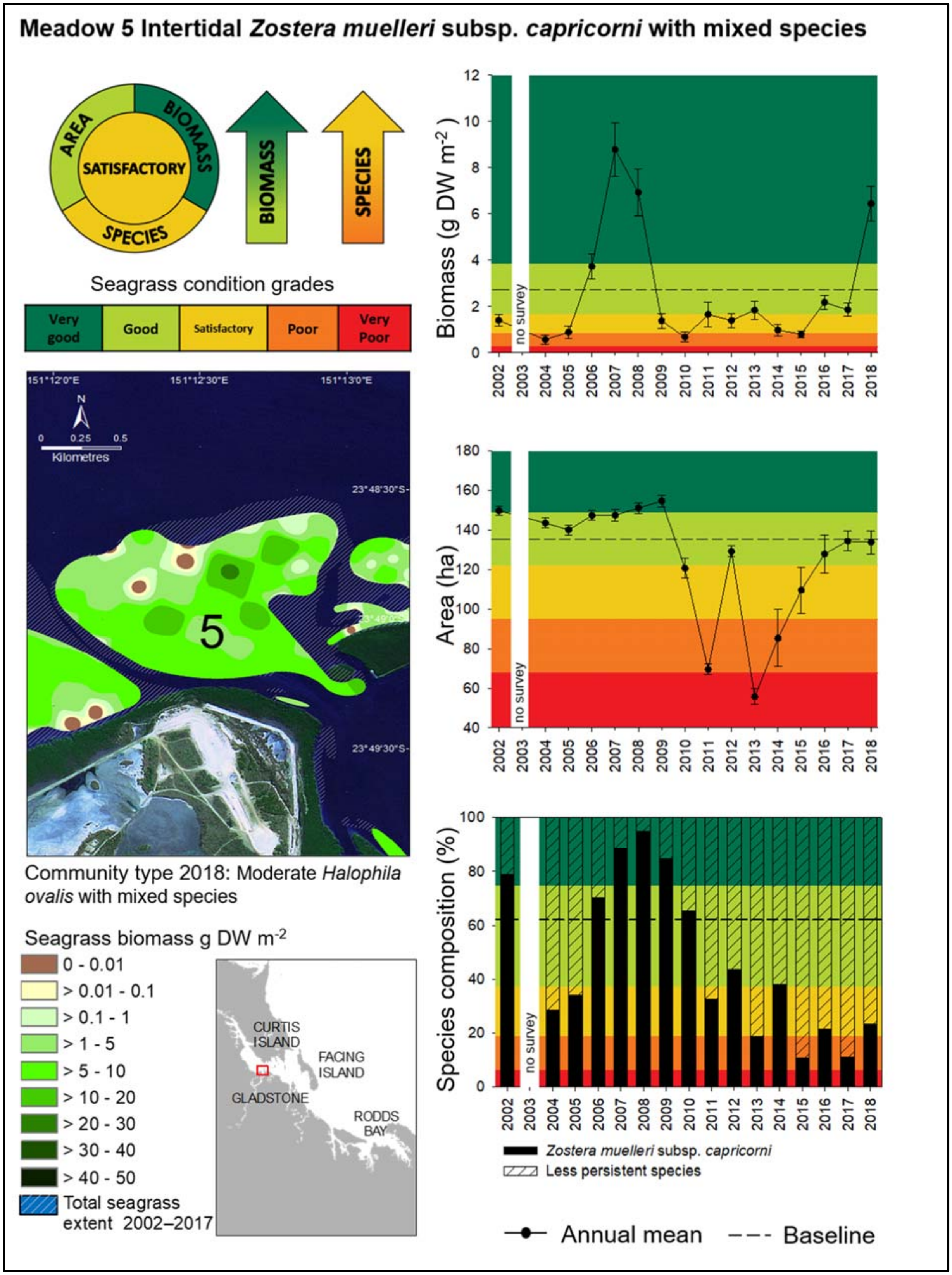



**Figure 17**. Changes in meadow area, biomass and species composition for seagrass at Meadow 5, Wiggins Island (Western Basin Zone), 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

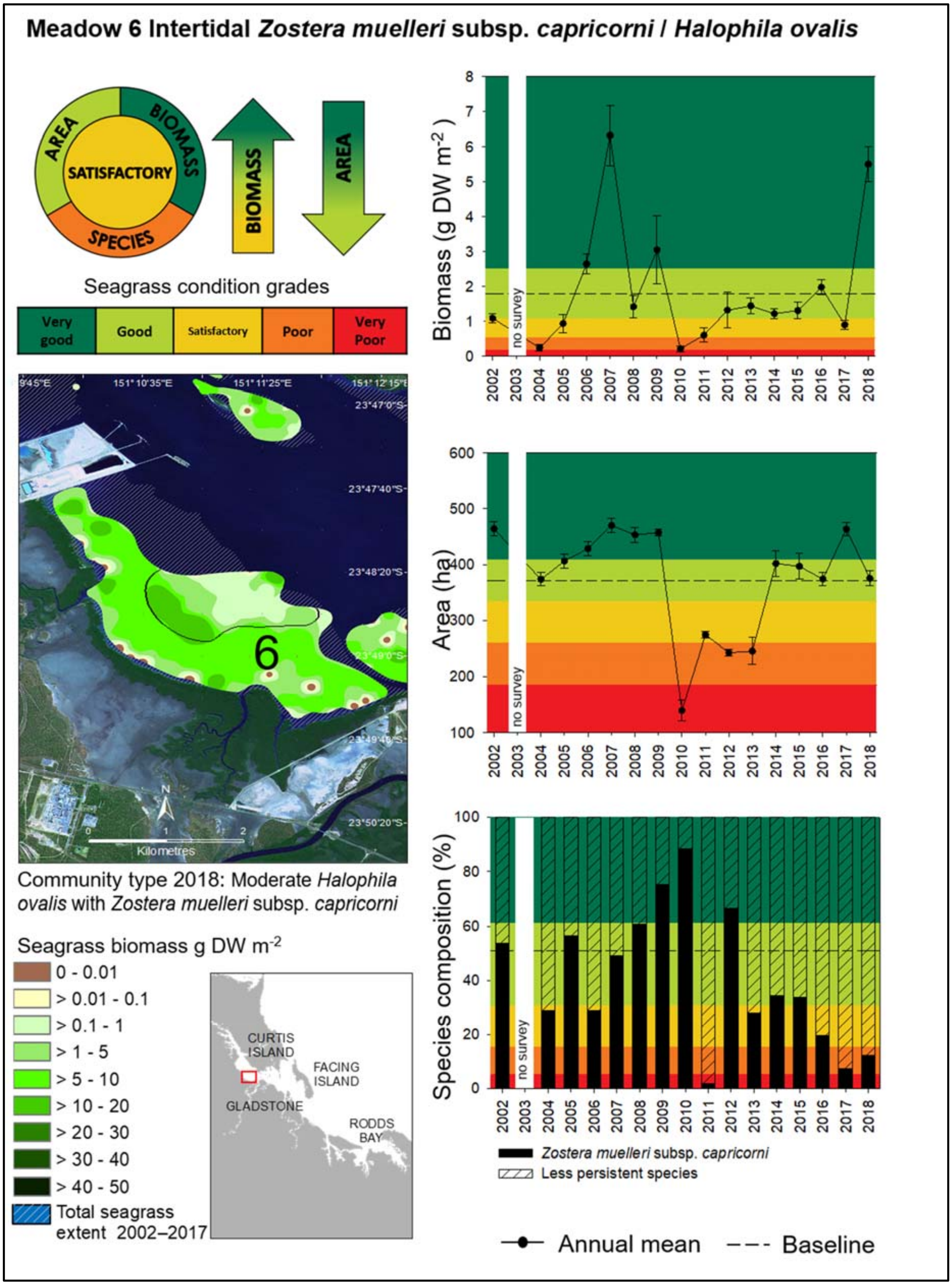



**Figure 18**. Changes in meadow area, biomass and species composition for seagrass at Meadow 6, South Fisherman's Landing (Western Basin Zone), 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

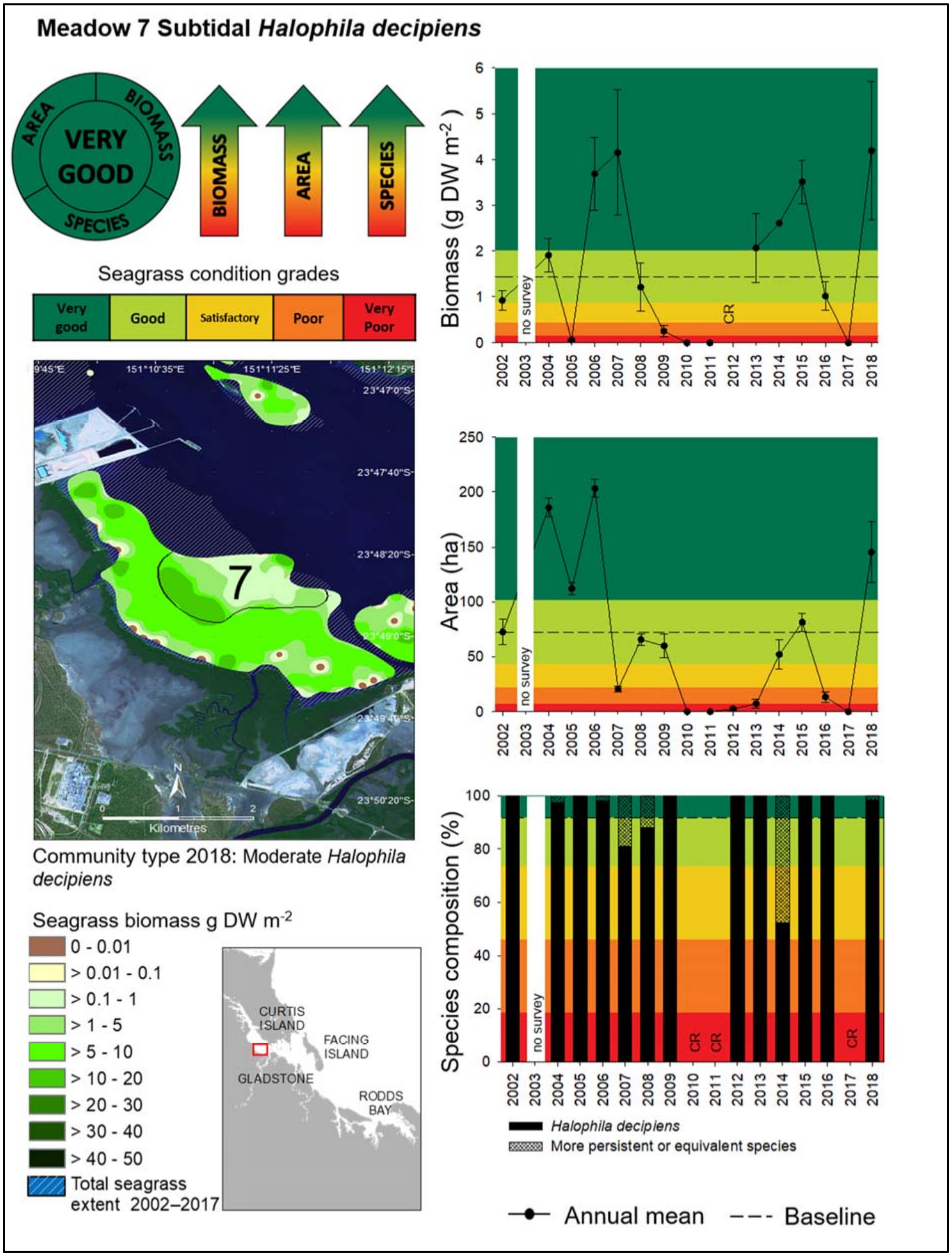



**Figure 19**. Changes in meadow area, biomass and species composition for seagrass at Meadow 7, South Fisherman's Landing (Western Basin Zone), 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate). CR = calculation restriction.

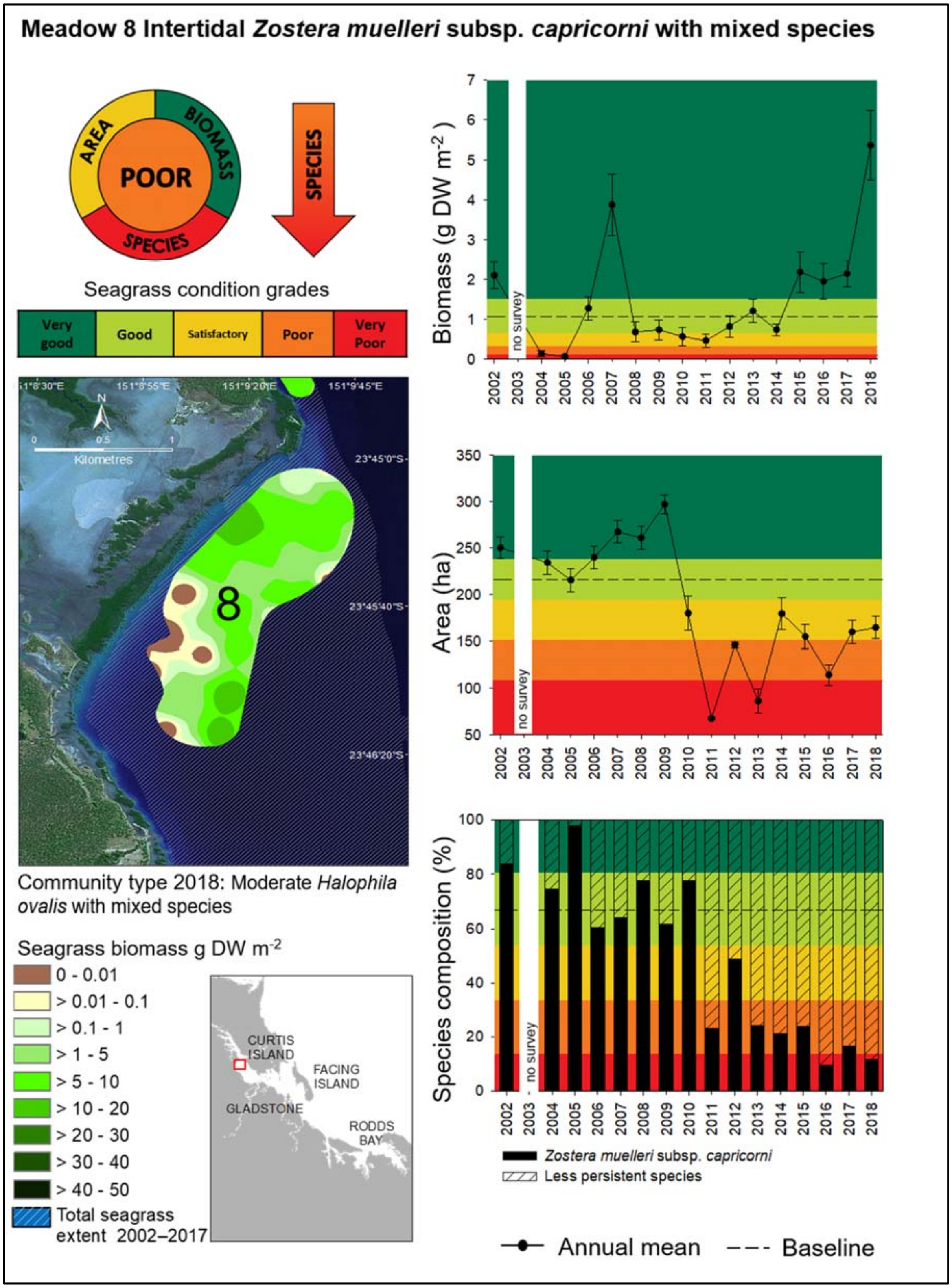



**Figure 20**. Changes in meadow area, biomass and species composition for seagrass at Meadow 8, North Fisherman's Landing (Western Basin Zone), 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

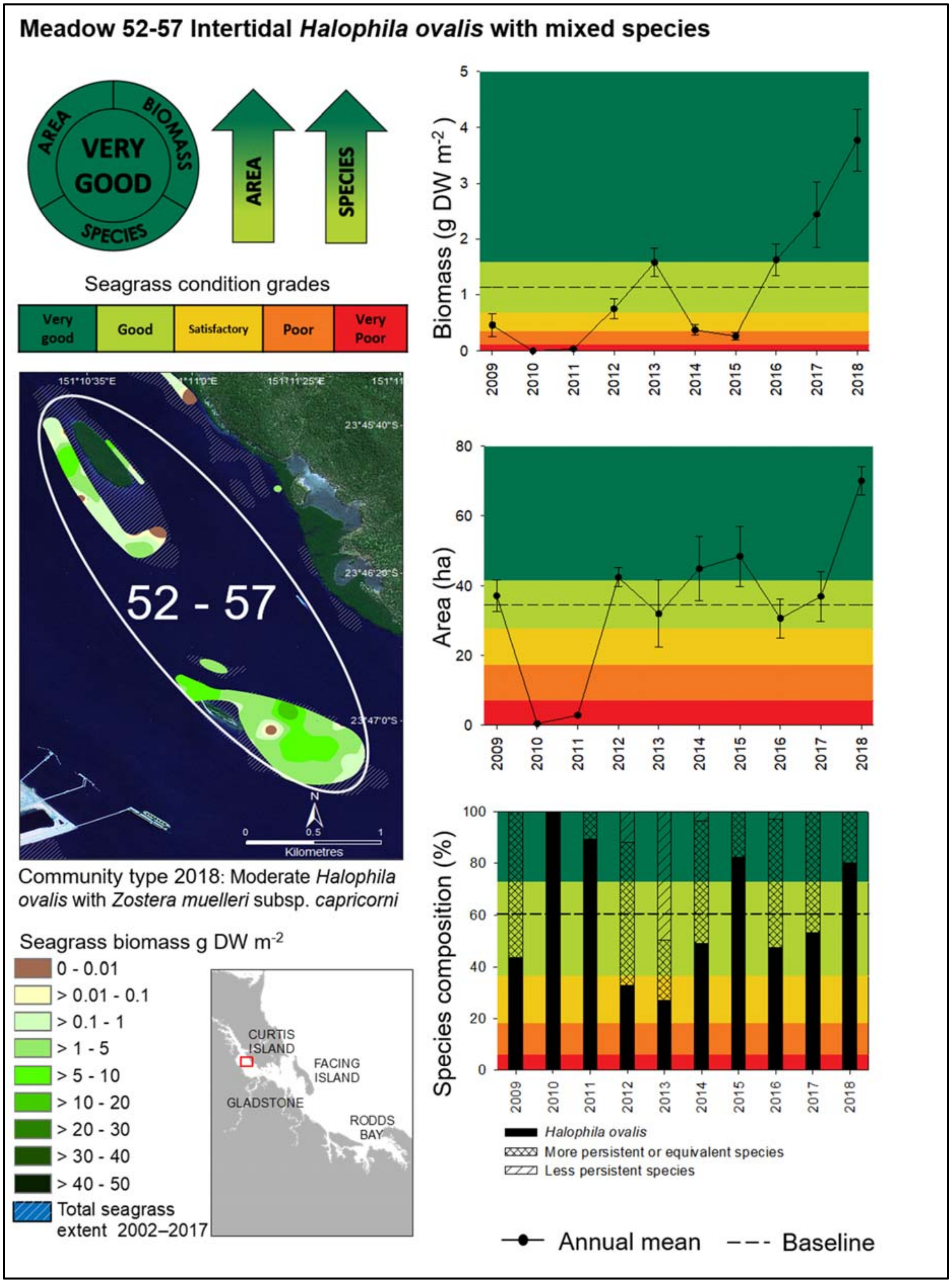



**Figure 21**. Changes in meadow area, biomass and species composition for seagrass at Meadows 52-57, Passage Islands (Western Basin Zone), 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

### *3.2.4 Inner Harbour*

Seagrasses in the Inner Harbour Zone covered an area of 200 ± 36 ha, similar to the 2017 distribution. Some meadows did retract and fragment in 2018, particularly in the bays north of Compigne Island and to the west (Meadows 85 and 62 & 63; Figure 23) as well as at South Trees (Meadow 58; Figure 23; Appendix 3). Meadows were isolated or aggregated patches of either light *Z. muelleri* subsp. *capricorni* or moderate *H. ovalis*; no other species were present in the Zone. Meadow biomass ranged from diminutive patches of *H. ovalis* to 5.59 ± 4 g DW $m^{-2}$ in the *Z. muelleri* subsp. *capricorni* meadow to the north of Compigne Island (Meadow 136; Figure 22; Appendix 3).

*Long-Term Monitoring Meadows*

The single monitoring meadow in the Inner Harbour remained in very poor condition for a fourth year in 2018 (Meadow 58; Figure 23; Appendix 3). The score was driven by extremely low biomass for a second year. Meadow biomass has generally remained poor since 2010, apart from a brief improvement in 2016 (Figure 23). Meadow area also continued to decline from its peak in 2014 with only a thin fragment remaining in the south-eastern corner of its historical extent (Figure 23). This meadow was completely lost in 2010 so recovery could only be initiated from seeds locally stored in the sediment or recruitment of propagules from elsewhere in Port Curtis, which can lead to extended timeframes for recovery. The good news is that in 2018 the key foundation species, *Z. muelleri* subsp. *capricorni* returned to the meadow for the first time in three years leading to the species composition improving to satisfactory condition for the first time in five years with 22% of meadow biomass from *Z. muelleri* subsp. *capricorni* (Figure 23; Appendix 4). This more stable species may lead to more sustained recovery now that it has re-established in the meadow.

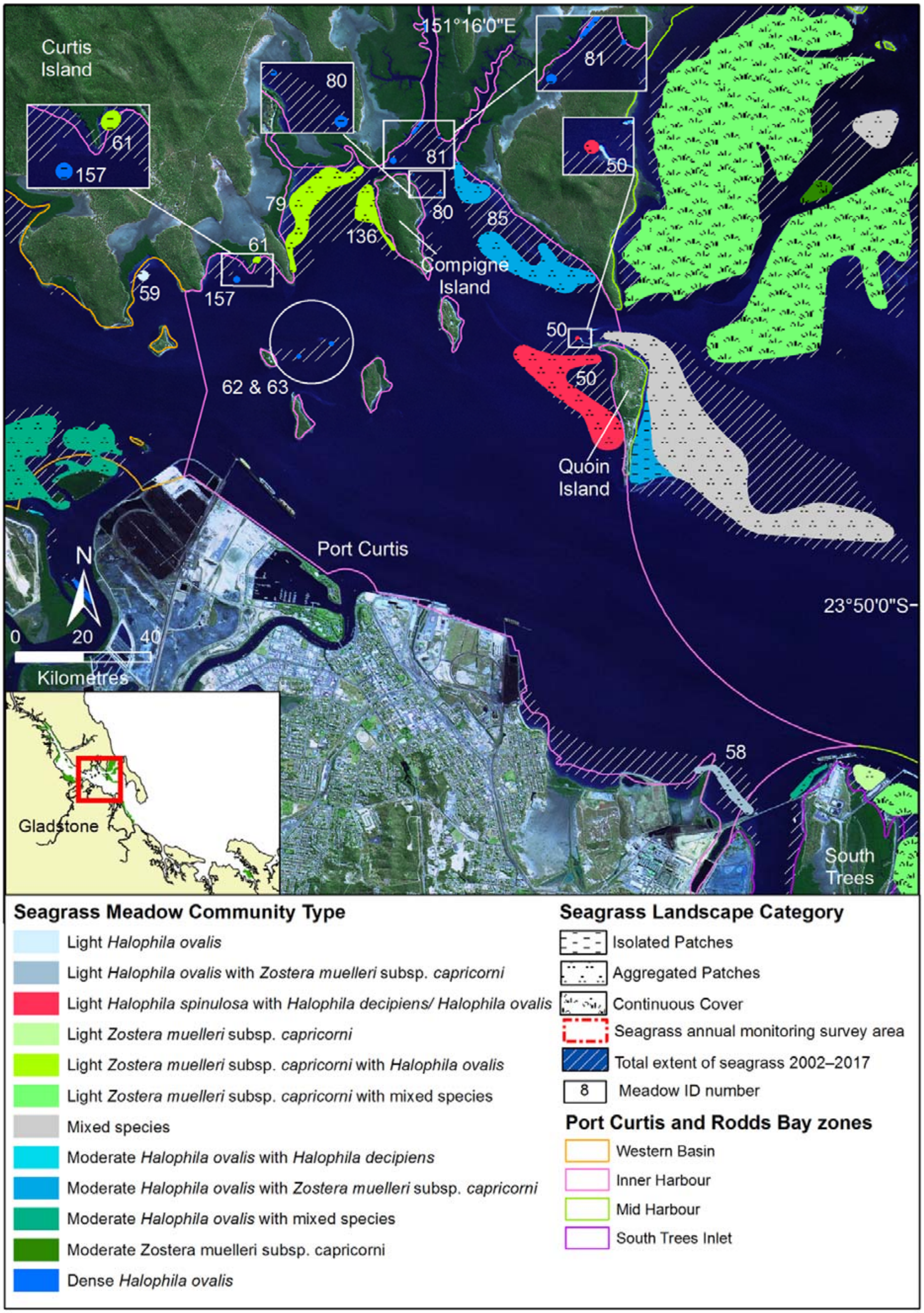



**Figure 22**. Seagrass distribution and community types in the Inner Harbour Zone, 2018.

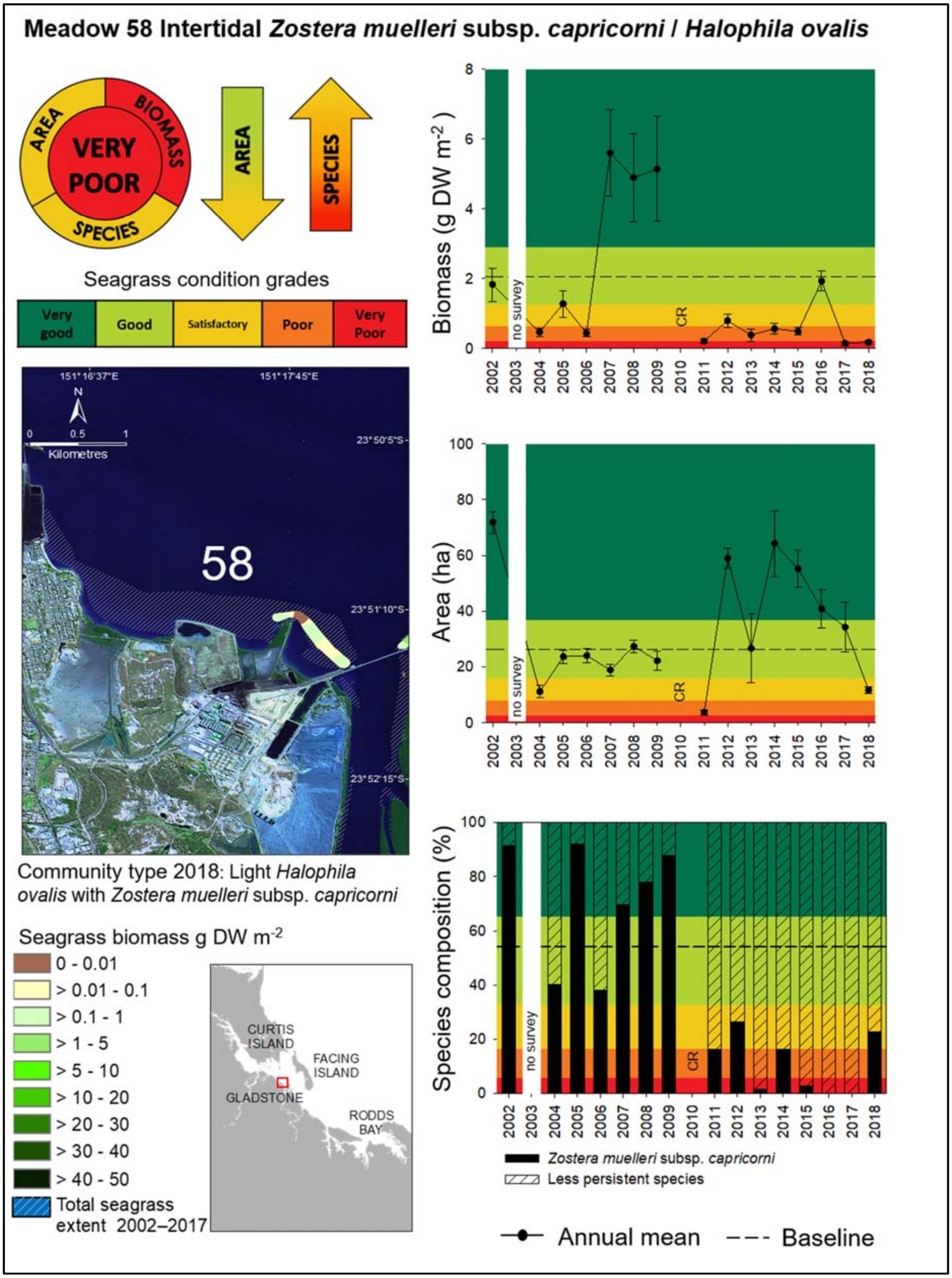



**Figure 23**. Changes in meadow area, biomass and species composition for seagrass at Meadow 58, South Trees Inlet Zone, November 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate). CR = calculation restriction.

### *3.2.5 Mid Harbour*

Seagrasses in the Mid Harbour Zone formed 15 individual meadows and covered an area of 1554 ± 217 ha. The area of individual meadows ranged from small patches (~0.05 ha) along Facing Island to the largest seagrass meadow surveyed (~615 ha) on the intertidal mud bank near Curtis Island (Meadows 74 and 43 respectively; Figure 24; Appendix 3). All five seagrass species found in Port Curtis were present in the Mid Harbour ranging from isolated patches of *H. ovalis* off Facing Island (Meadow 70, 72, 74) to 27.58 ± 8.62g DW $m^{-2}$ for a moderate, continuous cover of *Z. muelleri* subsp. *capricorni* adjacent to the shipping lane west of Facing Island (Meadow 137; Figure 24; Appendix 3).

*Long-Term Monitoring Meadows*

There are two monitoring meadows in the Mid Harbour Zone, a large intertidal meadow known locally as 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 15 year monitoring dataset. In 2018, its overall poor score is unchanged with the biomass score remaining in poor condition following a culmination of declines in seagrass over the past few 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 2018 (8.25 ± 1.08g DW $m^{-2}$) (Figure 25). Area for the meadow increased from 2017 to 2018 leading to an improvement in area score. A depression of the dominant *Z. muelleri* subsp. c*apricorni* since 2014 has led to a more mixed species meadow with greater than 25% of biomass now a result of the less persistent species *H. uninervis* and *H. ovalis* (Figure 25; Appendix 4).

**Meadow 48:**

Meadow 48 is a subtidal meadow on the eastern side of Quoin Island. Overall meadow condition was scored as satisfactory due to a combination of good area but poor species composition (Figure 26). The meadow was dominated by *H. spinulosa* and *H. ovalis* in place of the more persistent baseline species *H. uninervis* (Figure 26; Appendix 4). Meadow area declined from very good to good condition in 2018, and at ~240 ha was equal to the baseline (Figure 26). Biomass condition was very good for the first time in a decade (6.35 ± 1.04 g DW $m^{-2}$), and with the second greatest biomass recorded since monitoring began in 2002

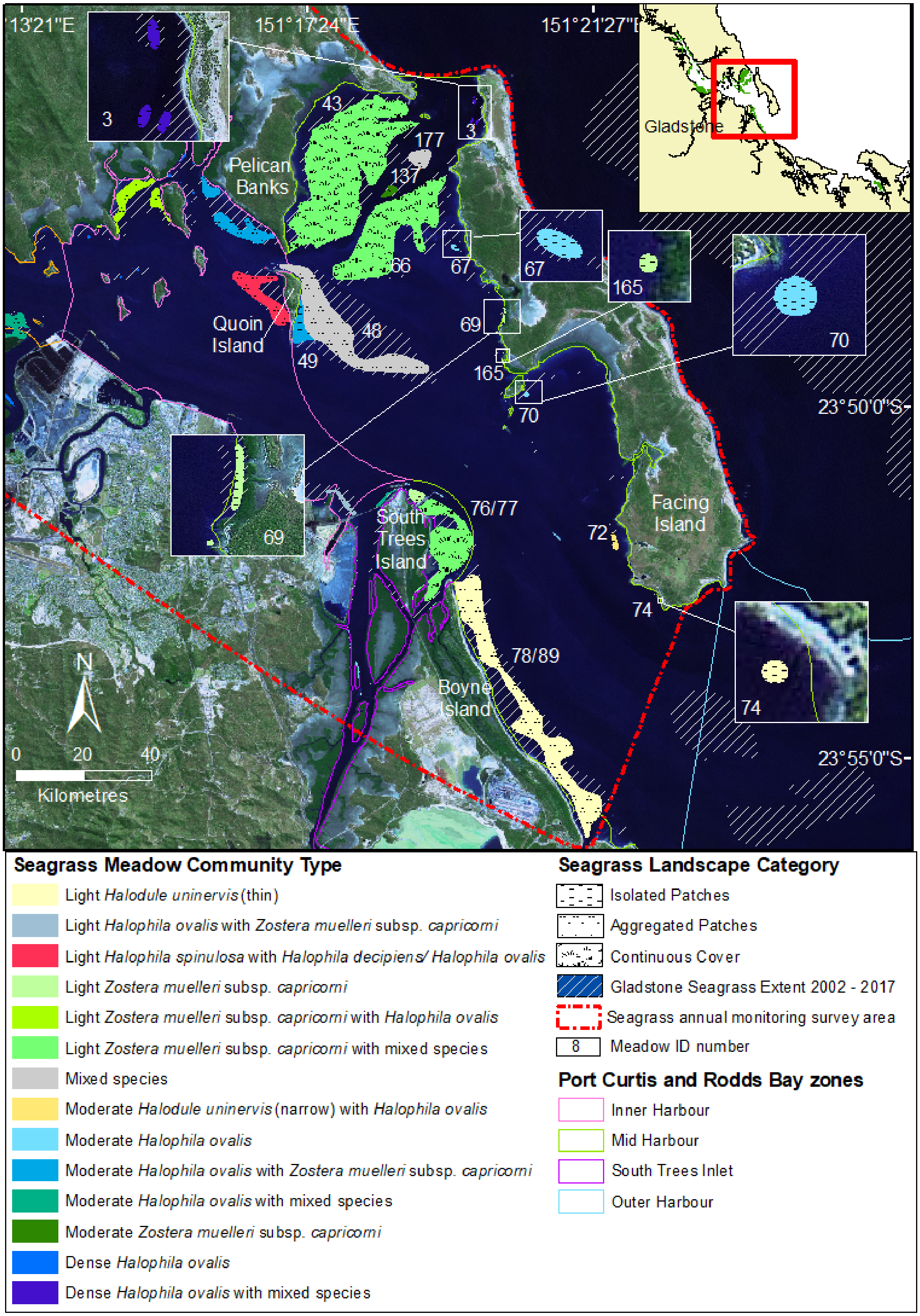



**Figure 24.** Seagrass distribution and community types in the Mid Harbour Zone, 2018.

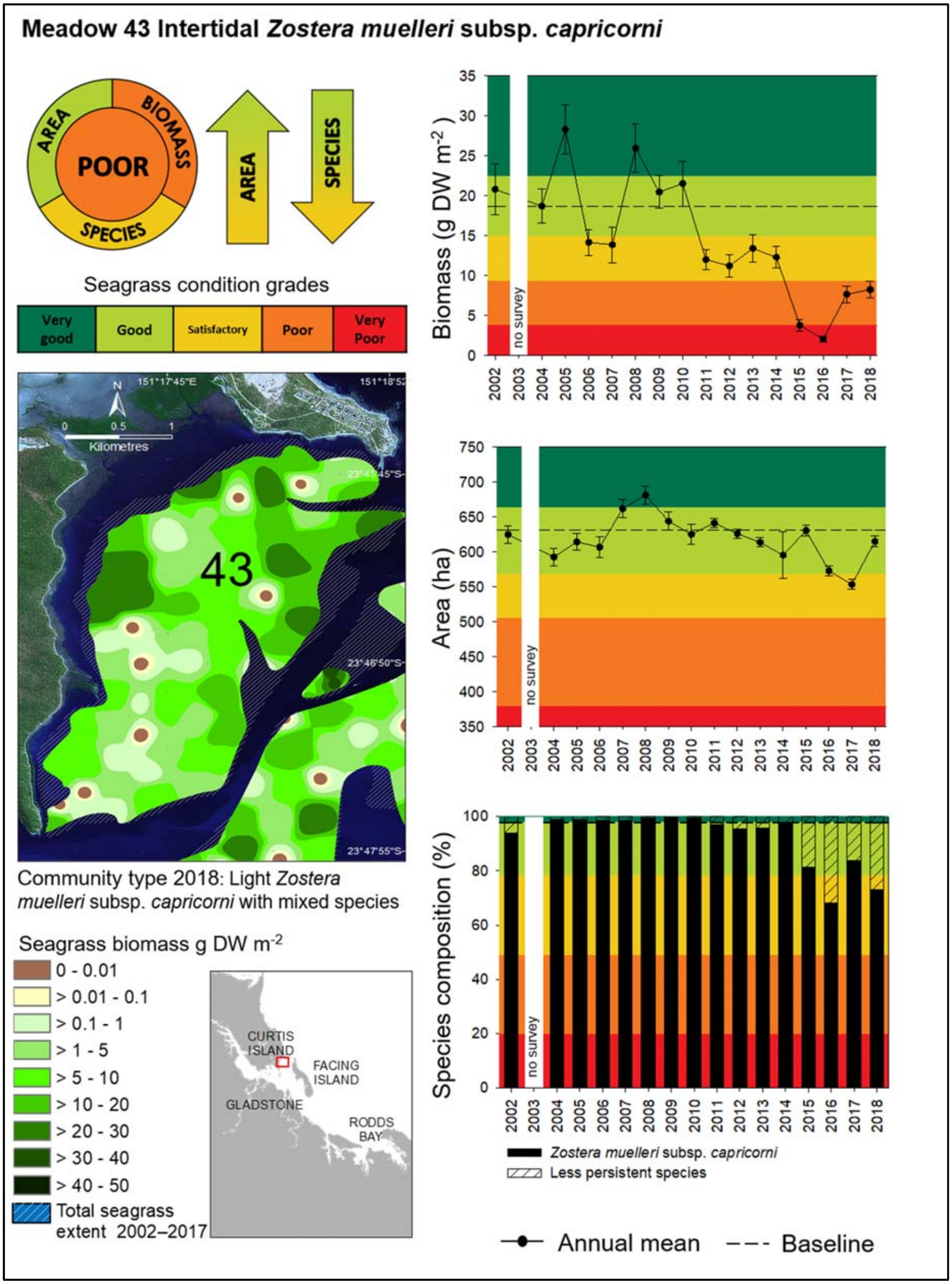



**Figure 25**. Changes in meadow area, biomass and species composition for seagrass at Meadow 43, Pelican Banks (Mid Harbour Zone), 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

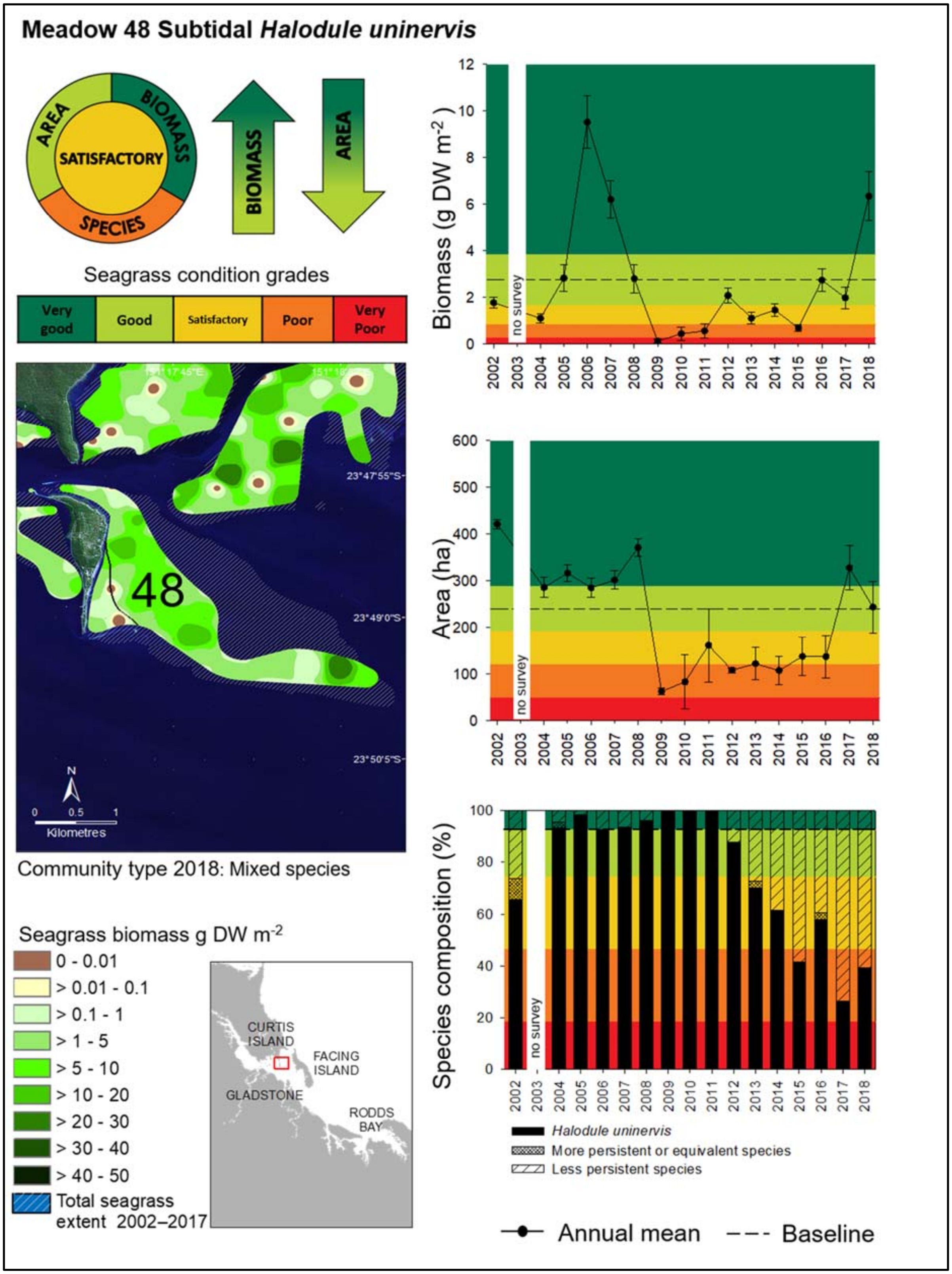



**Figure 26**. Changes in meadow area, biomass and species composition for seagrass at Meadow 48, Quoin Island (Mid Harbour Zone), November 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

### *3.2.6 South Trees Inlet (lower)*

The South Trees Inlet (lower) Zone consisted of eight meadows and covered an area of approximately 169 ± 18 ha, similar to the previous four years. The area of individual meadows ranged from small isolated patches with minimal biomass to the large, continuous cover intertidal meadow (~153 ha, 8.45 ± 1.44g DW $m^{-2}$) to the south of the wharf (Meadows 76-77; Figure 27; Appendix 3). *Zostera muelleri* subsp. *capricorni*, *H. uninervis,* and *H. ovalis* were present in the Zone. The larger meadows on the exposed banks surrounding the wharves were dominated by *Z. muelleri* subsp. *capricorni* and had DFTs present in the two largest meadows in this zone (Meadow 60 and 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 second year in a row, a significant recovery from the declines that began in 2009/2010 (Figure 28; Appendix 3). The aggregated patches landscape followed a pattern of decreasing biomass from the waterline to the mangrove fringe (Figure 28).

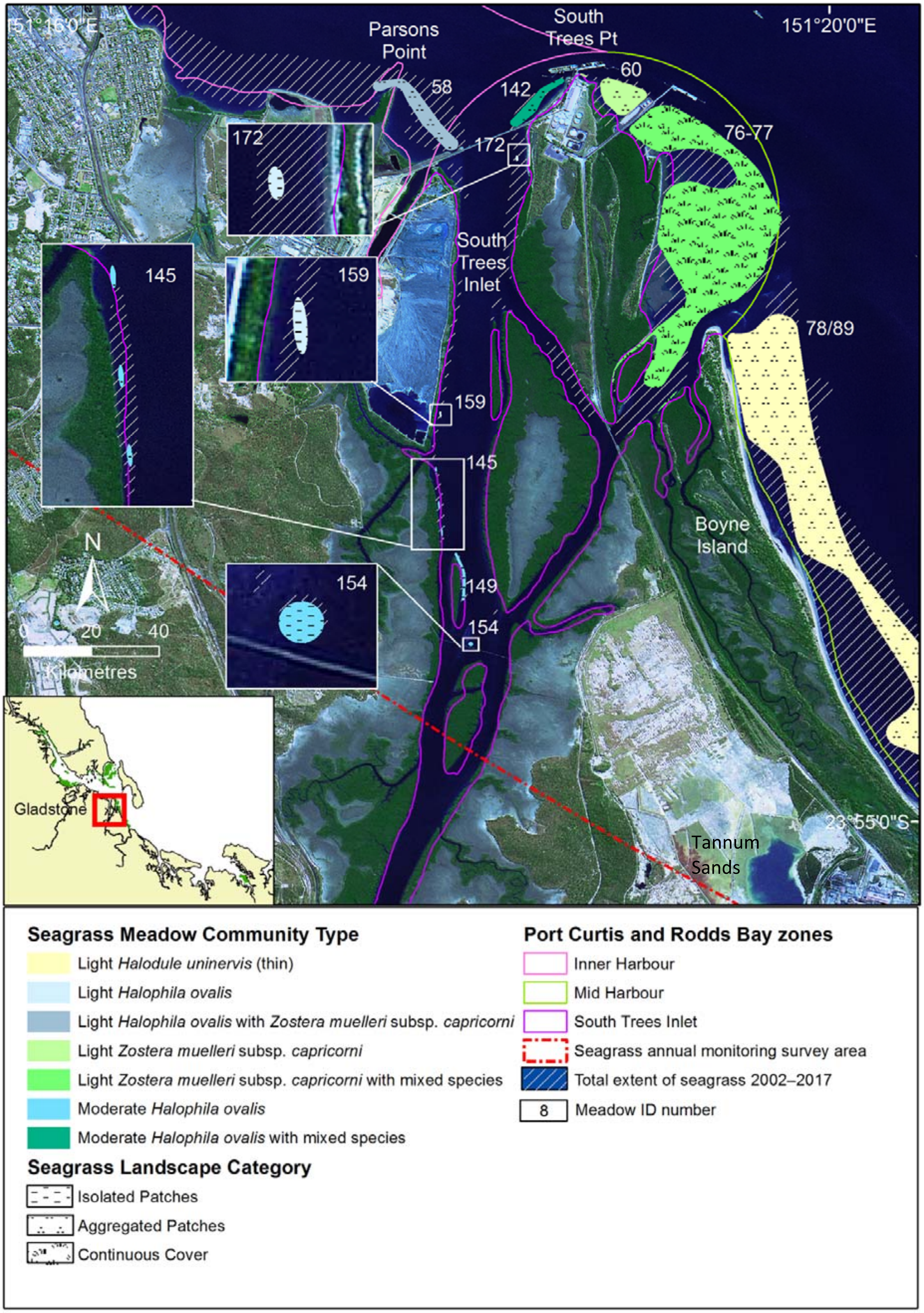



**Figure 27.** Seagrass distribution and community types at South Trees Inlet Zone, November 2018.

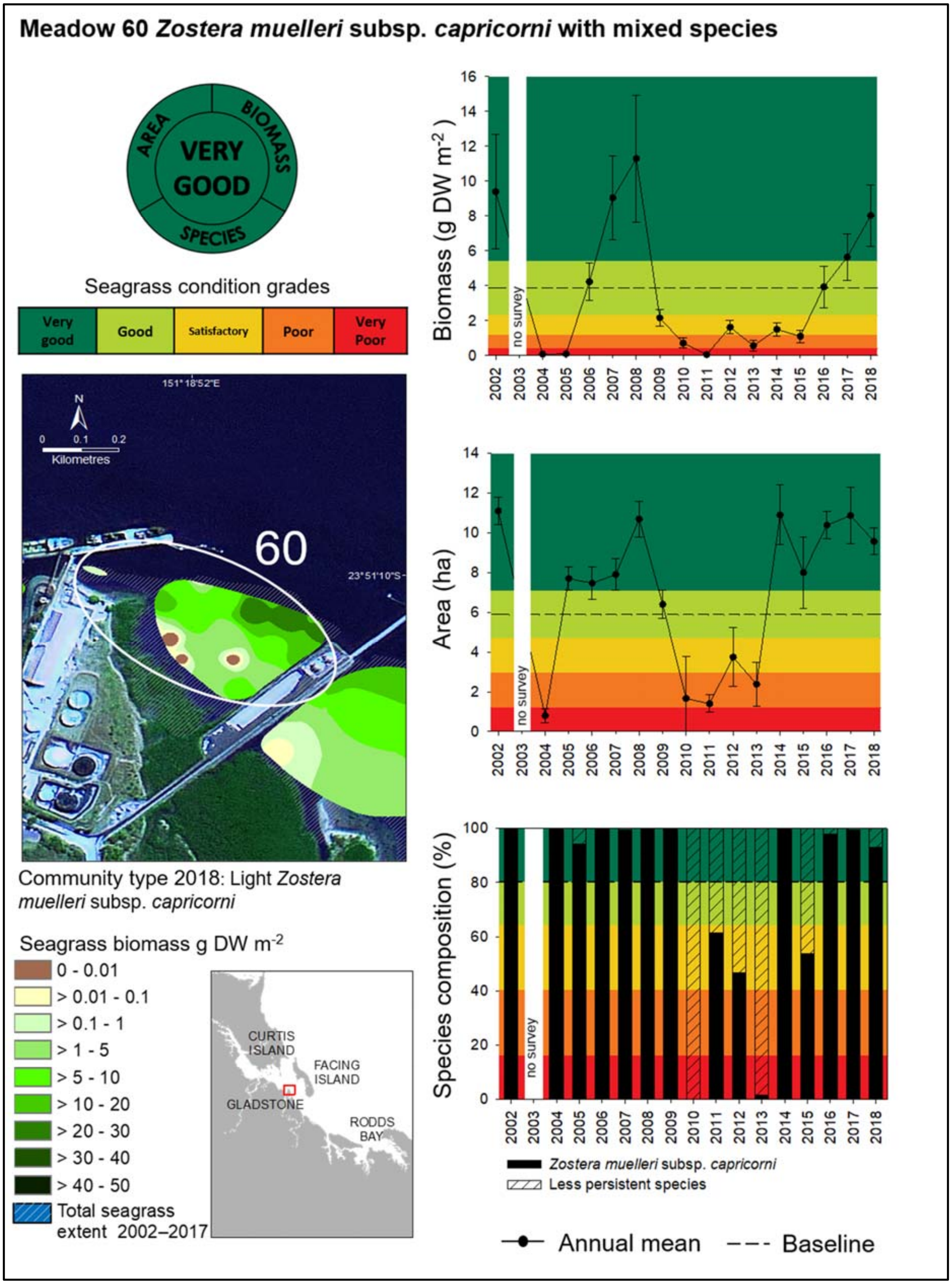



**Figure 28**. Changes in meadow area, biomass and species composition for seagrass at Meadow 60, South Trees Inlet Zone, November 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

### *3.2.7 Rodds Bay*

Since the inception of the Port Curtis monitoring program, three seagrass meadows are assessed in Rodds Bay to measure seagrass health in an area further removed from port activities. In 2018, Rodds Bay seagrasses improved substantially. 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. Total seagrass area in 2018 covered ~374 ha, a significant increase from 2017. Not all areas of the Rodds Bay Zone are assessed in the annual monitoring survey and large areas of seagrass also occur outside of the monitoring meadows.

*Long-Term Monitoring Meadows*

There are three intertidal monitoring meadows in the Rodds Bay Zone – Meadows 94, 96 and 104. Prior to 2010, these meadows consisted of continuous seagrass cover; however they currently form aggregated patches (Meadow 96) and isolated patches (Meadows 94 and 104; Figures 30-32).

**Meadow 94:**

Meadow 94 is the smallest monitoring meadow in Rodds Bay and improved to satisfactory condition in 2018 (Figure 30; Appendix 3). This is the first time the meadow obtained a score greater than poor since 2008. The meadow doubled in size from 2017 on the isolated intertidal mud bank, half of the meadow's maximum extent. Biomass is also the highest it has been since 2008 at 3.29 ± 1.15 gDW $m^{-2}$ with little change in the ratio of *Z. muelleri* subsp. *capricorni* relative to *H. ovalis* (Figure 30; Appendix 4).

**Meadow 96:**

Overall condition of Meadow 96 went from very poor to good in 2018 with improvements in all indicator scores (Figure 31; Appendix 3). Biomass had the most significant gains; up from <1 gDW $m^{-2}$ to 6.84 ± 1.55g DW $m^{-2}$, akin to baseline levels most concentrated in the middle to north-western quadrant of the meadow (Figure 31; Appendix 3). Area was in fact the highest ever recorded for Meadow 96 in the history of the monitoring program, and the increase in *Z. muelleri* subsp. *capricorni* over *H. ovalis* in the meadow placed the score up into good condition for species composition (Figure 31; Appendix 4).

**Meadow 104:**

Overall condition of Meadow 104 improved from very poor to poor condition in 2018 with shifts in all three metrics. Species composition improved the most dramatically with a 65% gain in *Z. muelleri* subsp. *capricorni* after a three year period of repeated declines (Figure 32; Appendix 4). Meadow 104 remains fragmented with biomass declining further up the mud bank (i.e. south-east; Figure 32).

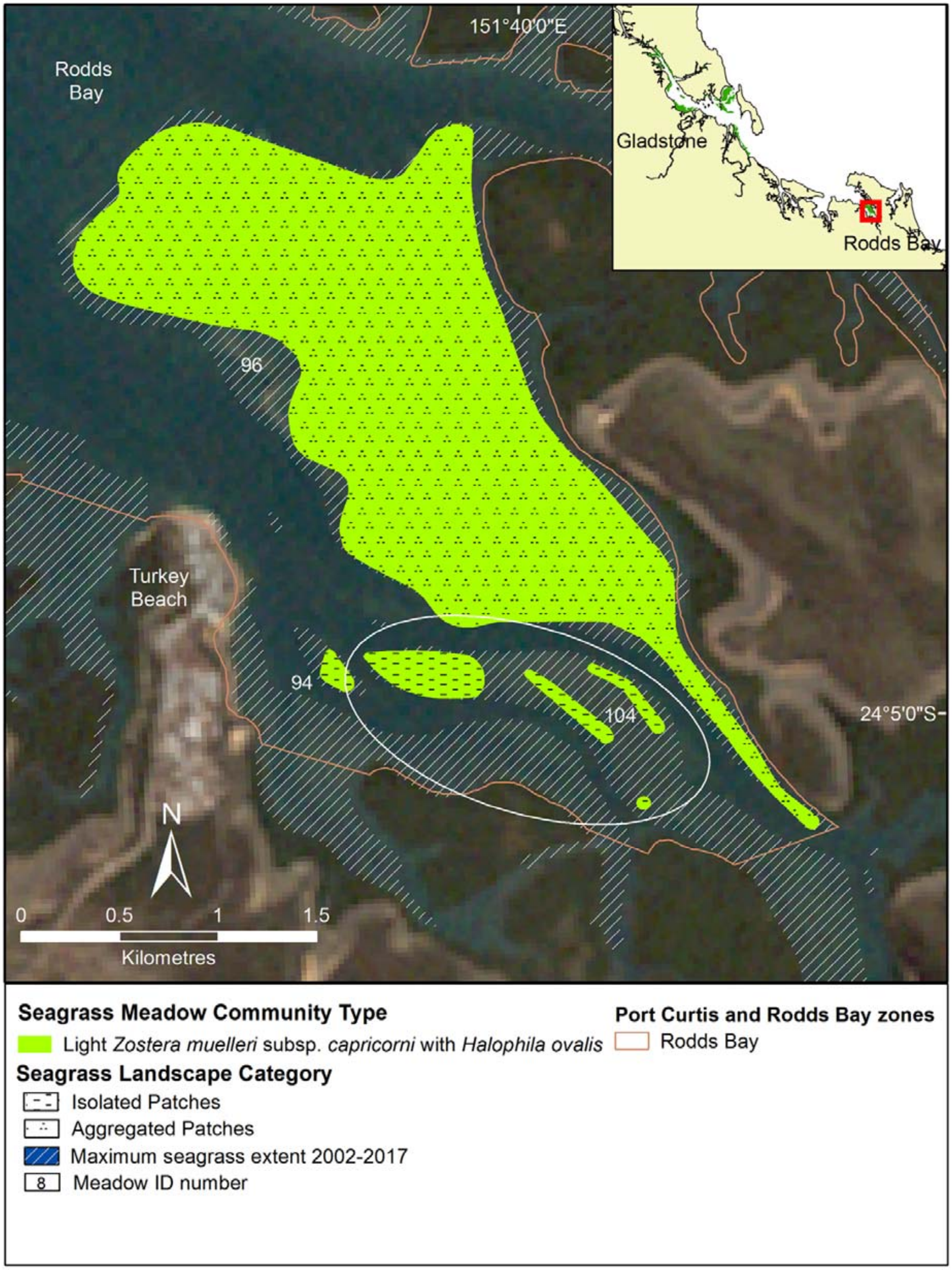



**Figure 29.** Seagrass distribution and community types in the Rodds Bay Zone, November 2018.

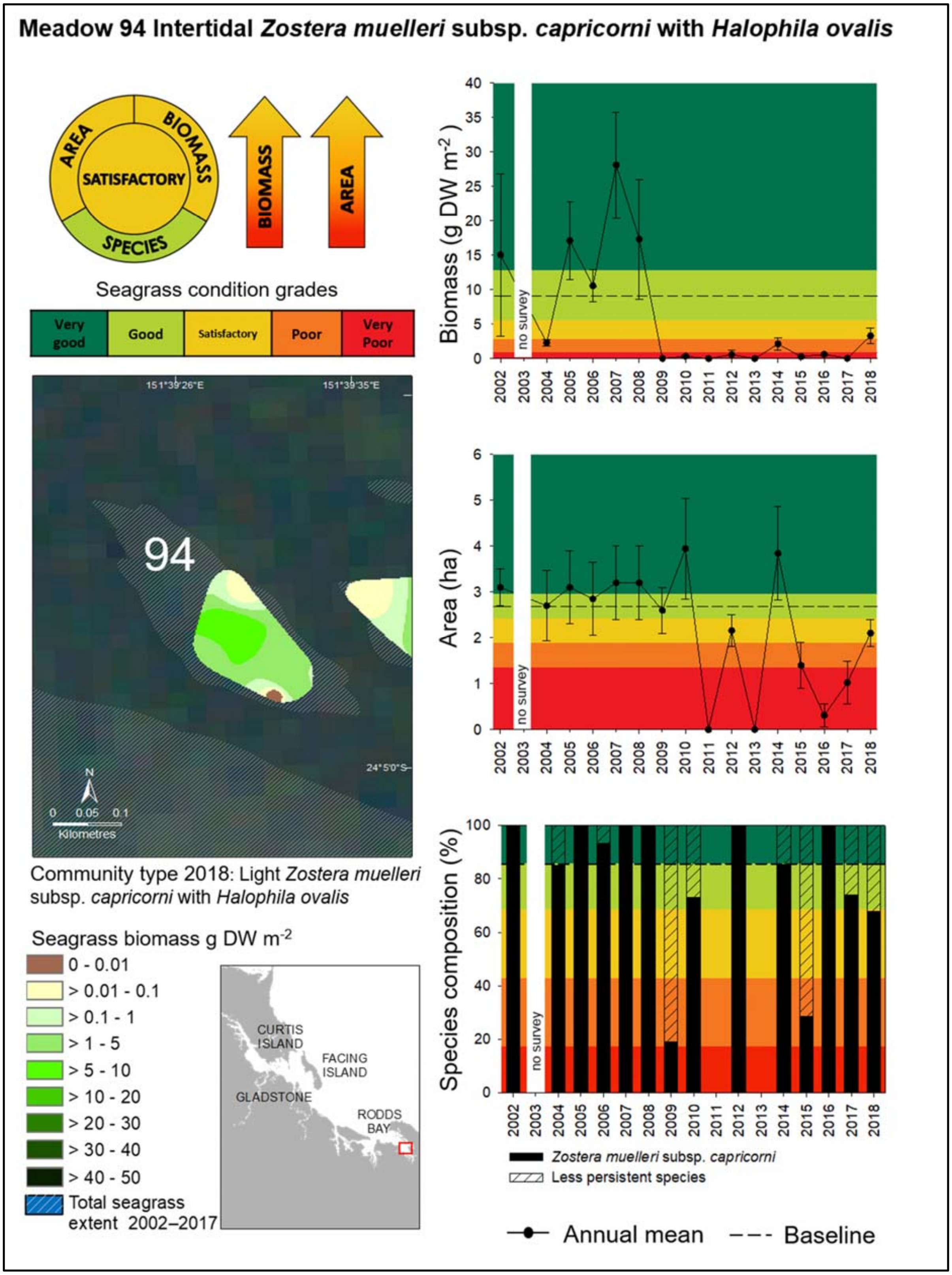



**Figure 30**. Changes in meadow area, biomass and species composition for seagrass at Meadow 94, Rodds Bay Zone, November 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

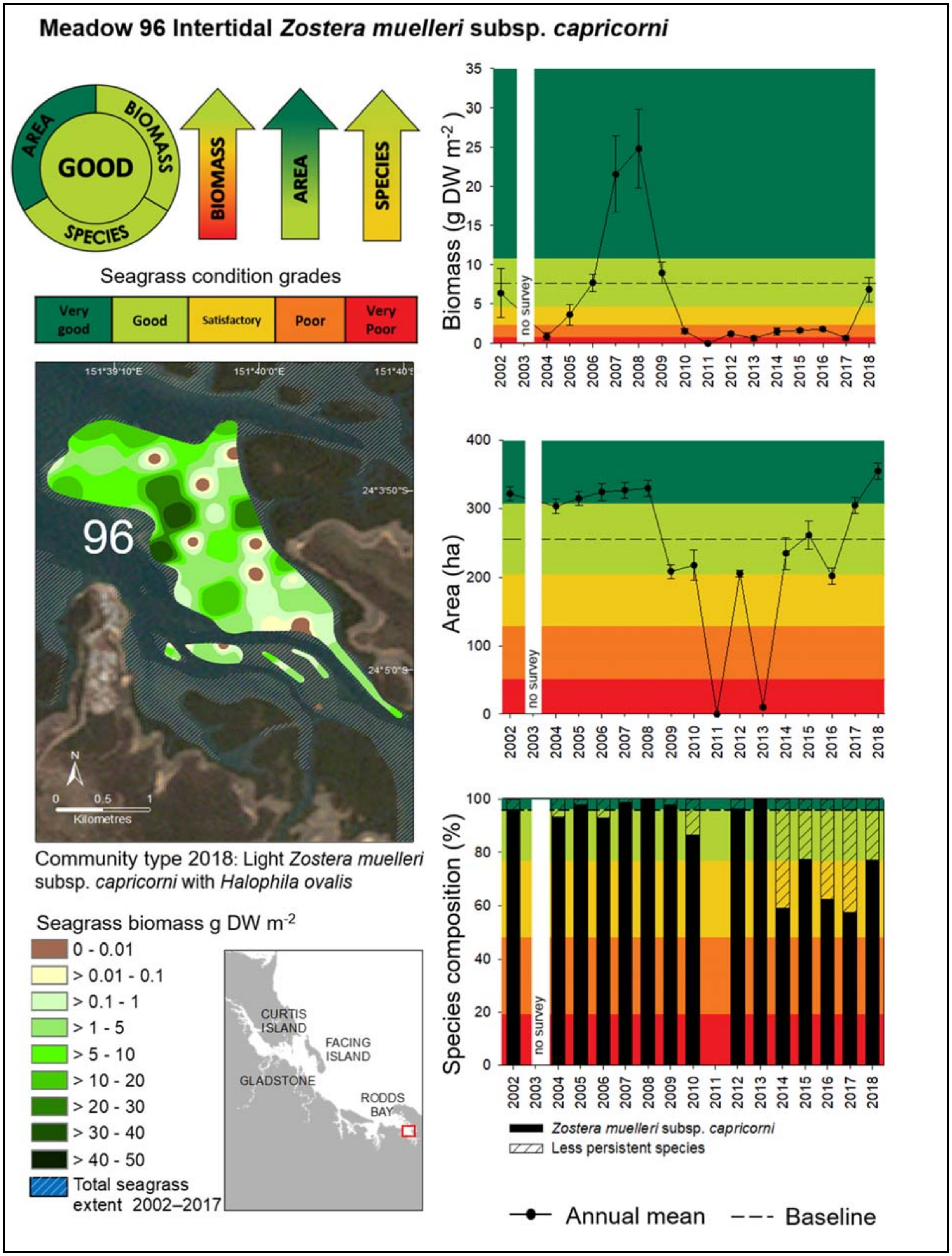



**Figure 31**. Changes in meadow area, biomass and species composition for seagrass at Meadow 96, Rodds Bay Zone, November 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

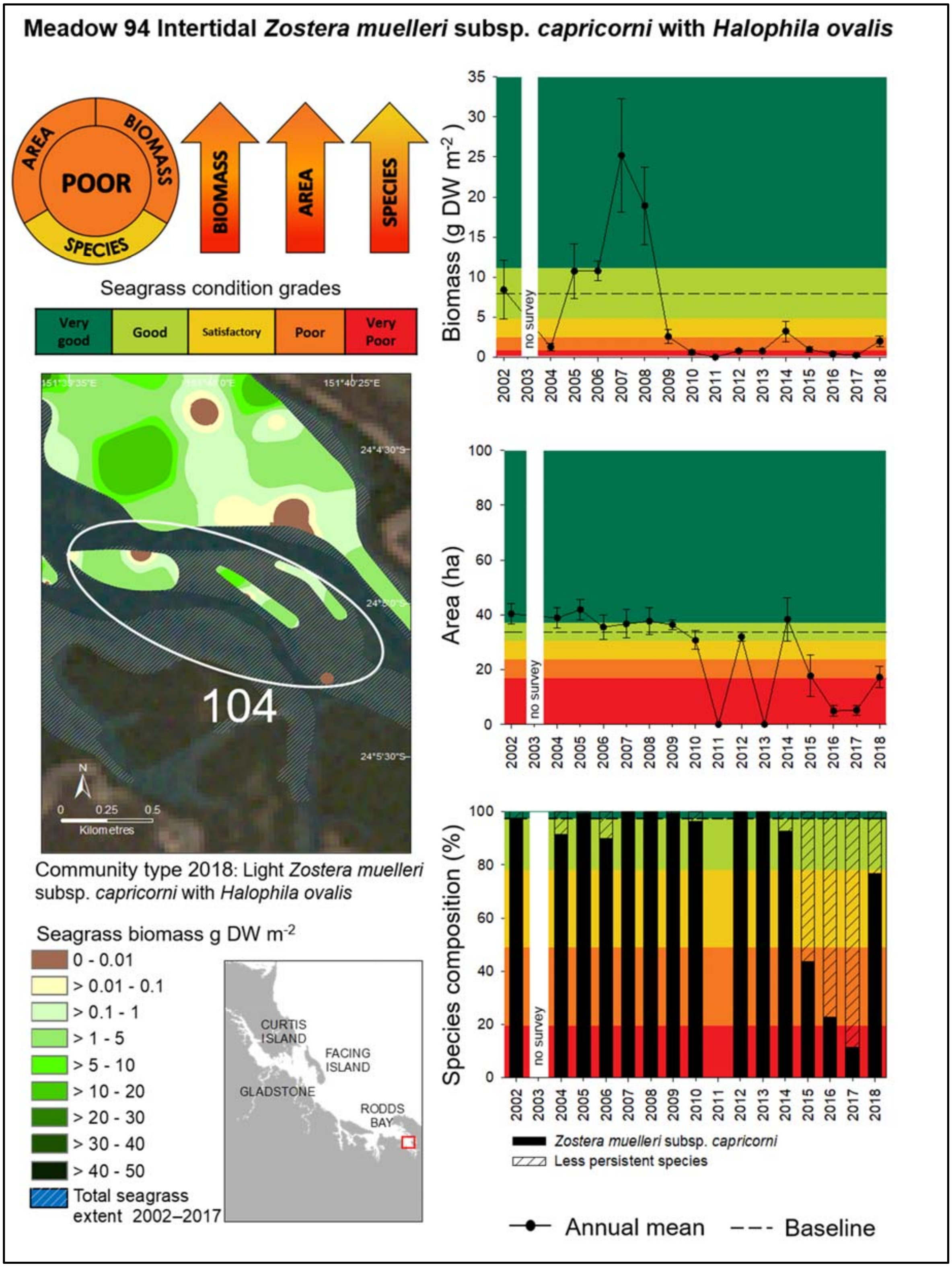


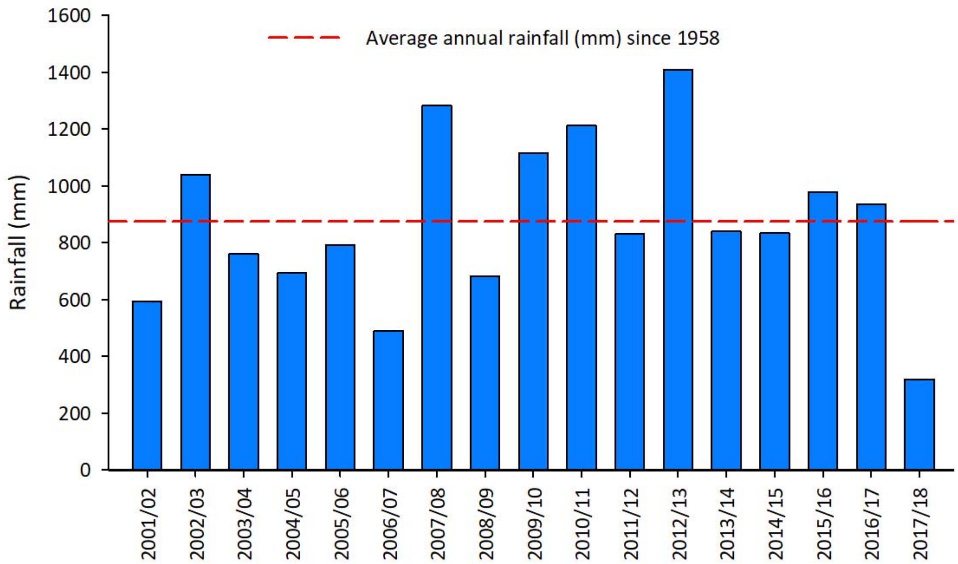

**Figure 32**. Changes in meadow area, biomass and species composition for seagrass at Meadow 104, Rodds Bay Zone, November 2002–2018 (biomass error bars = SE; area error bars = "R" reliability estimate).

## 3.3 Gladstone environmental conditions

### *3.3.1 Rainfall, riverflow, and tidal exposure*

Total annual rainfall in the 12 months preceding the November 2018 survey was the lowest since monitoring began (Figure 33A). The only substantial rainfall events occurred in February 2018, in line with expected wet season conditions, and in October 2018, just prior to the annual seagrass monitoring survey (Figure 33B). Neither event was above the long-term monthly average. River flow from the Calliope River was similar to low rainfall trends with only small flows in the wet season and all other months relatively dry and with little river flow (Figure 34). Annual total daytime exposure of seagrass meadows was near average (Figure 35).

A)




B)

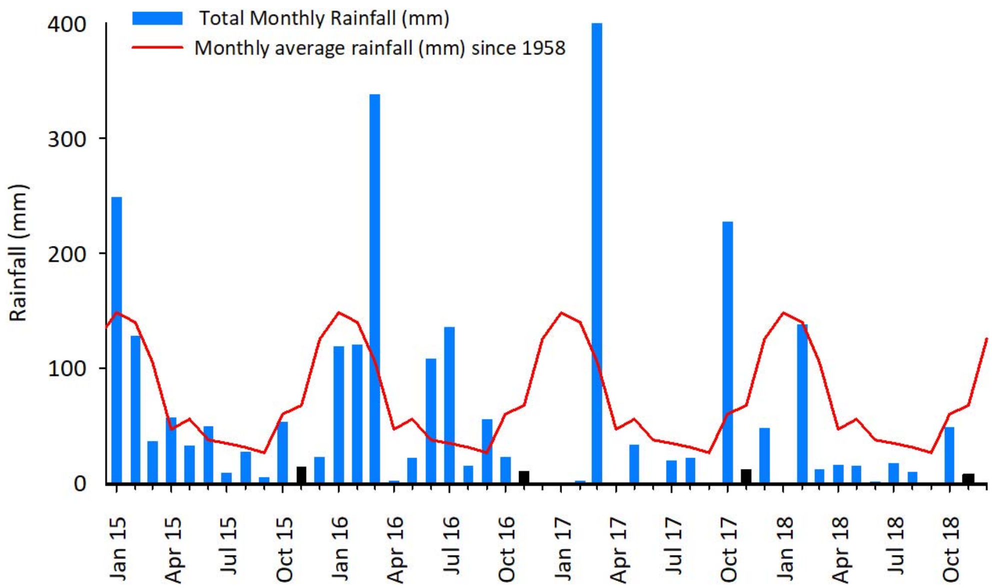



**Figure 33.** A) Gladstone annual rainfall (mm) and B) monthly rainfall (mm) totals; January 2015–November 2018. Black bars indicate October/November rainfall when seagrass was sampled (spring peak growth period).

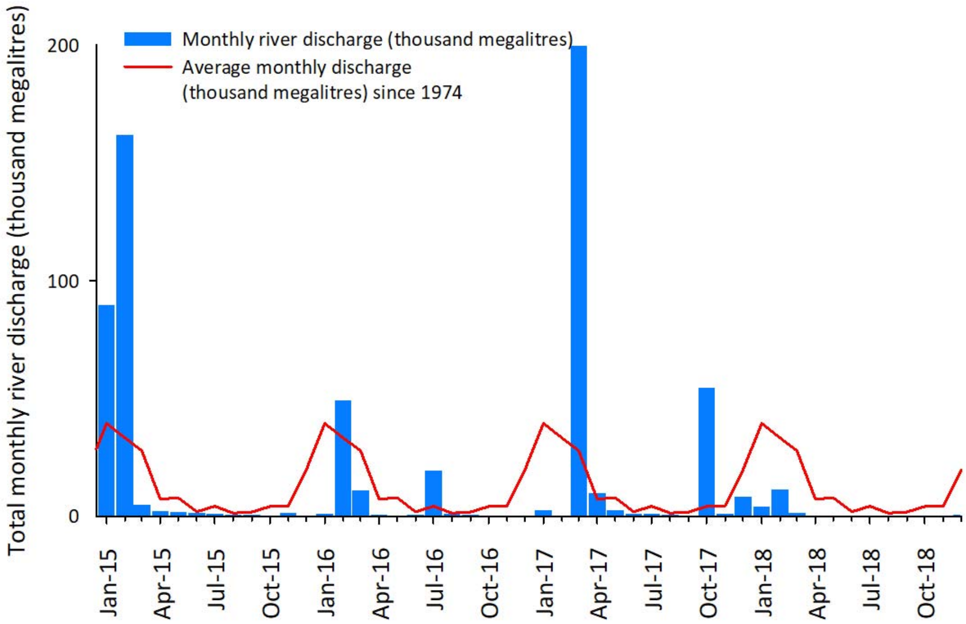



**Figure 34.** Monthly total river flow for the Calliope River (thousand megalitres); January 2015–November 2018.

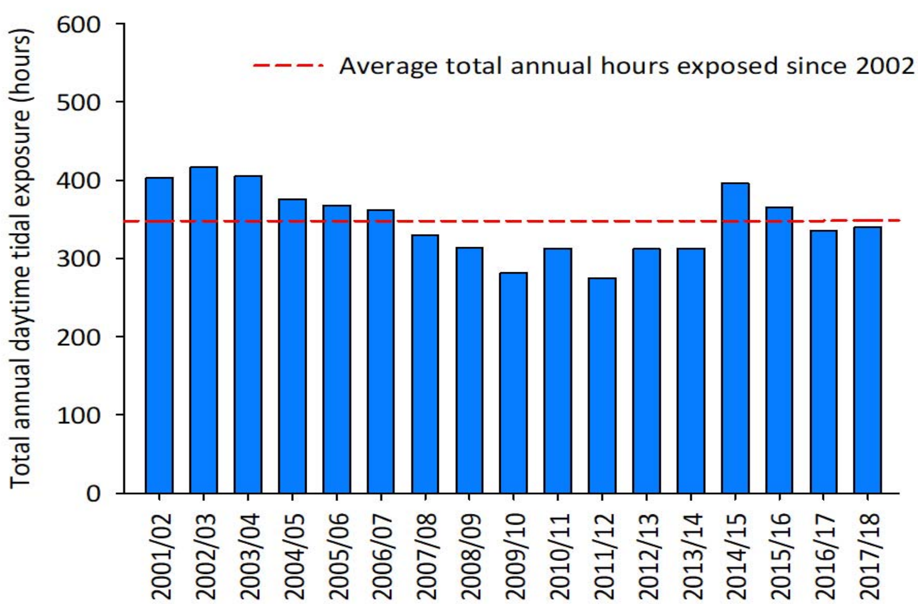



**Figure 35.** Total annual daytime hours exposed 2001/02 to 2017/18 (0600 – 1800; <1.0 m below mean sea level).

Analysis of overall meadow score against total annual river flow (Calliope River) and rainfall showed a strong relationship of river flow ($F = 25.84$, $p < 0.0001$; $r^2 = 0.28$) with overall meadow scores over the 2002-2018 annual monitoring program (Figure 36). A similar but less clear relationship was found with rainfall ($F = 8.3$, $p < 0.0001$, $r^2 = 0.23$), however, the residual plots from modelled river flow against meadow scores indicated it was the better of the two continuous covariates.

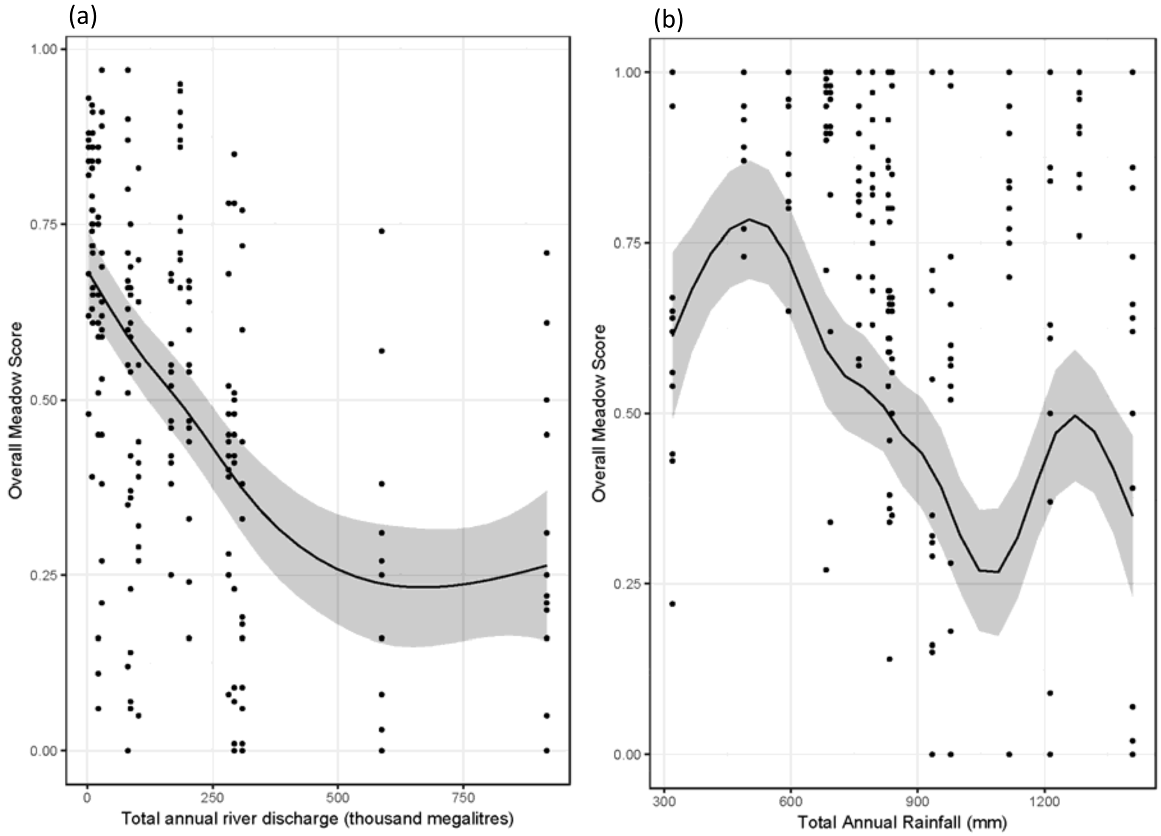



**Figure 36.** The effect of (a) total annual river flow for the Calliope River (thousand megalitres) and (b) total annual rainfall on overall meadow score for each monitoring meadow from 2002 – 2018. The non-linear trend is the fit of a quasibinomial generalized additive mixed model. Grey area is the 95% confidence interval.

# 4 DISCUSSION

Seagrasses in Port Curtis and Rodds Bay underwent substantial improvements in condition in 2018 and were classed as being in an overall satisfactory condition up from a poor condition in 2017. This improvement is attributed to stable seagrass condition in the South Trees, Inner, and Mid Harbour meadows accompanied by significant improvements to seagrass in The Narrows, Western Basin, and Rodds Bay zones. In particular, Rodds Bay monitoring meadows underwent substantial recovery for the first time since major losses occurred in the Zone in 2009. Consequently, there was no relationship between proximity of port and anthropogenic activities and condition or improvement within meadows, suggesting that changes were related to overall environmental conditions rather than anthropogenic activity. The return of the only subtidal monitoring meadow in the Western Basin Zone with not only a substantial footprint, but also the highest biomass observed for the meadow since monitoring began in 2002 also helped improve the Port's collective seagrass condition.

Lower than average rainfall and river flow in 2018 was likely advantageous for seagrass growth throughout the Port Curtis and Rodds Bay area. Not only were accumulated levels down, but fewer episodic events led to more benign conditions. Analysis of the long-term patterns of seagrass condition from the 17 years of annual monitoring revealed a strong relationship with river flow and also to some extent rainfall in the region. Light monitoring at seagrass meadows in the port for the ongoing seagrass monitoring program ceased in 2016 and therefore a direct correlation between lower rainfall/river flow and the seagrass' benthic light environment for the entire length of the program and associated growing conditions cannot be made. However, previous monitoring in the area between 2009 and 2016 connected with the WBDDP has shown that benthic light increases with fewer significant weather events. Additionally, slightly below average number of tidal exposure hours in 2018 also likely protected intertidal seagrasses from any extreme desiccation and thermal stress (Unsworth et al. 2012). Trends in seagrass recovery reinforce that less stochastic and mild environmental conditions in 2018 were likely the biggest driver of improved seagrass condition.

Despite an increase or stabilisation of most meadow scores, less stable colonising species frequently maintained an increased proportion of, or dominated many Western Basin intertidal meadows. For some, this resulted in a lower overall meadow score despite achieving above average condition for biomass and area. The presence of these more variable colonising species can be an indicator of past disturbance and the beginning of seagrass meadow recovery (Rasheed 2004). The Western Basin is also an area with naturally turbid waters and shifting mud banks which can make for difficult conditions for a more persistent species to maintain a foothold. It may in fact be that some Western Basin meadows will continually oscillate between the larger bladed *Z. muelleri* subsp. *capricorni* and a more variable *Halophila* spp. dominated community. The drier conditions recorded during 2018 favoured stabilising growth and we did see some meadows gain a higher proportion of the larger *Z. muelleri* subsp. *capricorni*. If drier conditions continue in 2019, we expect to see continued gains of the larger more persistent species during the subsequent monitoring period.

For seagrass meadows in Rodds Bay, 2018 was the first substantial recovery of these meadows since large declines occurred in 2009 and 2010, culminating in the complete loss of all three meadows in 2011. The recovery of these meadows since then has lagged behind many of the other seagrass areas in the monitoring program. Where complete loss of the standing crop of seagrass meadows 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 is in contrast to many other meadows in Port Curtis, which although experiencing substantial losses in 2011 maintained some presence of seagrasses where more rapid asexual spread from existing plants could occur. Similar differences in the trajectory of recovery have been recorded elsewhere in Queensland where monitoring has been conducted. In Cairns, where near meadow scale losses occurred leading up to 2011, recovery of meadows has taken longer than 7 years and is still in progress (Reason & Rasheed 2018). Yet in Townsville, where significant declines in seagrass occurred but some presence of seagrass was maintained in meadows and recovery has been substantially more rapid, largely returning to the pre-disturbance state within 3 years (Bryant et al. 2019).

While many of the seagrass meadows showed considerable improvement, the largest and historically densest area of seagrass in Port Curtis at Pelican Banks remained at a relatively low biomass leading to a poor overall meadow condition. Area did improve somewhat in 2018, but it coincided with a decline in the proportion of the persistent species Z*. muelleri* subsp. *capricorni*. Given its historical importance as the most stable seagrass meadow in the region, a continued trajectory of recovery in the future remains key to marine environmental health in Port Curtis.

There are a range of potential contributors to the lack of seagrass biomass recovery at Pelican Banks in recent years. 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)). Both of these large herbivore species have the potential to significantly impact the state of seagrasses, with examples of major meadow losses recorded in other locations as a direct result of herbivory (Christianen et al. 2014). Large numbers of green turtles are known to frequent the meadow, but it is unclear if population levels or feeding behaviour (i.e. cropping) in the area has substantially changed to affect canopy height. Research has been underway in Port Curtis to measure the potential effects of grazing pressure on seagrass meadow biomass and how this may alter meadow structure and condition. Preliminary results found excluding megaherbivores (turtles and dugong) from areas increased seagrass biomass at Pelican Banks and at South Trees Inlet (Meadow 76-77). Widespread use of Port Curtis and Rodds Bay seagrass meadows for dugong feeding indicate seagrasses in the region continue to provide a valuable food source to megaherbivore populations, including adjacent to port infrastructure and industrial activity. Furthermore, the prevalence of dugong feeding trails and turtle sightings suggest megaherbivore grazing/cropping may in fact be an important component of the overarching drivers of seagrass condition in not just the Pelican Banks meadow, but in other port zones.

Movement and accumulation of sediments can also influence seagrass condition (Cabaco et al. 2008). Observations by field team members provide some anecdotal evidence that movement of sediment and accumulation on the southernmost section of Pelican Banks may have led to the reduction in seagrass biomass most apparent at this end of the meadow. However, direct measurements have not been made of sediment change with only indirect evidence from a 2016 study of seagrass seed banks in which coring in the area indicated a deeper burial of seeds (Bryant et al. 2016).

## 4.1 Comparisons with Queensland-wide monitoring program and seagrass resilience

The marked improvement in seagrass meadow condition in Port Curtis and Rodds Bay was generally consistent with seagrass trends along Queensland's east coast between Cairns and Port Curtis. Recovery has differed somewhat by location, but most have improved following significant losses in 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. 2017; McKenna et al. 2017; Bryant et al. 2019). Each location varies in recovery by local climate as well as the severity of the initial decline. For example, a reprieve from cyclones in the region in 2012 was reflected by lower rainfall and river flow relative to 2010 and 2011, which corresponded with improved meadow condition in Gladstone. The significant rainfall and flooding associated with TC Debbie in March 2017 coincided with analogous impacts to seagrass condition across the ports affected by this weather event: Hay Point, Abbot Point, and Port Curtis (Chartrand et al. 2018). The overall drier conditions, consequential low river flow, and low tidal exposure in 2018 led to sustained or improved scores in monitoring meadows from Cairns, Townsville, Mackay, as well as Port Curtis and Rodds Bay.

Reductions in meadow area, biomass, and stable/persistent species during years of extreme weather events reduce both the adult plant population and limit the resources available for seagrasses to initiate recovery. When limited or no adult plants remain, recovery will depend upon seed banks in the sediment or sexual propagules sourced from nearby locations (Jarvis and Moore 2010; Duarte and Sand-Jensen 1990; Phillips and Lewis 1983). Under these circumstances the rate of recovery is likely to be much slower, particularly where no local or nearby sources of propagules exist. For example in Mourilyan Harbour there are multiple years of complete meadow loss and seagrass remains in very poor condition with little prospect of seagrass recovery without some form of restoration (Reason and Rasheed 2018). In this context, meadows in Port Curtis have shown reasonable resilience and ability to recover. Sustained seagrass growth during 2019 would likely ensure replenishment of seed reserves and an opportunity for the adult populations to further increase in biomass to improve resilience buffers.

Seagrass meadows away from Queensland's east coast have generally 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) (Sozou et al. 2017), Weipa (Sozou and Rasheed 2018) and Karumba (Shepherd et al. 2018) did not experience the same declines in 2010-2016. Seagrass condition in Weipa was good in 2018 (McKenna and Rasheed in prep) while Karumba did decline likely due to TC Nora which passed directly over the region in early 2018.

## 4.2 Seagrass changes and the Western Basin Dredging and Disposal Project

Beyond encompassing the latest instalment of the annual long-term ambient seagrass monitoring program that has been running since 2002, this report is also the last of the annual assessments formally connected with the post dredge monitoring requirements from the Western Basin Dredging and Disposal Project (WBDDP). A range of seagrass monitoring and research initiatives were conducted as part of the WBDDP in addition to the commitment to continue this established annual monitoring program for five years post dredging. They include:

1. More frequent seagrass monitoring (at least quarterly) linked with in situ water quality and light monitoring between 2009 and 2016 covering pre-, during and post- dredging phases (see Chartrand et al. 2017 for more details).

2. Expanding the established long-term ambient annual monitoring program to include re-mapping and assessment of all seagrasses in the Western Basin area each year in addition to the selected annual monitoring meadows (results captured within this report).

3. Research to establish and implement local seagrass light requirements as a management tool during the WBDPP (see Chartrand et al. 2012; 2016; Petrou et al 2013 for more details)

4. Research to develop sub-lethal indicators of seagrass stress (see: Macreadie et al. 2014; Schliep et al. 2014; 2015)

Collectively these initiatives allowed for a comprehensive understanding of seagrass condition throughout the project as well as significant advances in the ability to effectively manage seagrasses during dredging projects. This included the first application of a seagrass relevant light threshold for operational management of a dredge in Australia (Chartrand et al. 2016).

Detailed analysis of the drivers of seagrass change were possible from the 2009-2016 monitoring dataset where continuous water quality monitoring matched with seagrass assessments, encompassing pre, post and during the WBDDP were available. Results of that analysis (see Chartrand et al. 2017) found that changes to seagrasses were best explained by a positive relationship with mean monthly light levels at the sites and negatively by three month cumulative river flow. These results match well with the analysis presented in this report on the full 17 year annual data set that indicates flow of the major rivers (represented by the Calliope River) is significantly correlated with changes to seagrass condition (see above discussion).

Frequent severe climate events, rather than dredging activities associated with the WBDDP were identified as the likely main driver of seagrass declines recorded in the Western Basin Region. The major declines in seagrass distribution occurred before the onset of the major capital dredging activities and occurred at the out of port reference site (Rodds Bay) as well as in other seagrass monitoring areas of the Queensland east coast at the time (Chartrand et al. 2017). The degree to which WBDDP may have had an interactive effect on subsequent seagrass recovery was not possible to disentangle from the significant storm and river flow events due to their co-incident timing. The period from 2009 to 2016 in Gladstone was characterised by higher than average rainfall during the majority of wet seasons, punctuated by two of the most extreme flood events on record for the region. This makes it difficult to ascertain what, if any, additional impact dredging may have had on seagrass condition and recovery. However, the comprehensive water quality monitoring program from 2009-2016 has shown that light levels were maintained above the locally derived light requirements for seagrass at the areas that were required to be managed in the WBDDP during the dredging campaign (Chartrand et al. 2016).

Despite the strong correlation of seagrass change with river flow and severe climate events, a range of additional factors such as sediment dynamics and grazing pressure (as discussed above) are also potential drivers of seagrass declines but not monitored in the program.

Results of this latest annual survey, five years post-completion of WBDDP dredging, have found seagrasses to be in an overall satisfactory condition benchmarked against their 17 year monitoring history. Apart from the direct permitted seagrass loss due to the WBDDP reclamation area, seagrasses in 2018 covered the majority of their historical footprint and improvements in biomass and species composition were in line with the favourable environmental conditions for seagrass growth over the previous 12 months. The seagrass dynamics observed in the program were consistent with the expected major climate drivers of seagrass change and the continued high level of use of the meadows by dugongs and green turtles point to the maintenance of a functional seagrass ecosytem.

## 4.3 Implications for port management

Port Curtis meadows maintained or increased their spatial footprint and at least some presence of the key foundation species in 2018 as well as biomass increases for many meadows. If conditions remain favourable, we would expect to see further improvements in seagrass meadows for Port Curtis in 2019. The resilience of some Port Curtis and Rodds Bay meadows may still be low due to the prevalence of a less persistent species throughout the meadow. Activities that could reduce water quality in Port Curtis and Rodds Bay should be carefully considered in order to not impede further recovery of seagrass meadows during favourable weather and climate conditions. Where such activities are planned, managing water quality and particularly benthic light to be sufficient for seagrass growth (Chartrand et al. 2016) will be important for maintenance of seagrasses and the services they provide.

Port Curtis and Rodds Bay seagrasses have struggled to return to pre-disturbance levels following the major declines that occurred between 2009 and 2010. The step-wise improvement in the overall score may be the start of an upward trend in seagrasses for the region. Despite, the repeated disturbances from climate, floods, cyclones and anthropogenic activities over the last seven years, seagrass generally remains within the majority of its historical extent. The greater prevalence of less stable seagrass species in many meadows, indicate seagrasses are still not fully recovered and likely remain less resilient to future pressures or impacts than they otherwise would be. The general improvement in seagrasses is a strong foundation for further potential recovery of meadows in 2019, 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 Gladstone Harbour 2014 pilot report card (Bryant et al. 2014b). The 2002–2012 period incorporates a range of conditions present in Gladstone Harbour, 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 Harbour 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 Gladstone Harbour report card.

| Grade | Description | Score Range | |
|---|---|---|---|
| | | Lower bound | Upper bound |
| A | Very good | $\geq$0.85 | 1.00 |
| B | Good | $\geq$0.65 | $<$0.85 |
| C | Satisfactory | $\geq$0.50 | $<$0.65 |
| D | Poor | $\geq$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 (Figure 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).

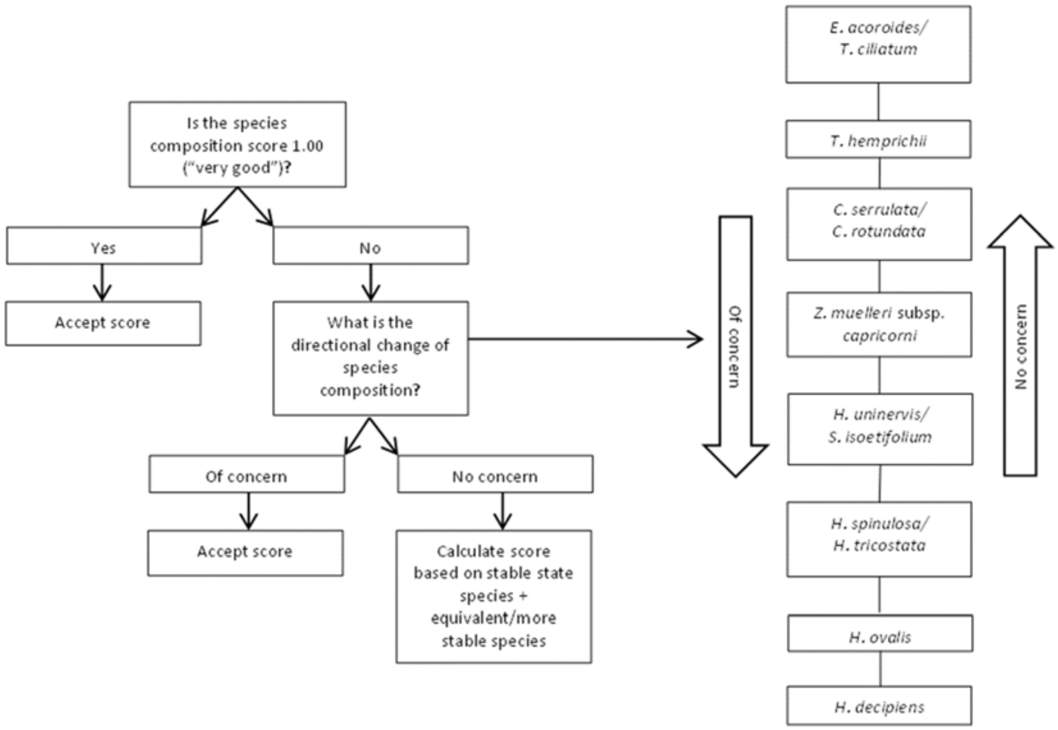



**Figure 10.** (a) Decision tree and (b) directional change assessment for grading and scoring seagrass species composition.

## 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 2018.

1. Determine the grade for the 2018 (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 ($A_{satisfactory}$):

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

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:

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

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:

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

5. Determine the area score for 2017 ($Score_{2016}$) by scaling $A_{prop}$ against the score range (SR) for the satisfactory grade ($SR_{satisfactory}$), i.e. 0.15 units:

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

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

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.

| Meadow ID | Biomass ± SE (g DW m-2) | Area ± R (ha) | Community Type | Landscape Category | Species Present |
|---|---|---|---|---|---|
| **THE NARROWS ZONE** | | | | | |
| 1 | 7.8 ± 5.9 | 1.91 ± 0.55 | Light *Zostera muelleri* subsp. *capricorni* with *Halophila ovalis* | Isolated Patches | *Z. muelleri; H. ovalis* |
| 10 & 17 | 13.23 ± 6.02 | 14.94 ± 5.77 | Light *Zostera muelleri* subsp. *capricorni* with *Halophila ovalis* | Aggregated Patches | *Z. muelleri, H. ovalis* |
| 13 | 4.05 ± 4.05 | 95.99 ± 30.14 | Moderate *Halophila ovalis* with *Zostera muelleri* subsp. *capricorni* | Isolated Patches | *H. ovalis, Z. muelleri, H. decipiens* |
| 19 | 2.69 ± 0.69 | 66.1 ± 7.66 | Moderate *Halophila ovalis* with *Zostera muelleri* subsp. *capricorni* | Aggregated Patches | *H. ovalis, Z. muelleri* |
| 21 | 5.01 ± 1.22 | 172.3 ± 11.4 | Light *Zostera muelleri* subsp. *capricorni* with *Halophila ovalis* | Aggregated Patches | *Z. muelleri, H. ovalis, H. decipiens* |
| 22 | 8.67 ± 0 | 23.89 ± 10.15 | Dense *Halophila decipiens* with *Halophila ovalis* | Aggregated Patches | *H. decipiens, H. ovalis* |
| 23 | 5.27 ± 0.61 | 105.92 ± 13.37 | Moderate *Halophila ovalis/ Zostera muelleri* subsp. *capricorni* | Continuous Cover | *H. ovalis, Z. muelleri, H. decipiens* |
| 25 | 4.1g | 0.38 ± 0.05 | Moderate *Halophila ovalis* with *Halophila decipiens* | Isolated Patches | *H. ovalis, H. decipiens* |
| 26 | 7.13 | 0.33 ± 0.04 | Dense *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 28 | 5.05 ± 1.42 | 21.1 ± 4.03 | Light *Zostera muelleri* subsp. *capricorni* with mixed species | Isolated Patches | *Z. muelleri, H. ovalis, H. decipiens* |
| 29 | 7.67 ± 1.36 | 58 ± 7.36 | Light *Zostera muelleri* subsp. *capricorni/ Halophila decipiens* | Aggregated Patches | *Z. muelleri, H. decipiens, H. ovalis* |
| 33 | 3.39 ± 0.75 | 78.92 ± 22.64 | Moderate *Halophila ovalis* | Continuous Cover | *H. ovalis, Z. muelleri* |
| 178 | 0.82 | 0.84 ± 0.15 | Light *Halophila ovalis* | Isolated Patches | *H. ovalis* |

| Meadow ID | Biomass ± SE (g DW m-2) | Area ± R (ha) | Community Type | Landscape Category | Species Present |
|---|---|---|---|---|---|
| **GRAHAM CREEK ZONE** | | | | | |
| 2 | n.a. | 0.36 ± 0.05 | Light *Halophila decipiens* | Isolated Patches | *H. decipiens* |
| 15 | 2.87 | 3.72 ± 1.11 | Moderate *Halophila ovalis* | Aggregated Patches | *H. ovalis* |
| 34 | 1.18 ± 0.98 | 8.51 ± 1.23 | Moderate *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 36 | 1.62 ± 0.72 | 4.74 ± 0.96 | Light *Zostera muelleri* subsp. *capricorni* | Isolated Patches | *Z. muelleri* |
| 37 & 41 | 4.52 ± 0.81 | 32.24 ± 5.04 | Moderate *Halophila ovalis* with *Zostera muelleri* subsp. *capricorni* | Aggregated Patches | *H. ovalis, Z. muelleri* |
| 38 | n.a. | 0.51 ± 0.13 | Light *Halophila decipiens* | Isolated Patches | *H. decipiens* |
| 141 | 2.4 | 0.43 ± 0.08 | Moderate *Halophila ovalis* | Aggregated Patches | *H. ovalis* |
| 168 | 1.73 | 0.56 ± 0.1 | Light *Zostera muelleri* subsp. *capricorni* | Isolated Patches | *Z. muelleri* |
| 175 | n.a. | 0.15 ± 0.03 | Light *Halophila decipiens* | Isolated Patches | *H. decipiens* |
| **WESTERN BASIN ZONE** | | | | | |
| 4 | 4.32 ± 0.82 | 33.4 ± 4.35 | Moderate *Halophila ovalis* with mixed species | Aggregated Patches | *H. ovalis, Z. muelleri, H. decipiens* |
| 5 | 6.44 ± 0.75 | 133.81 ± 5.88 | Moderate *Halophila ovalis* with mixed species | Aggregated Patches | *H. ovalis, H. decipiens, Z. muelleri* |
| 6 | 5.51 ± 0.51 | 375.34 ± 13.52 | Moderate *Halophila ovalis* with *Zostera muelleri* subsp. *capricorni* | Continuous Cover | *H. ovalis, Z. muelleri* |
| 7 | 4.2 ± 1.51 | 145.33 ± 27.8 | Moderate *Halophila decipiens* | Isolated Patches | *H. decipiens, H. ovalis* |
| 8 | 5.38 ± 0.86 | 164.59 ± 12.06 | Moderate *Halophila ovalis* with mixed species | Aggregated Patches | *H. ovalis, H. decipiens, Z. muelleri* |
| 9 | n.a. | 1.23 ± 0.3 | Light Halophila decipiens | Isolated Patches | *H. decipiens* |
| 11 | 3.33 ± 1.95 | 0.38 ± 0.08 | Moderate *Halophila decipiens* | Isolated Patches | *H. decipiens* |
| 32 | 6.89 | 2.87 ± 0.94 | Dense *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 42 | 0.72 ± 0.26 | 13.17 ± 2.99 | Light *Halophila ovalis* with *Zostera muelleri* subsp. *capricorni* | Isolated Patches | *H. ovalis, Z. muelleri* |
| 44 | 1.1 | 0.25 ± 0.1 | Moderate *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 52-57 | 3.77 ± 0.55 | 70.05 ± 4.05 | Moderate *Halophila ovalis* with *Zostera muelleri* subsp. *capricorni* | Isolated Patches | *H. ovalis, Z. muelleri* |
| 59 | n.a. | 1.53 ± 0.47 | Light *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 139 | 3.23 | 0.58 ± 0.46 | Moderate *Halophila ovalis* with *Halophila decipiens* | Isolated Patches | *H. ovalis, H. decipiens* |

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 |
|---|---|---|---|---|---|
| **INNER HARBOUR ZONE** | | | | | |
| 50 | 4.04 ± 1.21 | 67.37 ± 10.79 | Light *Halophila spinulosa* with *Halophila decipiens/Halophila ovalis* | Aggregated Patches | *H. spinulosa, H. decipiens, H. ovalis, Z. muelleri* |
| 58 | 0.17 ± 0.06 | 11.7 ± 1.12 | Light *Halophila ovalis* with *Zostera muelleri* subsp. *capricorni* | Aggregated Patches | *H. ovalis, Z. muelleri* |
| 61 | 5.59 | 0.87 ± 0.18 | Light *Zostera muelleri* subsp. *capricorni* with *Halophila ovalis* | Isolated Patches | *Z. muelleri, H. ovalis* |
| 62 & 63 | 4.01 | 0.7 ± 0.23 | Dense *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 79 | 4.86 ± 1.21 | 38.53 ± 8.36 | Light *Zostera muelleri* subsp. *capricorni* with *Halophila ovalis* | Aggregated Patches | *Z. muelleri, H. ovalis* |
| 80 | 7.52 | 0.4 ± 0.17 | Dense *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 81 | 4.25 ± 1.18 | 2.26 ± 1.33 | Dense *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 82 | 5.54 | 0.18 ± 0.08 | Dense *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 85 | 3.13 ± 0.73 | 63.19 ± 11.75 | Moderate *Halophila ovalis* with *Zostera muelleri* subsp. *capricorni* | Aggregated Patches | *H. ovalis, Z. muelleri* |
| 136 | 5.59 ± 4 | 13.93 ± 2.29 | Light *Zostera muelleri* subsp. *capricorni* with *Halophila ovalis* | Aggregated Patches | *Z. muelleri, H. ovalis* |
| 157 | 7.13 | 0.64 ± 0.15 | Dense *Halophila ovalis* | Isolated Patches | *H. ovalis* |

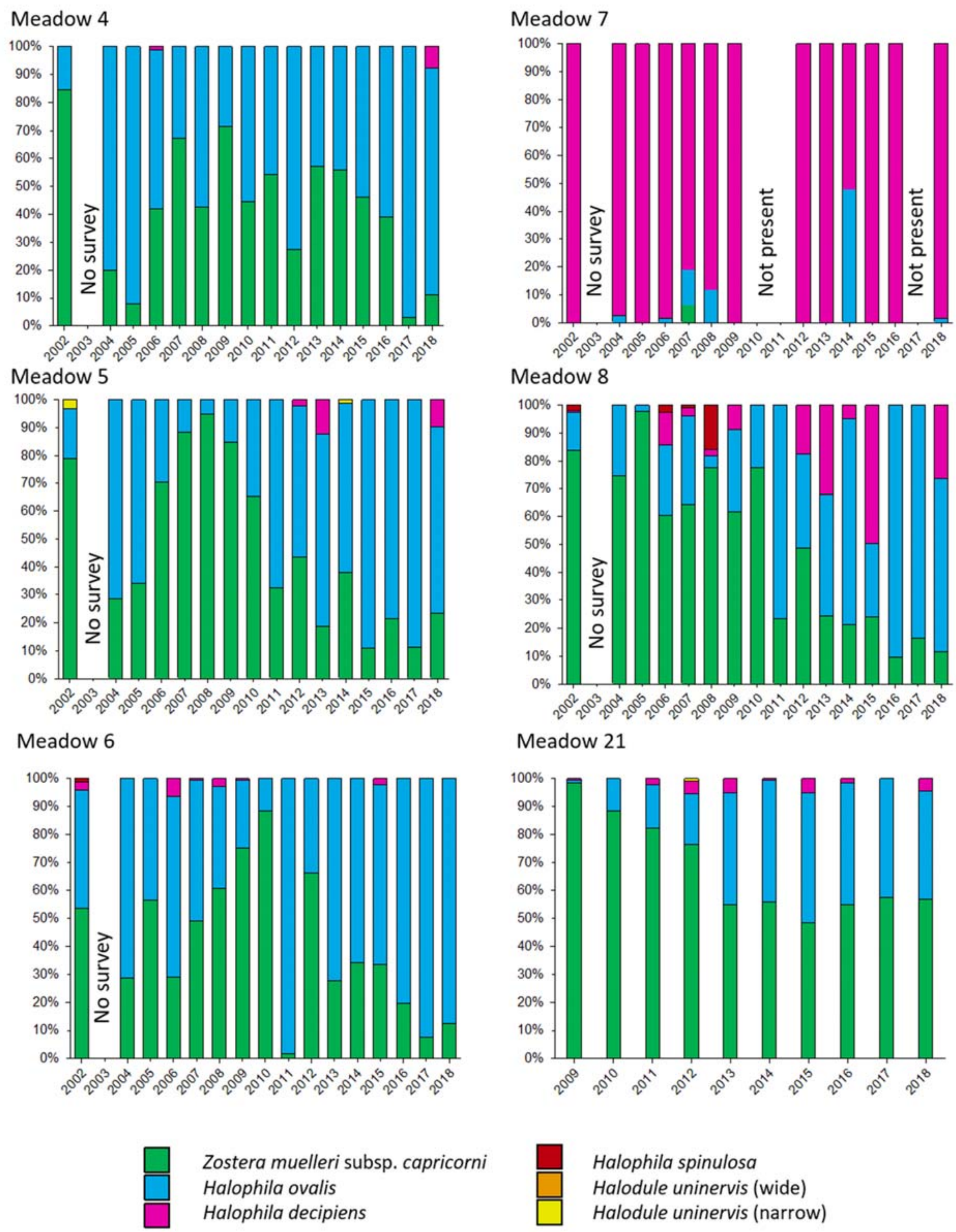
| | | | | | |
|---|---|---|---|---|---|
| **MID HARBOUR ZONE** | | | | | |
| 3 | 6.15 ± 2.54 | 2.93 ± 1.31 | Dense *Halophila ovalis* with mixed species | Isolated Patches | *H. ovalis, H. decipiens, Z. muelleri* |
| 43 | 8.25 ± 1.08 | 615.06 ± 7.59 | Light *Zostera muelleri* subsp. *capricorni* with mixed species | Continuous Cover | *Z. muelleri, H. ovalis, H. uninervis* |
| 48 | 6.35 ± 1.04 | 243.71 ± 55 | Mixed species | Aggregated Patches | *H. uninervis, H. ovalis, H. spinulosa* |
| 49 | 1.65 ± 0.82 | 26.53 ± 1.59 | Moderate *Halophila ovalis* with *Zostera muelleri* subsp. *capricorni* | Isolated Patches | *H. ovalis, Z. muelleri* |
| 66 | 8.05 ± 1.41 | 307.68 ± 53.61 | Light *Zostera muelleri* subsp. *capricorni* with mixed species | Continuous Cover | *Z. muelleri, H. ovalis, H. uninervis (wide) H. spinulosa* |
| 67 | 1.94 | 2.3 ± 1.31 | Moderate *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 69 | 13.34 ± 7.71 | 2.57 ± 1.82 | Light *Zostera muelleri* subsp. *capricorni* | Isolated Patches | *Z. muelleri* |
| 70 | 3.18 | 1.27 ± 0.43 | Moderate *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 72 | 2.79 | 5.83 ± 2.35 | Moderate *Halodule uninervis* (narrow) with *Halophila ovalis* | Isolated Patches | *H. uninervis (thin), H. ovalis* |

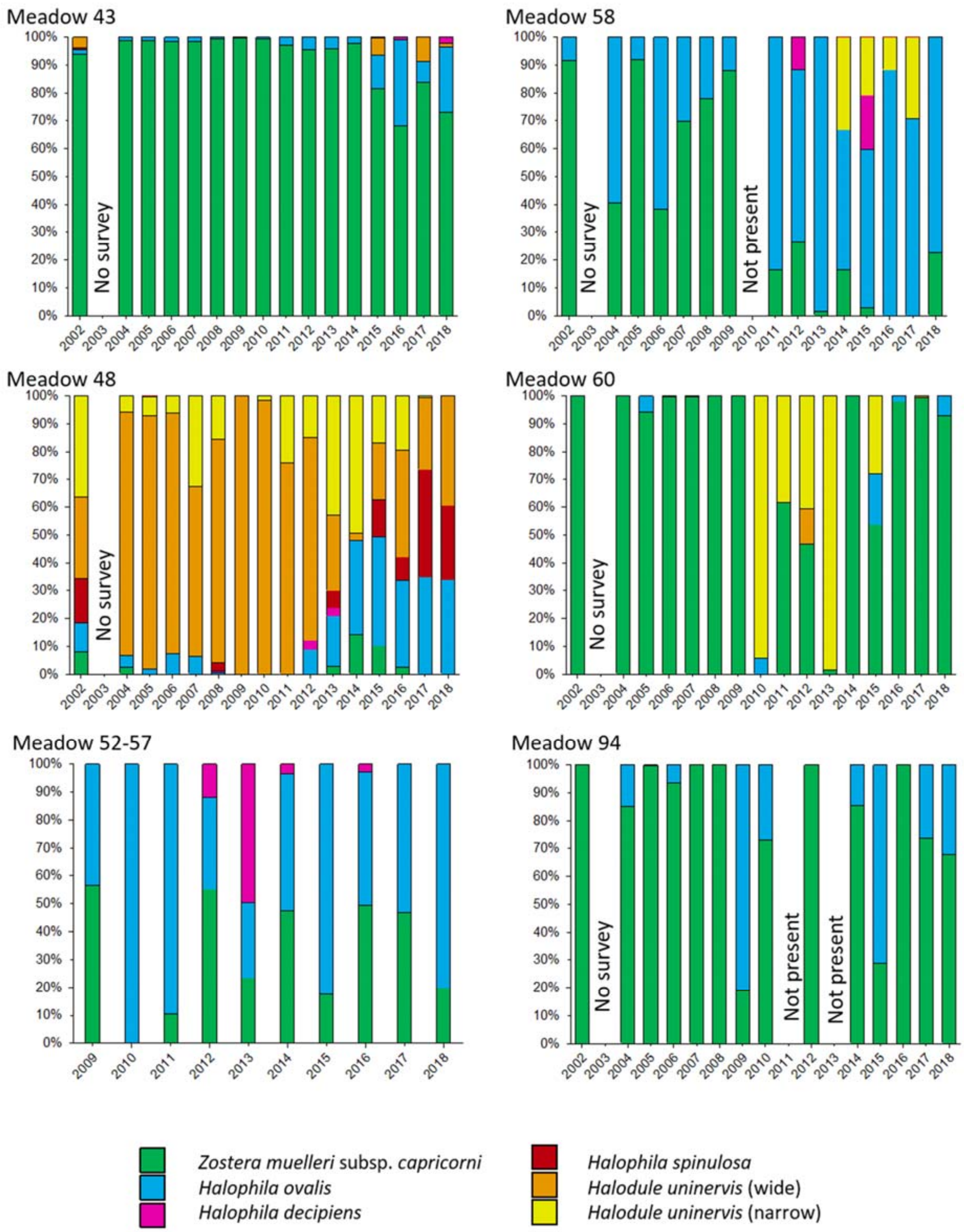
n.a. – biomass not available due to grab sampling

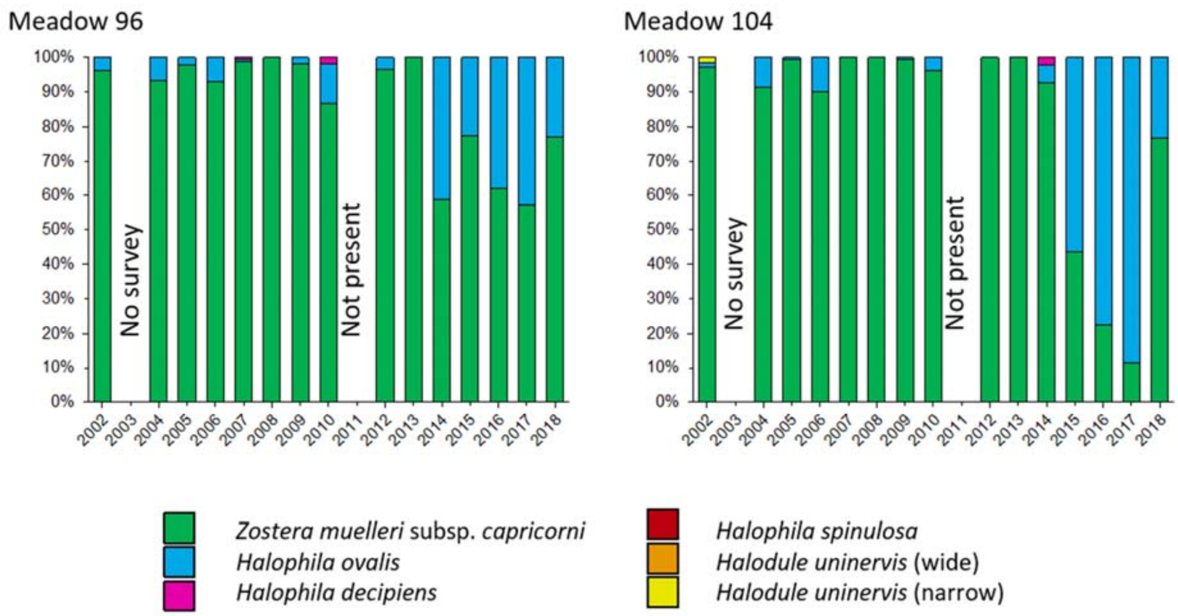
| Meadow ID | Biomass ± SE (g DW m-2) | Area ± R (ha) | Community Type | Landscape Category | Species Present |
|---|---|---|---|---|---|
| **MID HARBOUR ZONE (cont.)** | | | | | |
| 74 | 0.14 | 0.05 ± 0.02 | Light *Halodule uninervis* (thin) | Isolated Patches | *H. uninervis (thin)* |
| 76 - 77 | 8.45 ± 1.44 | 152.94 ± 14.84 | Light *Zostera muelleri* subsp. *capricorni* with mixed species | Continuous Cover | *Z. muelleri, H. uninervis (wide and narrow), H. ovalis* |
| 78 & 89 | 5.98 ± 0.89 | 317.33 ± 86.84 | Light *Halodule uninervis* (thin) | Aggregated Patches | *H. uninervis (thin and wide), H. ovalis, H. decipiens* |
| 137 | 27.58 ± 8.62 | 7.67 ± 1.15 | Moderate *Zostera muelleri* subsp. *capricorni* | Continuous Cover | *Z. muelleri, H. ovalis* |
| 165 | 8.58 ± 3.1 | 0.43 ± 0.21 | Light *Zostera muelleri* subsp. *capricorni* | Isolated Patches | *Z. muelleri* |
| 177 | 4.15 ± 2.49 | 21.13 ± 3.57 | Mixed species | Aggregated Patches | *H. ovalis, H. uninervis (wide and thin)* |
| **SOUTH TREES INLET ZONE** | | | | | |
| 60 | 8.01 ± 1.77 | 9.57 ± 0.67 | Light *Zostera muelleri* subsp. *capricorni* | Aggregated Patches | *Z. muelleri, H. ovalis* |
| 142 | 2.09 ± 1.54 | 5.13 ± 1.4 | Moderate *Halophila ovalis* with mixed species | Aggregated Patches | *H. ovalis, H. decipiens, Z. muelleri* |
| 145 | 3.34 ± 1.78 | 0.29 ± 0.1 | Moderate *Halophila ovalis* | Aggregated Patches | *H. ovalis* |
| 149 | 3.47 ± 1.68 | 1.2 ± 0.49 | Moderate *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 154 | 1.06 | 0.13 ± 0.03 | Moderate *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 159 | 0.82 | 0.1 ± 0.03 | Light *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| 172 | n.a. | 0.13 ± 0.03 | Light *Halophila ovalis* | Isolated Patches | *H. ovalis* |
| **RODDS BAY ZONE** | | | | | |
| 94 | 3.29 ± 1.15 | 2.1 ± 0.3 | Light *Zostera muelleri* subsp. *capricorni* with *Halophila ovalis* | Isolated Patches | *Z. muelleri, H. ovalis* |
| 96 | 6.84 ± 1.55 | 355.08 ± 11.74 | Light *Zostera muelleri* subsp. *capricorni* with *Halophila ovalis* | Aggregated Patches | *Z. muelleri, H. ovalis* |
| 104 | 1.99 ± 0.64 | 17.29 ± 3.91 | Light *Zostera muelleri* subsp. *capricorni* with *Halophila ovalis* | Isolated Patches | *Z. muelleri, H. ovalis* |

n.a. – biomass not available due to grab sampling

## Appendix 4. Detailed species composition, 2002–2018




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
Zostera muelleri subsp. capricorni
Halophila ovalis
Halophila decipiens
Halophila spinulosa
Halodule uninervis (wide)
Halodule uninervis (narrow)


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