Seagrasses in Port Curtis and Rodds Bay 2022
Annual long-term monitoring

March 2023 | Report No. 23/19

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Seagrasses in Port Curtis and Rodds Bay 2022

Annual long-term monitoring survey

A report for Gladstone Ports Corporation

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The report may be cited as
Smith T.M., Reason C., Firby L. and Rasheed M.A. (2023) Seagrasses in Port Curtis and Rodds Bay 2022 Annual long-term monitoring. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 23/19, James Cook University, Cairns, 51 pp.

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Acknowledgments:
This project was funded by Gladstone Ports Corporation Ltd. We wish to thank the many TropWATER staff for their valuable assistance in the field, laboratory and data processing.

KEY FINDINGS

Seagrass Condition 2022

Satisfactory

1. Seagrasses in Port Curtis and Rodds Bay were surveyed from the 7th – 17th of October 2022 as part of a long-term annual monitoring program.

2. Overall, seagrass condition was satisfactory after three years of good condition.

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

4. All meadows in the Western Basin, the Narrows and South Trees Inlet were in good or very good condition, except for one ephemeral deep-water meadow (Meadow 7) and Meadow 8 north of Fisherman's Landing that were in satisfactory condition.

5. Seagrass meadows in the Inner Harbour and Mid Harbour were in poor or very poor condition, with the exception of the meadow at Quoin Island (Meadow 48) which was in good condition.

6. The large Pelican Banks meadow adjacent to Curtis Island decreased in biomass and was in poor condition after being in satisfactory condition in 2021.

7. The declines in seagrass were not confined to port areas with the out of port reference meadows in Rodds Bay also in poor condition, pointing to regional drivers of change.

8. Above average rainfall and average river flow likely led to less favourable seagrass growing conditions and contributed to declines in seagrass biomass and condition in some meadows.

IN BRIEF

Seagrass monitoring in Port Curtis and Rodds Bay commenced in 2002 and has been conducted annually since 2004. Fourteen monitoring meadows are assessed annually and the condition of the meadows evaluated based on variations in three key seagrass metrics - biomass, area and species composition. The current program has been developed to meet Gladstone Port Corporation's obligations pertaining to the Long-Term Maintenance Dredging Management Plan and includes annual mapping and monitoring of 14 coastal seagrass monitoring meadows and five-yearly mapping of all coastal and deep water seagrass in Port Curtis and Rodds Bay. Monitoring meadows represent the range of different seagrass community types in Port Curtis and Rodds Bay (Figure 1) and every five years all seagrasses within the greater port limits are reassessed (last done in 2019).

Overall, seagrass condition in 2022 was satisfactory. Seagrass has been in good condition for the previous three years and declines in seagrass biomass particularly in the Inner Harbour and Rodds Bay have driven the change in condition. In 2022, seven of the fourteen individual monitoring meadows were rated as being in good or very good condition (Figures 2, 3 and section 3 for more details). In the Western Basin and north to the Narrows, seagrass remained in good condition with five of the seven monitoring meadows in these zones in good or very good condition. Outside the Western Basin, only the meadows at Quoin Island (Meadow 48) and at South Trees Inlet (Meadow 60) were in good condition despite a large (> 10 g DW m^{-2}) decrease in biomass at this meadow. All three monitoring meadows in the out of port reference area at Rodds Bay were in poor condition as a result of decreases in biomass. The seagrass meadow at the Inner Harbour (Meadow 58) was in very poor condition due to a large decrease in biomass and the absence of persistent seagrass *Zostera muelleri* spp. *capricorni* in the meadow. Seagrass in Port Curtis and Rodds Bay was in poor condition from 2010 until 2017 following widespread seagrass losses in 2009-10 resulting from high rainfall and flooding events associated with extended La Niña weather conditions. Decreases in seagrass biomass, area and changes in species composition in 2022 are likely related to local weather events. Rainfall and river flow from the Calliope River in the 12 months prior to the 2022 survey were higher than the previous four years and annual rainfall was the highest since 2012/13. Higher than average rainfall can lead to reductions in benthic light and impact the capacity for seagrass to grow, leading to decreases in biomass and changes in seagrass condition.

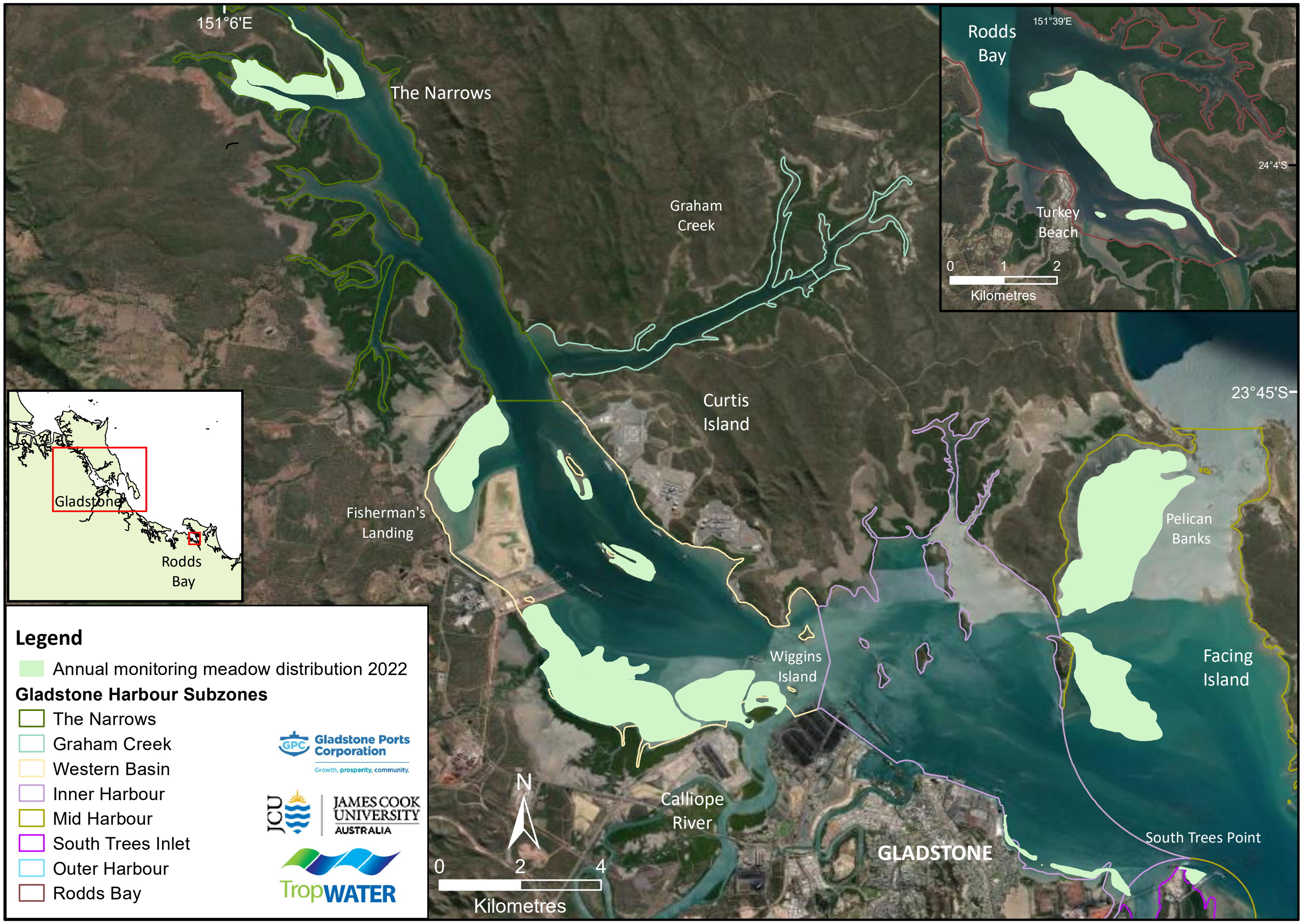
The seagrass meadow at Pelican Banks is historically the largest and highest biomass meadow in the Port Curtis and Rodds Bay region. In 2022, the meadow returned to being in poor condition after being in satisfactory condition in 2021. Both biomass and species composition decreased after reaching seven year peaks in 2021. With the exception of 2021, this meadow has had poor or very poor biomass since 2015 and undergone a reduction of the foundation species *Z. muelleri* over the six years prior to 2021 and once again in 2022. Loss of biomass and changes in species composition in this meadow are potentially linked to grazing by megaherbivores (green turtles and dugongs). Turtle and dugongs were commonly sighted during the survey, and Dugong Feeding Trails (DFTs) were common in the Western Basin and Pelican Banks. Seagrass losses in Hervey Bay from flooding events in early 2022 may have forced megaherbivores to migrate to Gladstone and this influx may have contributed to some of the observed declines in biomass at Pelican Banks and elsewhere in the survey. Direct measures of herbivory pressure were not carried out as part of this study.

Changes in the benthic light environment, including those associated with dredge plumes, can impact seagrass condition leading to losses in biomass and cover (Chartrand et al. 2018). However, the amount and period of light reduction required to create impacts means that dredging activity can generally be managed in a way that protects seagrasses from light related loss (Chartrand et al 2018), particularly for shorter duration maintenance programs. Annual maintenance dredging occurs within the Port of Gladstone each year in channels and facilities adjacent to seagrass meadows. Modelling and impact assessment of maintenance dredging plumes as well as plume field studies have been carried out in the Port of Gladstone (BMT 2017; 2019). These studies have shown dredging plumes can increase turbidity leading to reduced benthic light, but these conditions are short lived relative to ambient conditions (BMT 2017, 2019; Vision Environment 2021).

Results of this monitoring program show that in 2022 seagrass meadows closest to maintenance dredge activity were in good condition and in better condition than meadows in the out of port reference area in Rodds Bay.

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

Figure 1. Seagrass distribution in Port Curtis and Rodds Bay monitoring meadows in November 2022.



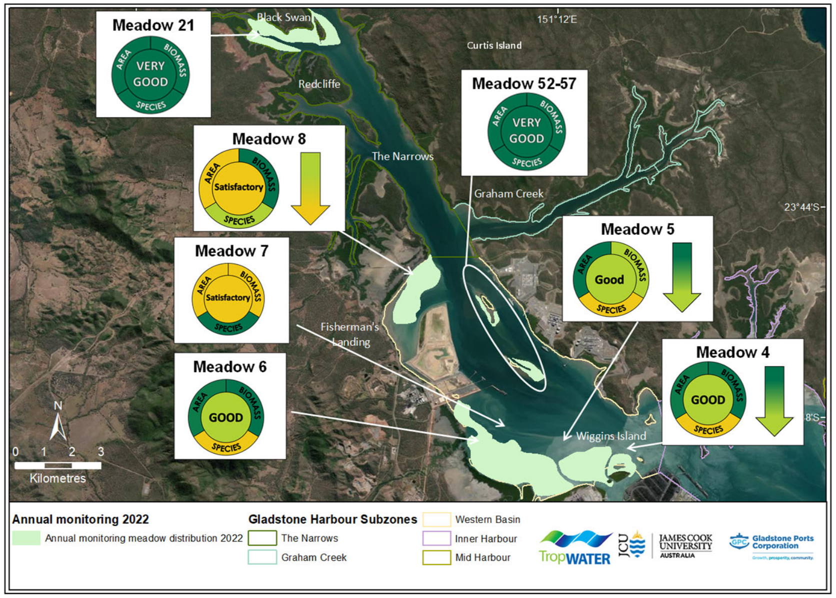


Figure 2. Seagrass distribution and meadow condition in The Narrows and Western Basin zones (Port Curtis), November 2022. Arrows indicate overall grade change from 2021.

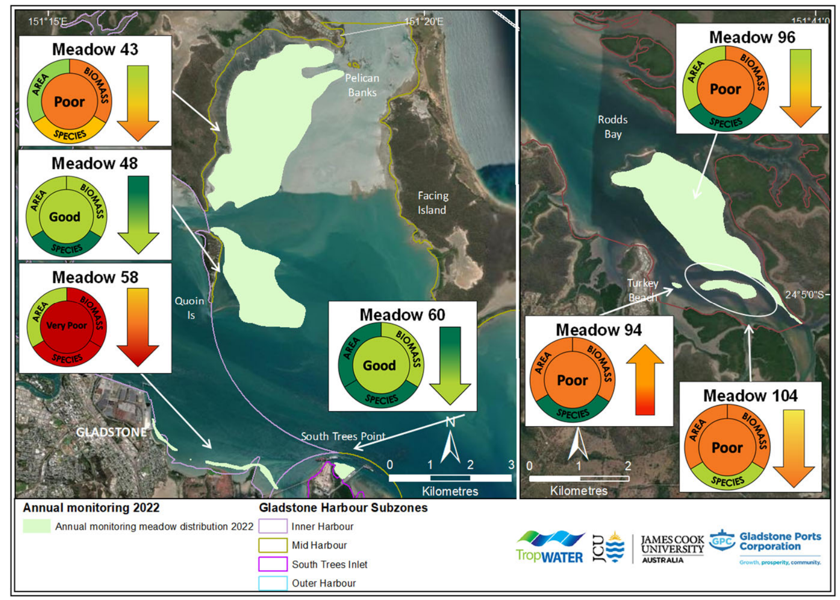


Figure 3. Seagrass distribution and meadow condition in the Inner Harbour, Mid Harbour, and South Trees Inlet zones (Port Curtis), and Rodds Bay, November 2022. Arrows indicate an overall grade change from 2021.

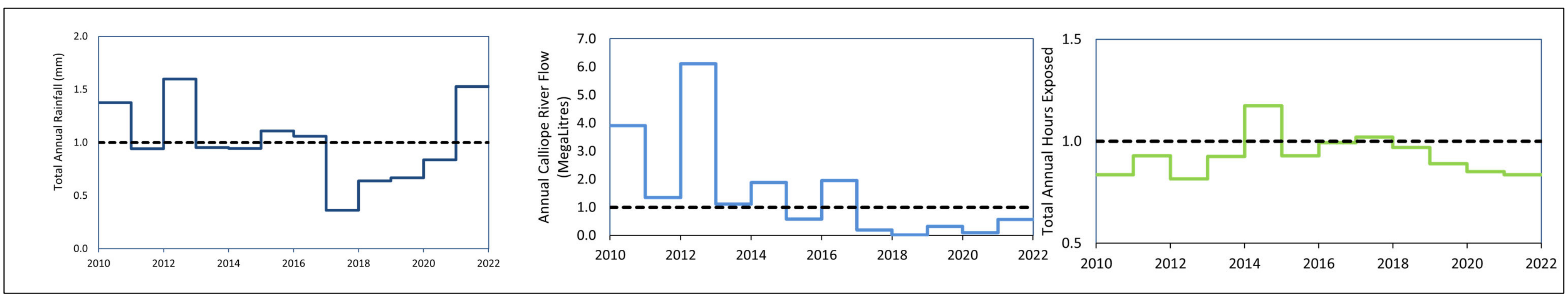


Figure 4. Climate trends in Port Curtis, 2010 to 2022. Change in climate variables as a proportion of the long-term average. See section 3.3 for detailed climate data for the Gladstone region.

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ACRONYMS AND ABBREVIATIONS

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

1 INTRODUCTION

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

1.1 Queensland ports seagrass monitoring program

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

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

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

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

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

1.2 Port Curtis and Rodds Bay seagrass monitoring program

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

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

The annual monitoring program has been adapted over the years in response to infrastructure developments within the port area including the Western Basin Dredging and Disposal Project (WBDDP) a capital dredging and development project that ran from 2011 to 2013. Adaptations and additions included:

1. Survey expansion to include all intertidal and shallow subtidal seagrass in the Port Curtis monitoring area from 2009-2018.
2. Two monitoring meadows (Meadows 21 and 52-57) added to the program in 2009 due to port developments in the Curtis Island area.
3. One meadow (Meadow 9) removed from the monitoring program in 2011 due to the Western Basin reclamation area's expansion at Fisherman's Landing.
4. All seagrass from The Narrows to Rodds Bay periodically remapped, extending into deep water and to offshore Port Curtis limits, in 2002, 2009, 2013, 2014 and 2019 (Smith et al. 2020; Carter et al. 2015; Bryant et al. 2014b; Thomas et al. 2010).
5. Monitoring of seagrass reproduction and seed banks at Pelican Banks, Rodds Bay and Wiggins Island between 2009 and 2016 (Reason et al. 2017a).

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

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

Annual monitoring and the additional programs have demonstrated inter- and intra-annual variability in seagrass meadow biomass, area and species composition in the region. Seagrass condition varies according to regional and local climate and weather conditions (Chartrand et al. 2019). Climate induced inter-annual variability is common throughout tropical seagrass meadows of the Indo-Pacific (Agawin et al. 2001). Seagrasses are also highly seasonal. Gladstone seagrass has two broad seasons; the growing season (July – January) when meadows typically increase in biomass and area in response to favourable conditions for growth; and the senescent season (February – June) when meadows typically retract and rely on carbohydrate stores or seeds to persist following wet season conditions such as flooding, poor water quality and light reductions (Chartrand et al. 2016). Annual monitoring is scheduled to coincide with the growing season when seagrass meadows are generally at their peak.

High rainfall, river outflow and tropical cyclones from the 2009/2010 and 2010/2011 La Niña led to significant seagrass losses in Port Curtis and Rodds Bay and more broadly across North East Queensland (Chartrand et al. 2019; McKenna et al. 2015; Rasheed et al. 2014). In extreme cases, such as in Rodds Bay, meadows were temporally lost (Rasheed et al. 2012; Carter et al. 2015). Recovery has been slow in many regions and many meadows in Port Curtis and Rodds Bay were in poor or very poor condition from 2011-2014 (Chartrand et al. 2019). Favourable climate conditions such as low rainfall and river outflow saw an improvement in meadow condition over the last 3-5 years, culminating in most meadows returning to near or above long-term average for condition indicators since 2019 (Smith et al. 2022). In this report we update seagrass condition for the 14 established monitoring meadows in 2022.

2 METHODS

2.1 Field surveys

Survey and monitoring methods followed the established techniques for TropWATER's Queensland-wide seagrass monitoring programs. Detailed methods used in Gladstone are in previous reports (Rasheed et al. 2005; Rasheed et al. 2003). Seagrass was surveyed 7th – 17th October 2022 during the peak seagrass growth period. Standardising surveys to every October-December allows for appropriate comparisons of seagrass condition among years. This survey involved mapping and assessing the 14 long-term monitoring meadows within Port Curtis and Rodds Bay.

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

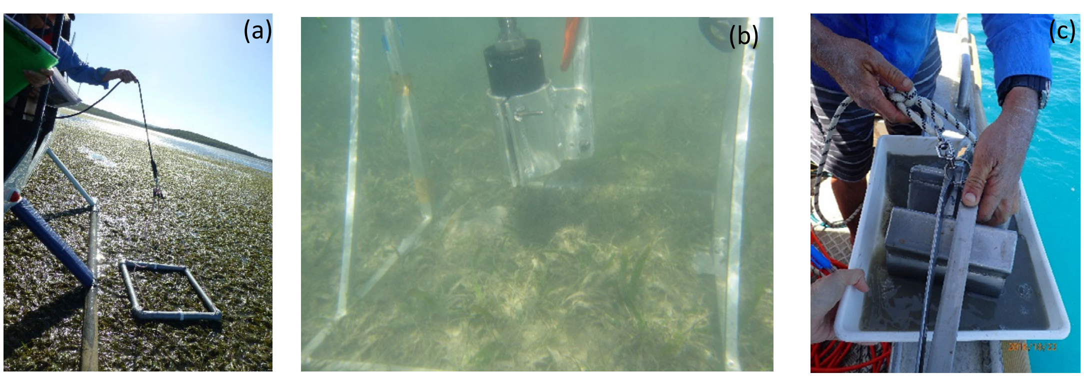


Figure 6. Seagrass monitoring methods in 2022. (a) helicopter survey of intertidal seagrass, (b, c) boat-based camera drops and van Veen grab for subtidal seagrass.

2.2 Seagrass biomass

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

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

2.3 Geographic Information System

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

2.3.1 Site layer

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

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

2.3.2 Interpolation layer

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

2.3.3 Meadow layer

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

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

Meadow boundaries were constructed using GPS marked meadow boundaries where possible, seagrass presence/absence site data, field notes, colour satellite imagery of the survey region (Source: ESRI), and aerial photographs taken during helicopter surveys. Meadow area was determined using the calculate geometry function in ArcGIS® 10.8. Meadows were assigned a mapping precision estimate (in metres) based on mapping methods used for that meadow (Table 1). Mapping precision ranged from ≤5 m for intertidal seagrass meadows with boundaries mapped by helicopter to ±50 m for subtidal meadows with boundaries mapped by distance between sites with and without seagrass. The mapping precision estimate was used to calculate a buffer around each meadow representing error; the area of this buffer is expressed as a meadow reliability estimate (R) in hectares.

Meadows were described using a standard nomenclature system developed for Queensland's seagrass meadows. Seagrass community type was determined using the dominant and other species' percent contribution to mean meadow biomass (for all sites within a meadow) (Table 2). Community density was based on mean biomass of the dominant species within the meadow (Table 3).

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

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

Table 2. Nomenclature for seagrass community types in Gladstone.

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

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

Density	Mean above-ground biomass (g DW m^{-2})				
	Halodule uninervis (thin)	*Halophila ovalis; Halophila decipiens*	*Halodule uninervis* (wide)	*Halophila spinulosa*	*Zostera muelleri* spp. *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.

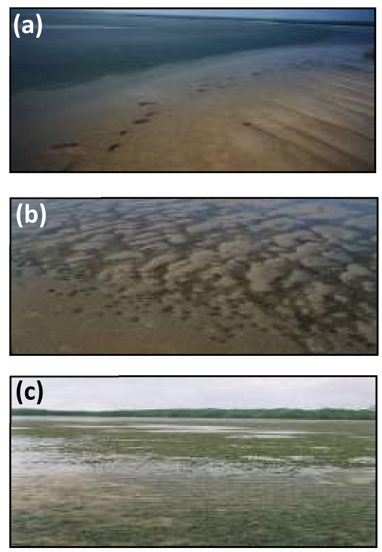


Figure 7. Seagrass meadow landscape categories: (a) Isolated seagrass patches, (b) aggregated seagrass patches, (c) continuous seagrass cover.

2.4 Environmental data

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

2.5 Seagrass condition index

A condition index was developed for seagrass monitoring meadows based on changes in mean above-ground biomass, total meadow area and species composition relative to a ten year baseline (see Carter et al. 2023 for full details). Seagrass condition for each indicator in each meadow was scored from 0 to 1 and assigned one of five grades: A (very good), B (good), C (satisfactory), D (poor) and E (very poor). Overall meadow condition is the lowest indicator score where this is biomass or area. Where species composition is the lowest score, it contributes 50% of the overall meadow score, and the next lowest indicator (area or biomass) contributes the remaining 50% (Carter et al. 2023).

3 RESULTS

3.1 Seagrass presence and species in Port Curtis and Rodds Bay

A total of 887 sites were assessed across the 14 seagrass monitoring meadows in 2022 (Figure 9). Four seagrass species from three families were observed during the survey (Figure 10). Total seagrass area was 2,344 ± 62 ha across the 14 monitoring meadows. In the Western Basin, seagrass covered 880 ± 21 ha, slightly lower than in 2021 (1015 ± 43 ha) but Rodds Bay seagrass area was 325 ± 14 ha, lower than in 2021 (382 ± 8 ha) and 2020 (433 ± 18 ha). Dugong feeding trails were observed at meadows 5, 6, 43 and 60 in the Western Basin, Mid Harbour and South Trees zones.

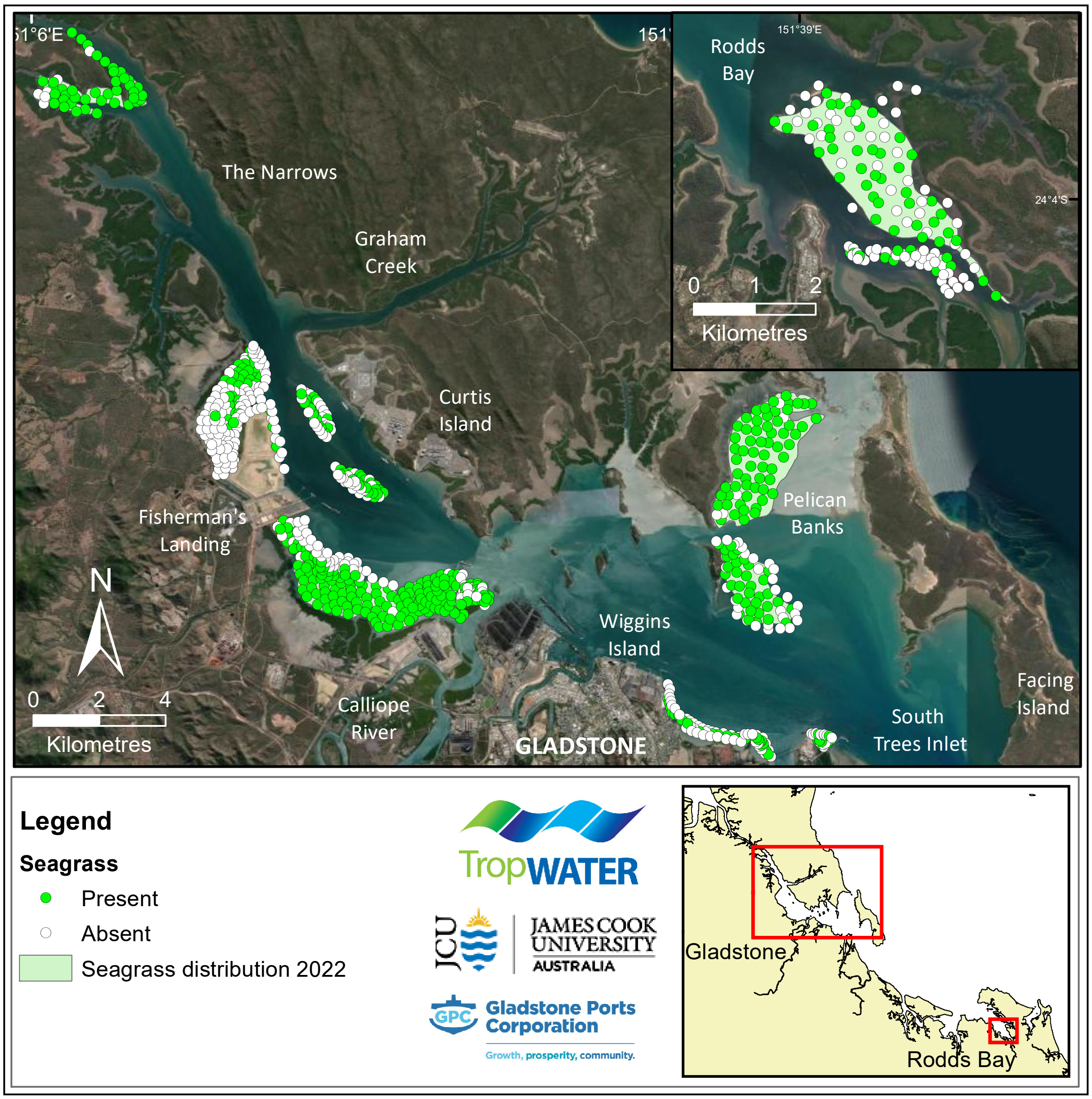


Figure 9. Seagrass presence/absence at seagrass assessment sites within Port Curtis and Rodds Bay in 2022.

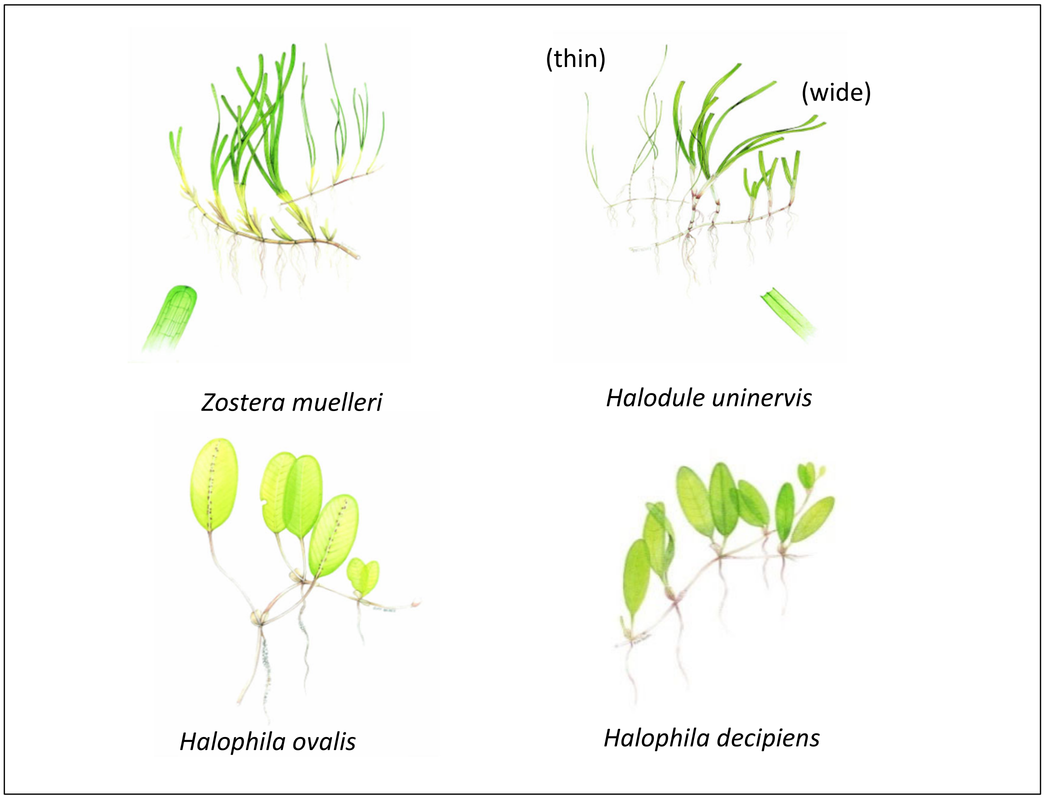


Figure 10. Seagrass species present in Port Curtis and Rodds Bay, 2022.

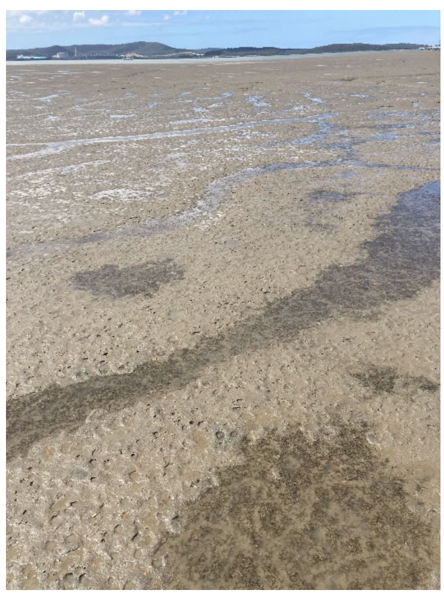


Figure 11. Dugong Feeding Trails on seagrass patches in Meadow 6.

3.2 Seagrass condition in Port Curtis and Rodds Bay

The overall condition for Port Curtis and Rodds Bay seagrass in 2022 was satisfactory after three years of good condition (Table 4). Half of the monitoring meadows were in good or very good condition. Seagrass in the Western Basin and the Narrows remained in generally good condition. There was a general decline in seagrass biomass in monitoring meadows outside the Western Basin resulting in declines in seagrass condition. Meadows at South Trees Inlet and Quoin Island (Meadow 48) remained in good condition despite declines in biomass. The Pelican Banks meadow (Meadow 43) returned to poor condition after improving to satisfactory in 2021 after being in poor condition for the previous six years. All three Rodds Bay meadows were in poor condition including a meadow (Meadow 94) that improved from very poor in 2021 to poor in 2022 after increases in area and species composition. The monitoring meadow at the Inner Harbour (Meadow 58) was in very poor condition after declining to poor in 2021 with both biomass declines and species composition changing to less persistent species.

Port Curtis and Rodds Bay has been partitioned into zones (see Figure 1) for the purposes of assessing water quality and for developing a regional report card (GHHP, 2022). We present the results for the 2022 seagrass monitoring for monitoring meadows in each of the zones.

Table 4. Grades and scores for seagrass indicators (biomass, area and species composition) for Port Curtis and Rodds Bay seagrass monitoring meadows, 2022. = very good condition, = good condition, = satisfactory condition, = poor condition, = very poor condition.

Zone	Monitoring meadow	Biomass score	Area score	Species composition score	Overall meadow score
The Narrows	21	0.93	0.96	0.96	0.93
Western Basin	4	1.00	1.00	0.56	0.78
	5	0.81	1.00	0.64	0.73
	6	0.96	0.87	0.5	0.69
	7	0.58	0.57	1.00	0.57
	8	0.86	0.58	0.76	0.58
	52–57	0.88	0.9	1.00	0.88
Inner Harbour	58	0.21	0.74	0.00	0.11
Mid Harbour	43	0.44	0.82	0.63	0.44
	48	0.71	0.79	0.94	0.71
South Trees Inlet	60	0.81	1.00	1.00	0.81
Rodds Bay	94	0.37	0.3	1.00	0.30
	96	0.46	0.84	0.9	0.46
	104	0.42	0.38	0.82	0.38
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 1).

3.2.1 The Narrows long-term monitoring meadows

The sole long-term monitoring meadow in The Narrows at Black Swan Island was in very good condition for the second year in a row and recorded the highest biomass of all monitoring meadows (Meadow 21; Figure 12). Mean biomass was 16.69 ± 2.05 g DW m^{-2} in 2022, slightly lower than in 2021 (17.52 g DW m^{-2}) when biomass was the greatest since 2009 (Figure 12). Seagrass meadow area covered 193.52 ± 8.25 ha and has remained consistent over the last four years. Species composition remained in very good condition in 2022 and was dominated by *Z. muelleri* (Figure 12; Appendix 4).

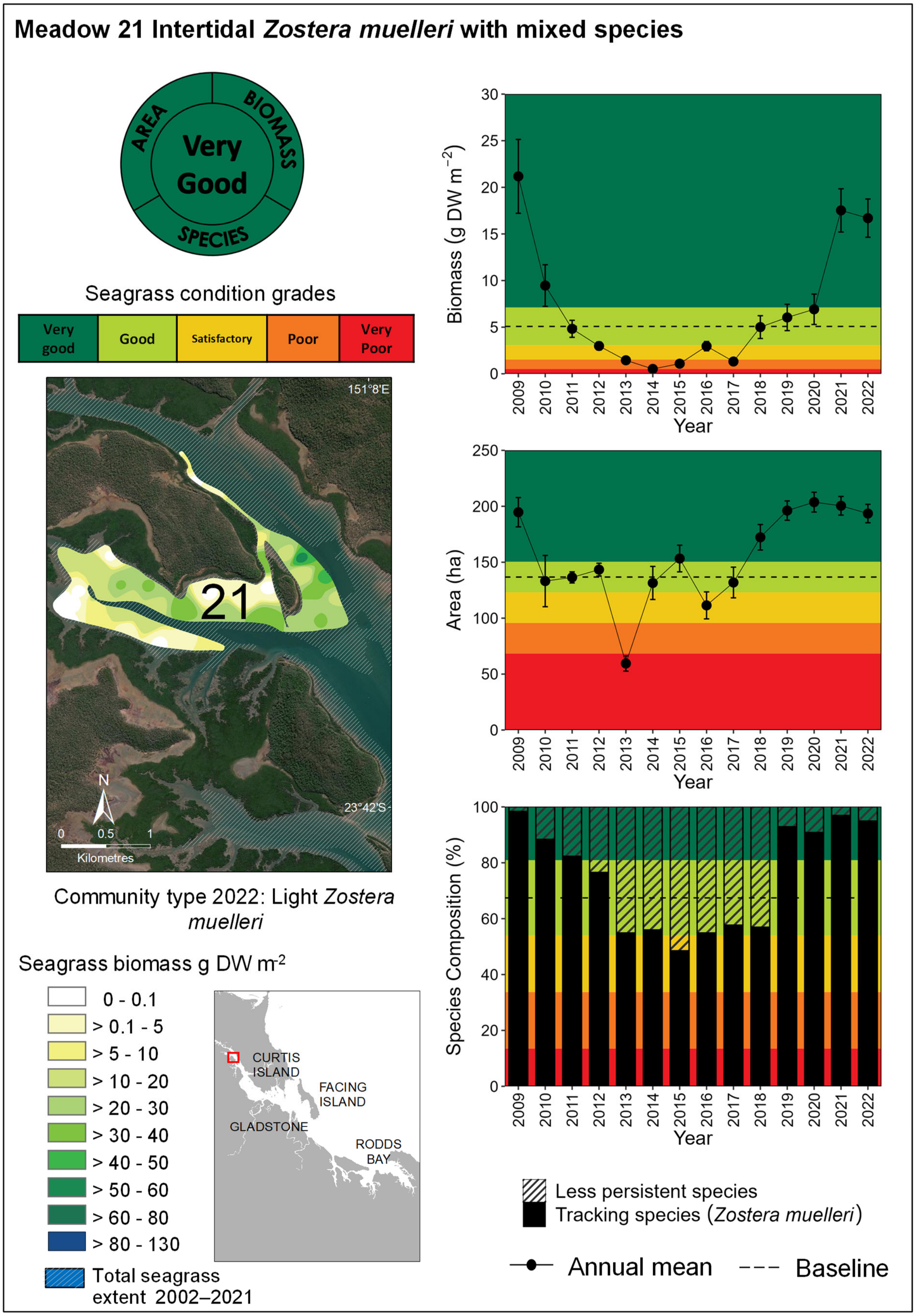


Figure 12. Changes in meadow area, biomass and species composition at Meadow 21, Black Swan (The Narrows Zone), 2009–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.2.2 Western Basin long-term monitoring meadows

There are six long-term monitoring meadows in the Western Basin Zone; five intertidal seagrass meadows and one subtidal meadow (Figures 1-3). All seagrass meadows in this zone were in satisfactory or better condition in 2022.

Meadow 4:

Meadow 4 at Wiggins Island was in good condition after three years in very good condition (Figure 12). Meadow area in 2022 was 45.30 ± 2.10 ha, similar to 2021 when it was 44.80 ± 1.9 ha and the highest since monitoring began in 2002. Meadow biomass continues to be in very good condition for the eleventh year in a row despite a small decline since 2021. Seagrass species composition was satisfactory after three years in very good condition as the persistent *Z. muelleri* has declined with the less persistent *H. ovalis* increasing (Figure 13; Appendix 2).

Meadow 5:

The intertidal *Z. muelleri* meadow west of Wiggins Island was in good condition in 2022 (Figure 13). Biomass in Meadow 5 in 2022 was 3.37 ± 0.56 g DW m^{-2} and was in good condition although lower than 2021 when it was 6.94 ± 0.91 g DW m^{-2} (very good condition) (Figure 13). Meadow area remained in very good condition for the second consecutive year and was one of the highest recorded in 20 years of monitoring. The proportion of persistent *Z. muelleri* in the meadow decreased and was rated satisfactory after three years of being in very good condition (Figure 14; Appendix 2).

Meadow 6:

Meadow 6 at South Fisherman's Landing is the largest meadow in the Western Basin covering 416.87 ± 6.22 ha. Overall meadow condition was good with biomass and area in very good condition. Meadow area recorded similar values to 2021 and biomass increased to 5.99 ± 0.48 g DW m^{-2}, the highest biomass since 2007. The proportion of persistent *Z. muelleri* in the meadow decreased to less than 20% and the meadow was dominated by *H. ovalis* which represented > 80% of the biomass (Figure 15; Appendix 2).

Meadow 7:

Meadow 7, the only subtidal monitoring meadow in the Western Basin, was in satisfactory condition for the third year in a row (Figure 15). This meadow has been highly variable in both biomass and area over the years, a typical trend of subtidal *Halophila* meadows. While seagrass biomass has been consistent for the past three years, meadow area has decreased to 31.48 ± 2.60 ha, less than half what it was in 2021 (77.23 ± 23.37 ha) (Figure 16; Appendix 1, 2). Species composition was in very good condition as only *H. decipiens* and more persistent species *H. ovalis* were recorded.

Meadow 8:

The intertidal Meadow 8 at North Fisherman's Landing was in satisfactory condition in 2022. Meadow biomass 1.68 ± 0.47 g DW m^{-2} was in very good condition for the eighth consecutive year. Meadow area covered 175.43 ± 3.19 ha in 2022 and was in satisfactory condition after three years in good condition (Figure 17). Species composition was similar to 2021 where meadow biomass consisted predominantly of *Z. muelleri* (68%) and remained in good condition (Figure 17).

Meadows 52-57:

The Passage Island meadows; Meadows 52-57, are a group of predominantly intertidal meadows surrounding the Passage Islands. In 2022 overall meadow condition was in very good condition for the second year in a row (Figure 18). Biomass increased slightly to 2.04 ± 0.53 g DW m^{-2} from 1.86 ± 0.42 g DW m^{-2} in 2021 and was in very good condition in both years. Meadow area and species composition were very similar to 2021 and were both in very good condition despite a small decline in area. Meadow biomass consisted predominantly of the persistent *Z. muelleri*, which represented 63% of meadow biomass, while *H. ovalis*, the species representative of the meadow, accounted for 31% of meadow biomass (Figure 18).

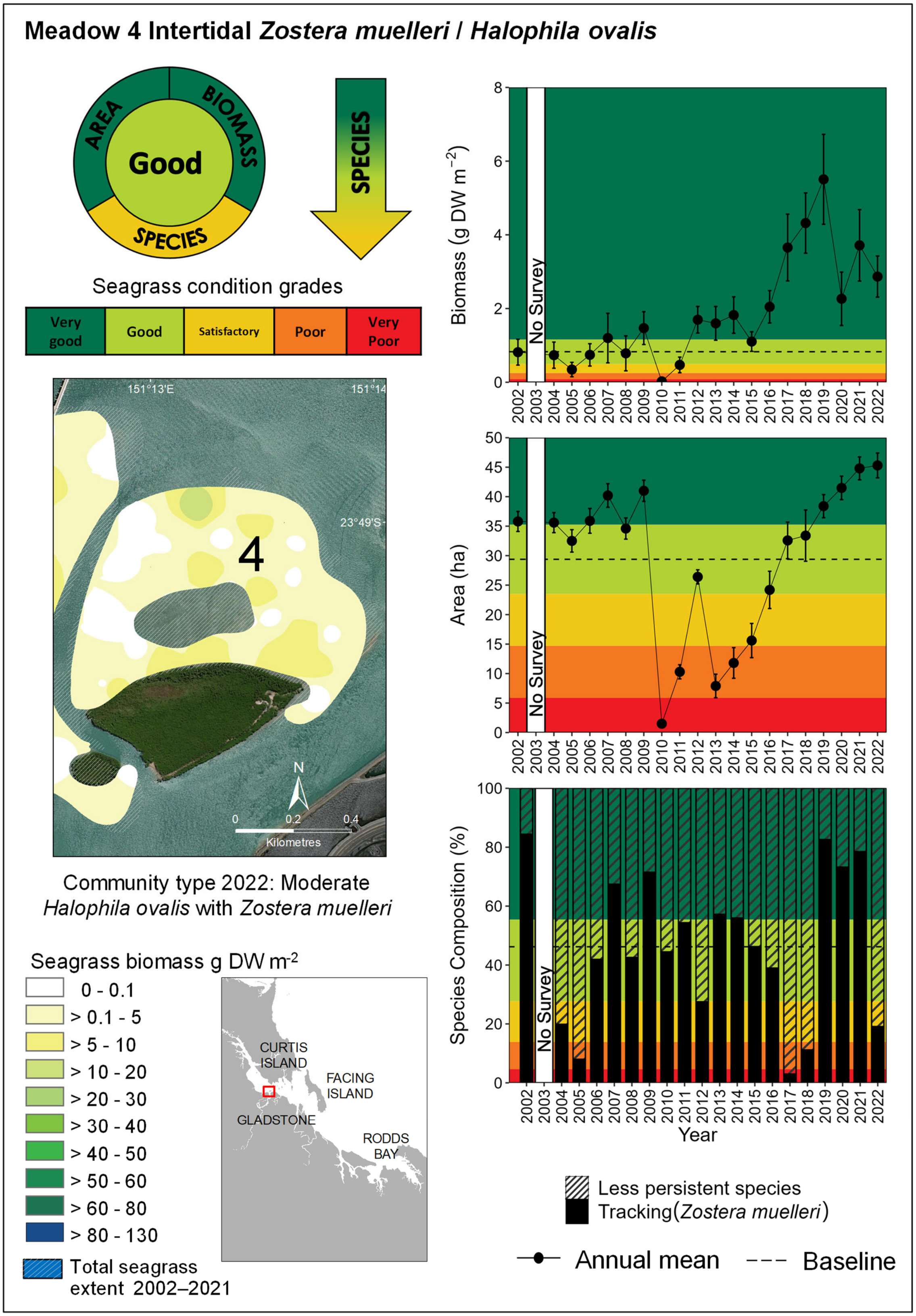


Figure 13. Changes in meadow area, biomass and species composition for Meadow 4, Wiggins Island (Western Basin Zone), 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

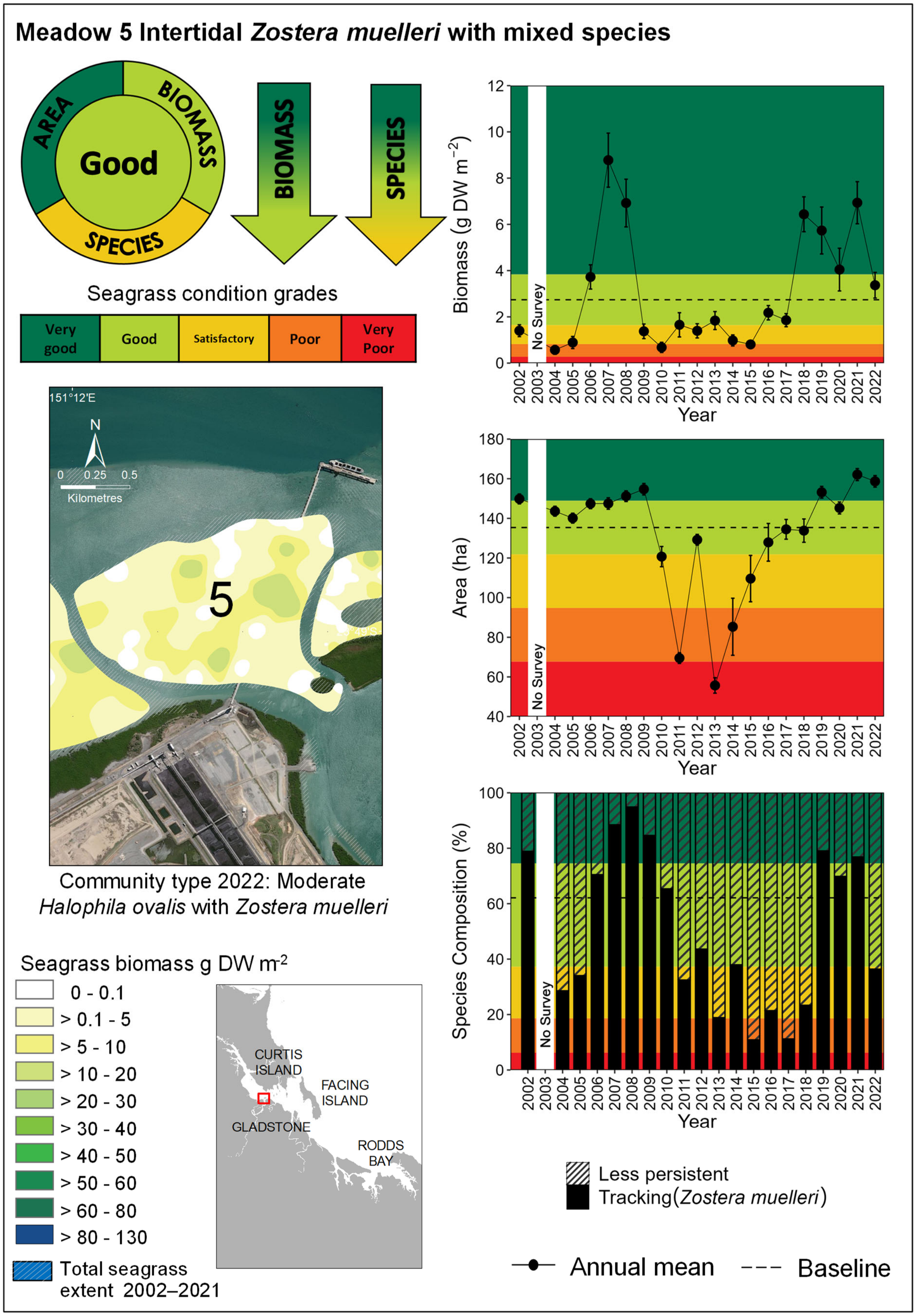


Figure 14. Changes in meadow area, biomass and species composition for Meadow 5, Wiggins Island (Western Basin Zone), 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

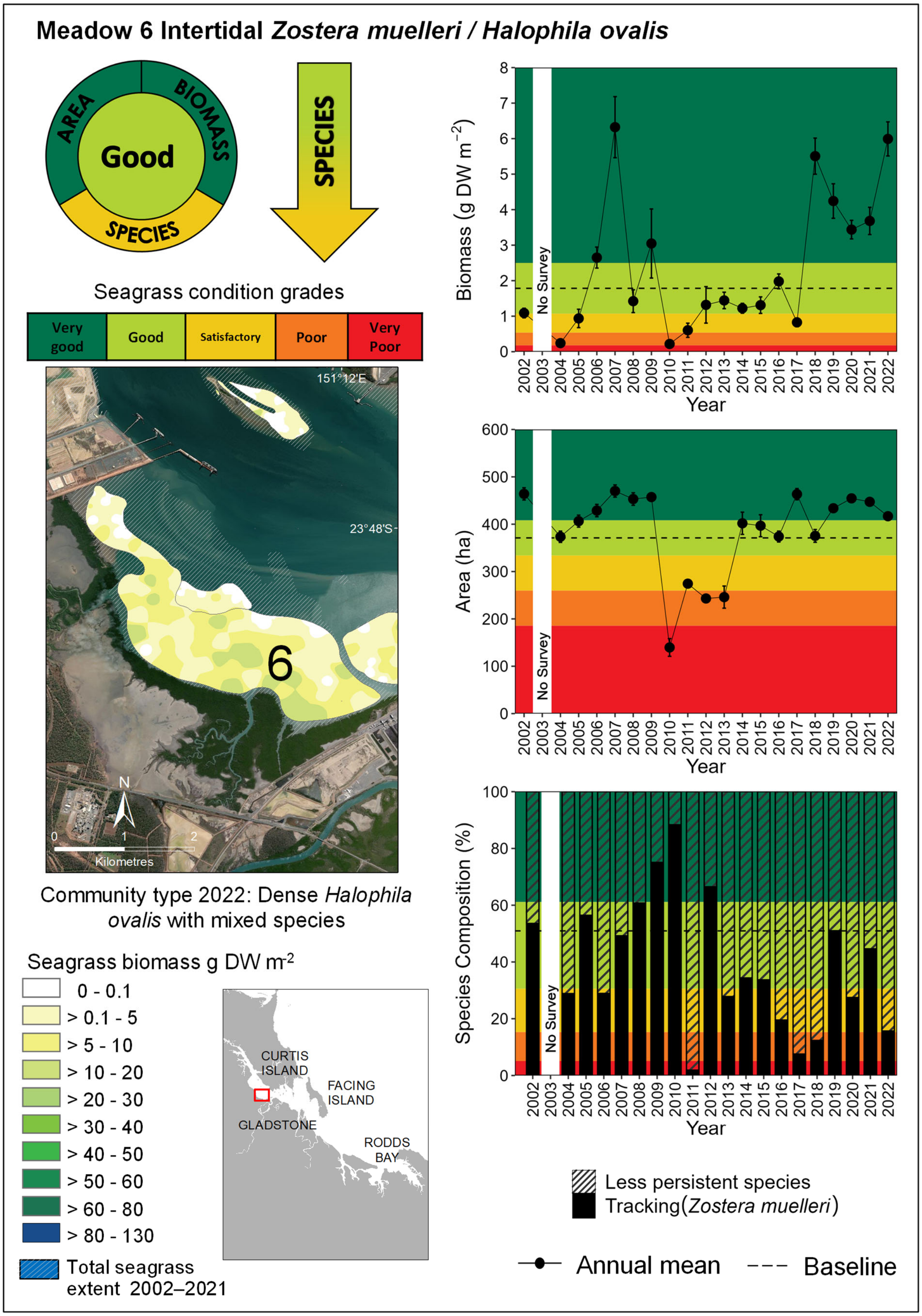


Figure 15. Changes in meadow area, biomass and species composition for Meadow 6, South Fisherman's Landing (Western Basin Zone), 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

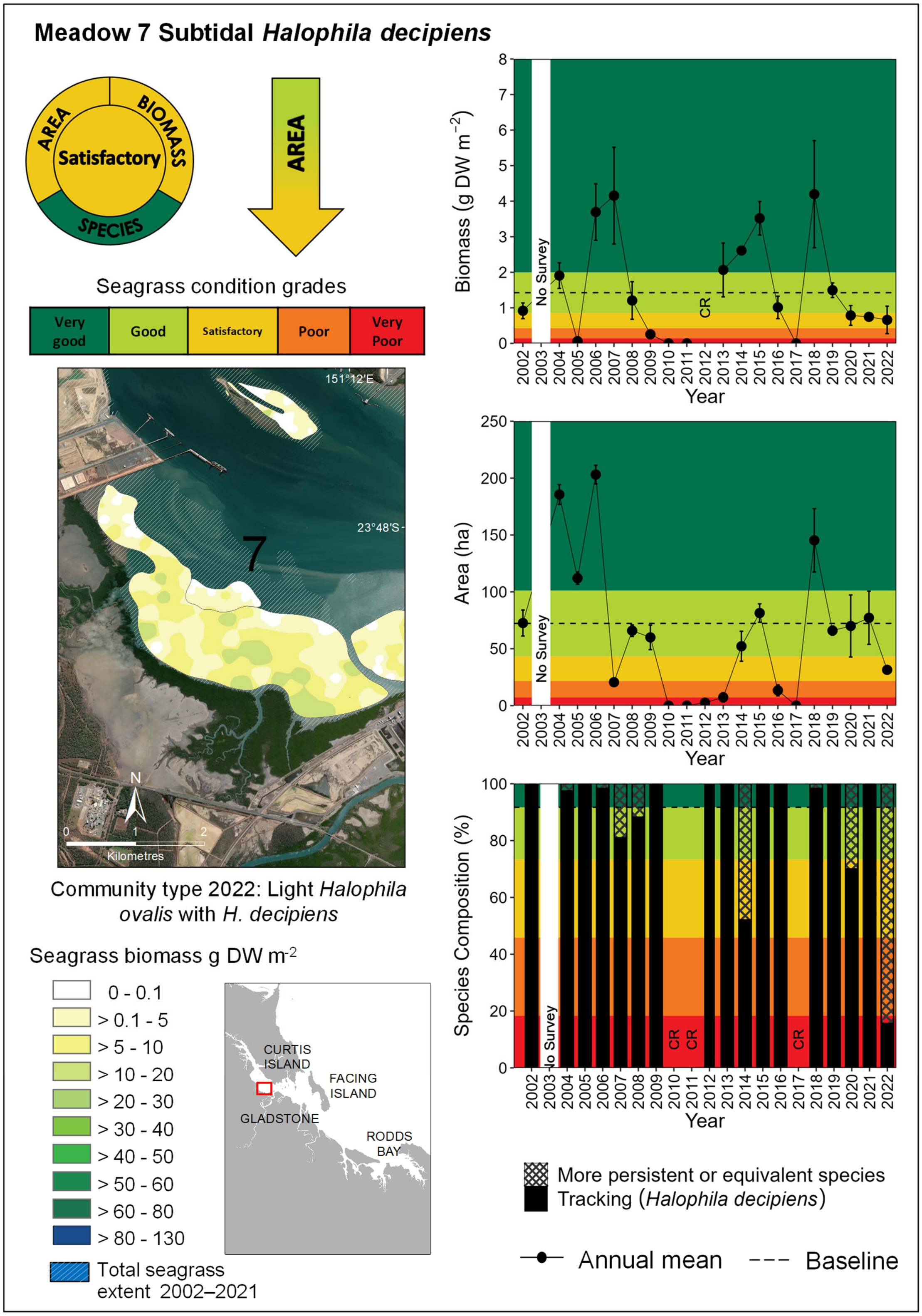


Figure 16. Changes in meadow area, biomass and species composition for Meadow 7, South Fisherman's Landing (Western Basin Zone), 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate). CR = calculation restriction due to the absence of seagrass (species composition) or biomass observations.

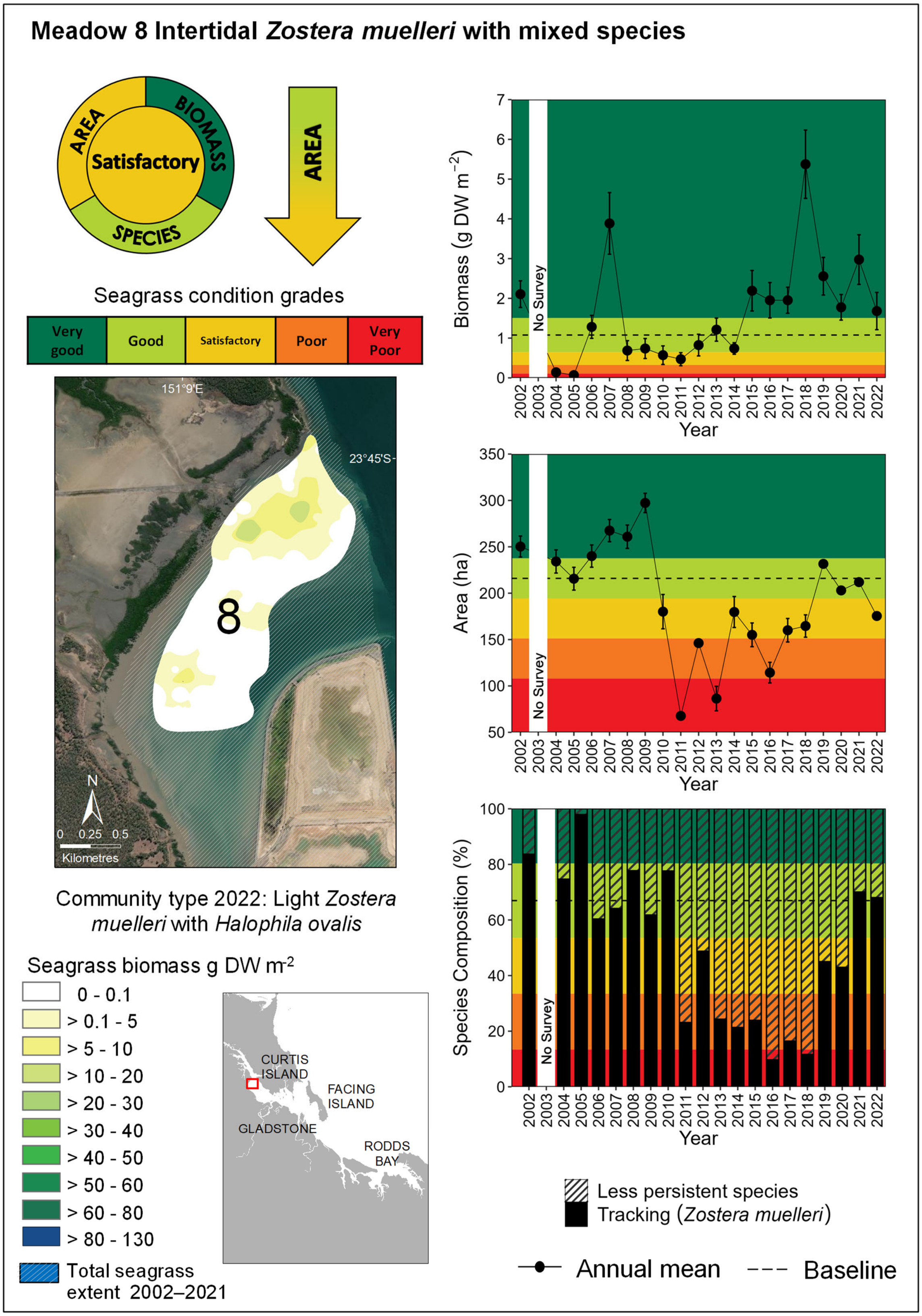


Figure 17. Changes in meadow area, biomass and species composition for Meadow 8, North Fisherman's Landing (Western Basin Zone), 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

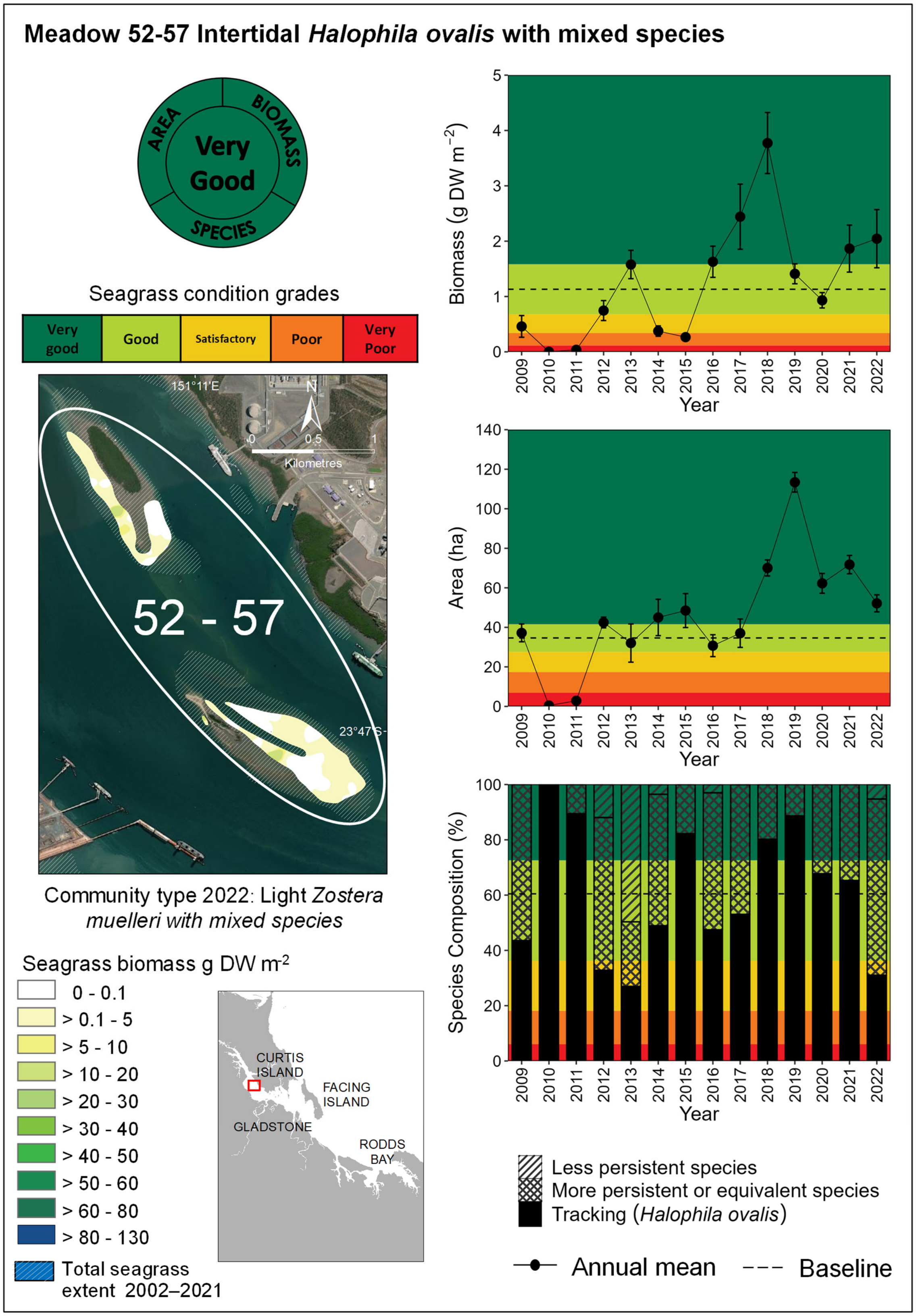


Figure 18. Changes in meadow area, biomass and species composition for Meadows 52-57, Passage Islands (Western Basin Zone), 2009–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.2.3 Inner Harbour long-term monitoring meadows

There is a single monitoring meadow at the Inner Harbour that stretches along the intertidal bank west from the mouth of the Calliope River as a narrow strip (Meadow 58; Figure 19).

Meadow 58

Seagrass meadow condition was very poor in 2022 after being in poor condition in 2021. It is the first time the meadow has been in very poor condition since 2018 (Figure 20). Biomass has declined from 2.24 ± 0.24 g DW m^{-2} and in good condition in 2021 to 0.17 ± 0.12 g DW m^{-2} and very poor condition in 2022. There was also a decline in meadow area from 2021 but this was still in good condition and just below the long term baseline. Species composition was very poor for the second year in a row, with no persistent *Z. muelleri* recorded in the meadow (Figure 20). Historically, species composition within meadow 58 fluctuates and has been very poor in six of the last ten years (Figure 20; Appendix 2).

3.2.4 Mid Harbour long-term monitoring meadows

There are two monitoring meadows in the Mid Harbour Zone, a large intertidal meadow on Pelican Banks (Meadow 43; Figure 21), and a subtidal meadow along the eastern side of Quoin Island (Meadow 48; Figure 22).

Meadow 43:

Meadow 43 is recognised as the largest, most productive, and most stable seagrass meadow in Port Curtis based on a 20-year monitoring dataset. In 2022, the meadow's overall score returned to poor condition after being satisfactory in 2021 following six years of being in poor or very poor condition (Figure 21). Meadow 43 covered an area of 648.93 ± 6.87 ha and was very similar to 2021 when it covered 646.07 ha and was in good condition both years. Meadow area has been above the long-term baseline for the last four years. Meadow biomass was 7.93 ± 0.75 g DW m^{-2} in 2022 lower than in 2021 when it was 10.75 g DW m^{-2} but higher than in 2019 and 2020. Species composition was in satisfactory condition in 2022 after being good in 2021 as the proportion of the persistent *Z. muelleri* recorded in the meadow declined to 75% from 91% in 2021 (Figure 21; Appendix 2).

Meadow 48:

Meadow 48 is a predominantly subtidal meadow on the eastern side of Quoin Island. Overall meadow condition was good for the second consecutive year (Figure 22). Both meadow area and species composition were similar to 2021. Meadow area was in good condition for the third year in a row and above the ten-year baseline. Species composition continued to be very good for the third year in a row and was dominated by *H. uninervis* (Figure 22). There was a decrease in biomass from 3.83 ± 0.42 g DW m^{-2} in 2021 to 2.27 ± 0.40 g DW m^{-2} in 2021 but was still rated in good condition.

3.2.5 South Trees Inlet long-term monitoring meadows

Meadow 60, the only monitoring meadow in this zone and is located between the two wharves at South Trees Inlet (Figure 23). The intertidal meadow traditionally consists of continuous *Z. muelleri*.

Meadow 60

The intertidal meadow was in good condition after five years of being in very good condition (Figure 21). Seagrass in Meadow 60 has had continuous cover over the last five years but in 2022 consisted of aggregated or isolated low biomass patches (Figure 19). There was a large decline in biomass from 18.22 g DW m^{-2} in 2021 to 4.73 ± 0.69 g DW m^{-2} in 2022. Biomass in 2021 was the highest recorded in the meadow and despite the large decline biomass was still considered in good condition and remained above the long-term baseline. (Figure 21). The meadow was comprised nearly entirely of the persistent *Z. muelleri,* and species composition was very good for the seventh year in a row (Figure 21).

Figure 19. Seagrass cover at Meadow 60 in 2022 (left) and 2021 (right) when biomass was the highest recorded across all monitoring years.

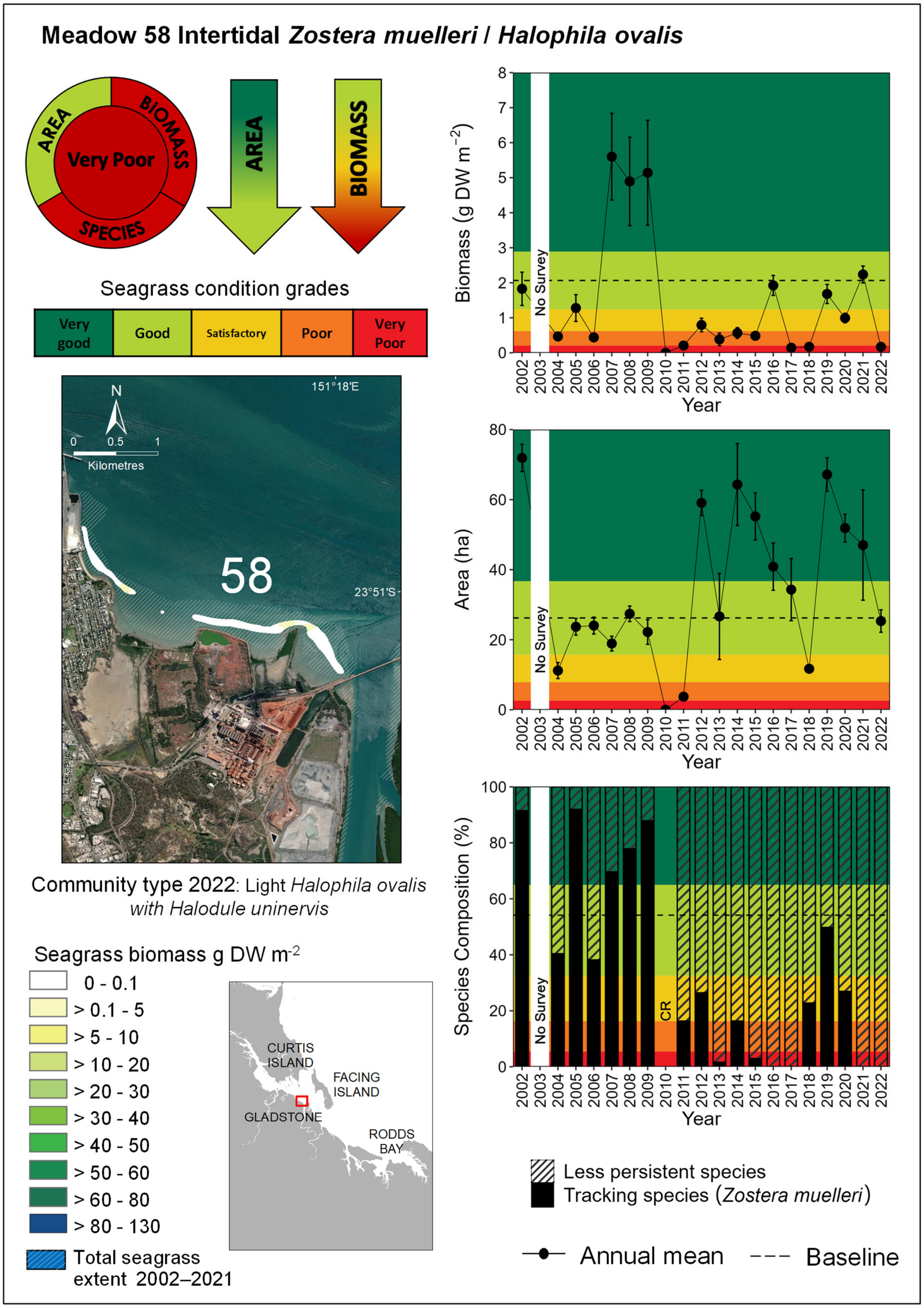


Figure 20. Changes in meadow area, biomass and species composition for Meadow 58, (Inner Harbour Zone), 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate). CR = calculation restriction due to the absence of seagrass.

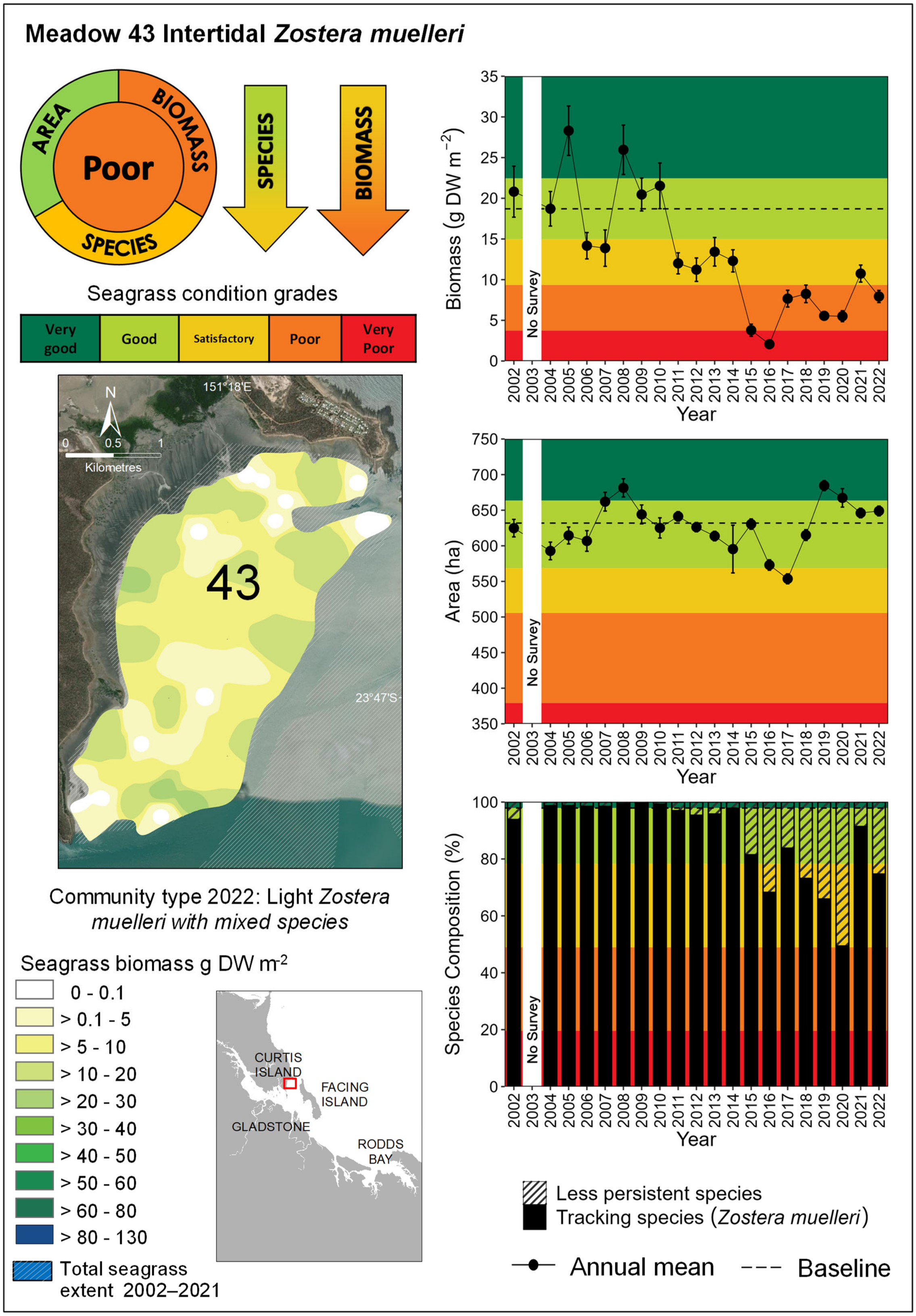


Figure 21. Changes in meadow area, biomass and species composition Meadow 43, Pelican Banks (Mid Harbour Zone), 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

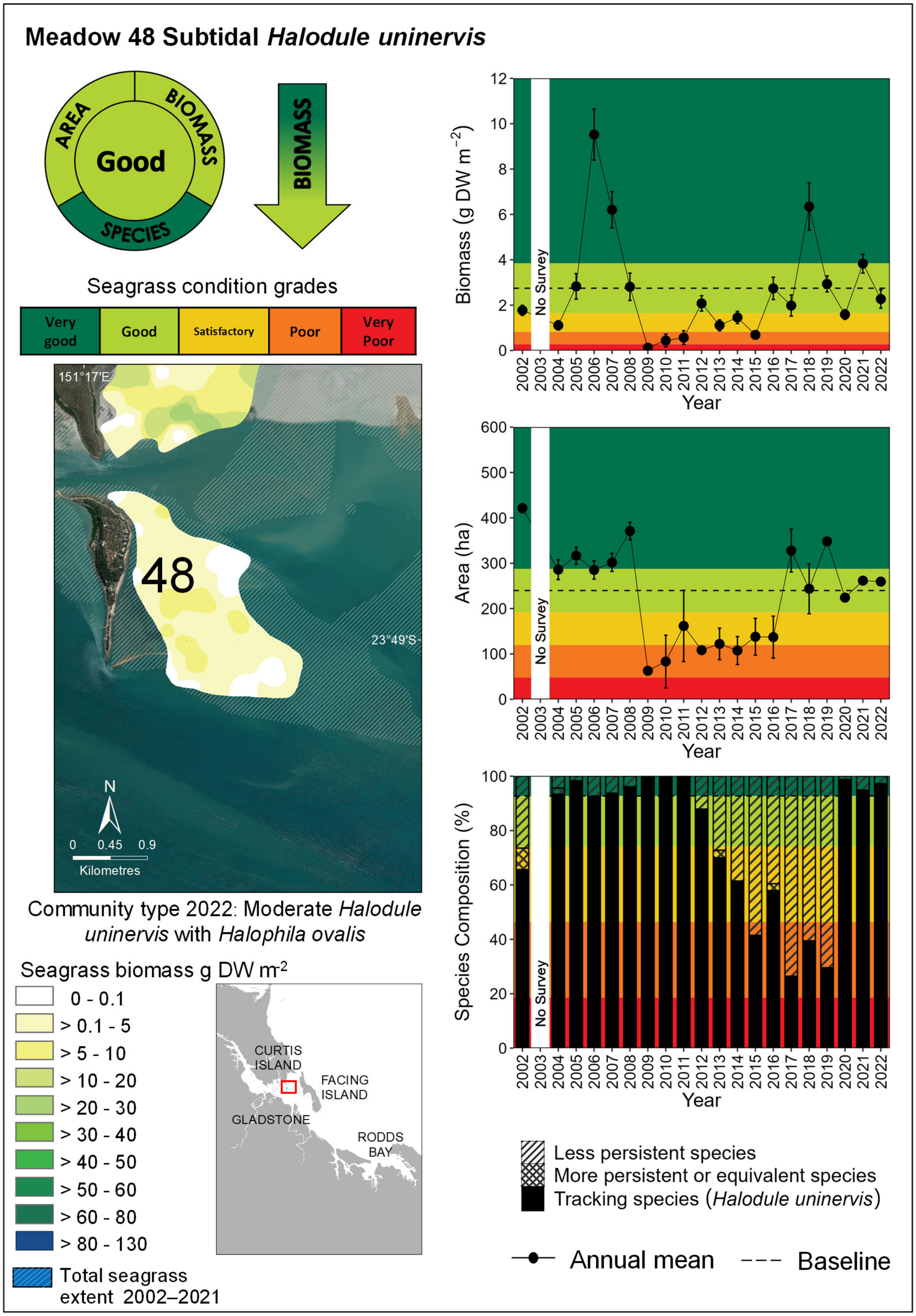


Figure 22. Changes in meadow area, biomass and species composition Meadow 48, Quoin Island (Mid Harbour Zone), 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

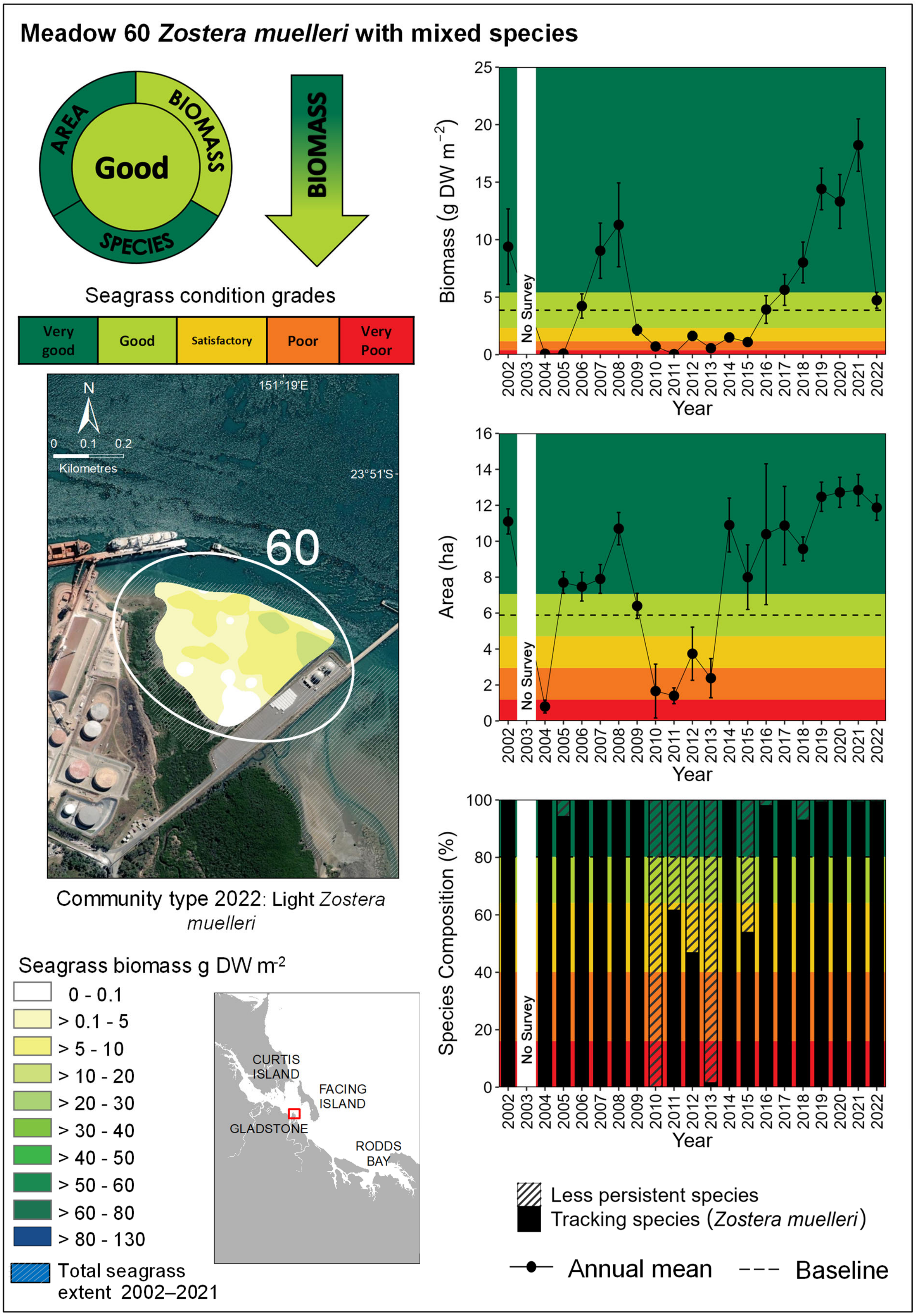


Figure 23. Changes in meadow area, biomass and species composition for Meadow 60, South Trees Inlet Zone, 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.2.6 Rodds Bay long-term monitoring meadows

Monitoring seagrass in Rodds Bay provides an opportunity to measure seagrass health in an area that is not exposed to port activities. Since the inception of the monitoring program, three meadows in Rodds Bay have been monitored as reference areas to compare to meadows within the port (Figures 22-26).

Meadow 94:

Meadow 94 is a small monitoring meadow in Rodds Bay that historically consists of continuous *Z. muelleri*. In 2022, small increases in meadow area and species composition resulted in the overall meadow score improving from very poor to poor (Figure 24). There was a large decline in seagrass area, biomass and species composition resulting in a very poor meadow score when only *H. ovalis* was recorded in the meadow. In 2022, *Z. muelleri* was the only species recorded, improving species composition to very good. The area of the meadow increased from 0.92 ± 0.21 ha in 2021 to 1.46 ± 0.52 ha in 2022, resulting in the score improving from very poor to poor. There was little change in meadow biomass, and it remained low (Figure 24)

Meadow 96:

Meadow 96 is the largest meadow in Rodds Bay and covers an area of 303.14 ± 10.76 ha (Figure 25). Overall meadow condition was poor as biomass declined for the third year in a row to 2.08 ± 0.38 g DW m^{-2}, less than half what it was in 2021 (4.55 g DW m^{-2}). Species composition was almost exclusively (97%) *Z. muelleri* and for the fourth consecutive year was above baseline levels.

Meadow 104:

Overall condition of Meadow 104 was poor after being satisfactory for the last two years (Figure 26). Biomass was 1.89 ± 0.98 g DW m^{-2} and in poor condition in 2022. It was lower than in 2021 when biomass was 2.90 ± 0.68 g DW m^{-2}, and despite having a lower condition, has shown little variation since 2020 (2.60 ± 0.90 g DW m^{-2}). Area decreased for the third consecutive year from good in 2020 to satisfactory in 2021 and poor in 2022 when it covered 20.46 ± 2.43 ha (Figure 24). Species composition was considered to be in good condition with the persistent *Z. muelleri* contributing 95% of meadow biomass (Figure 26).

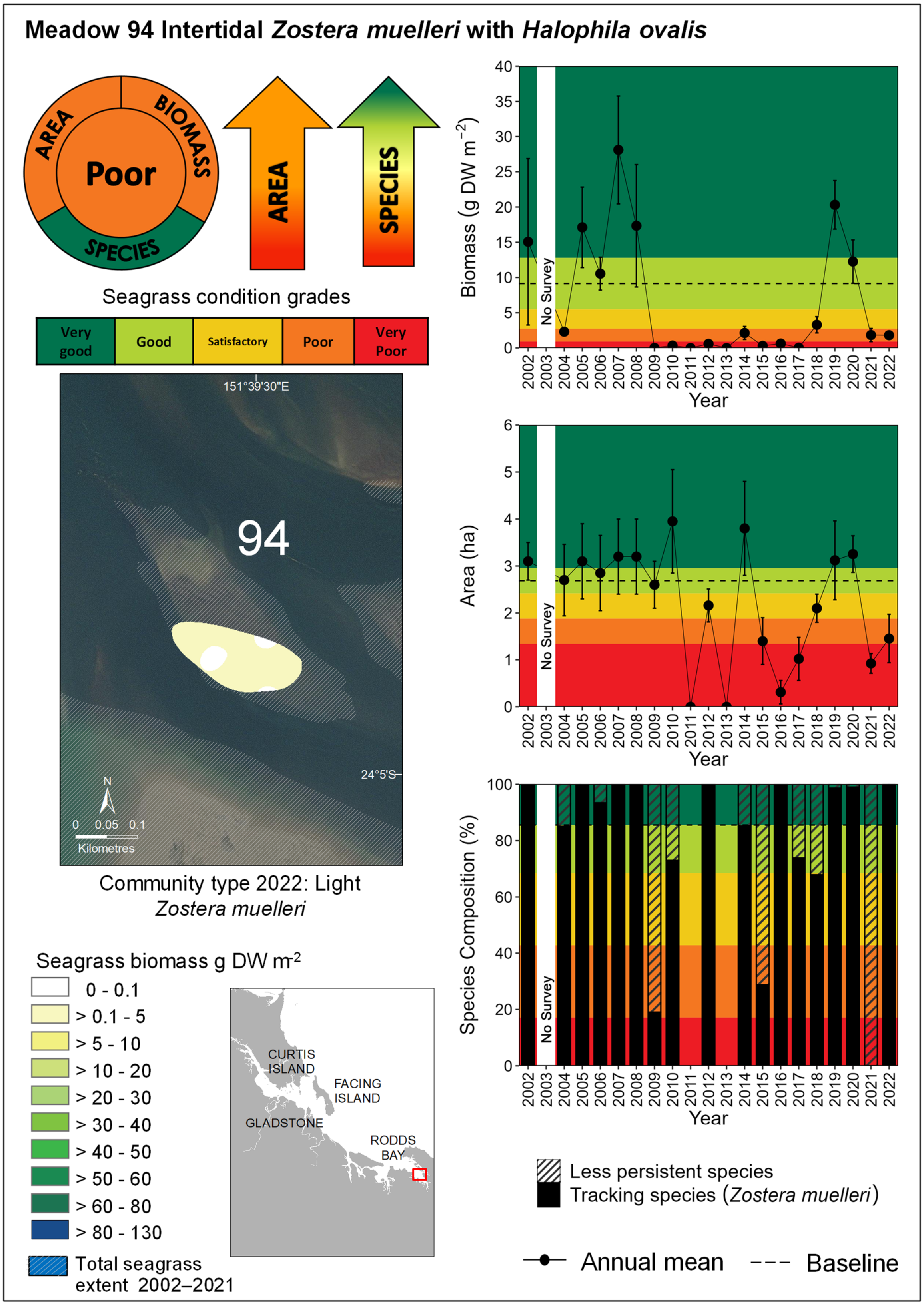


Figure 22. Changes in meadow area, biomass and species composition for Meadow 94, Rodds Bay Zone, 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

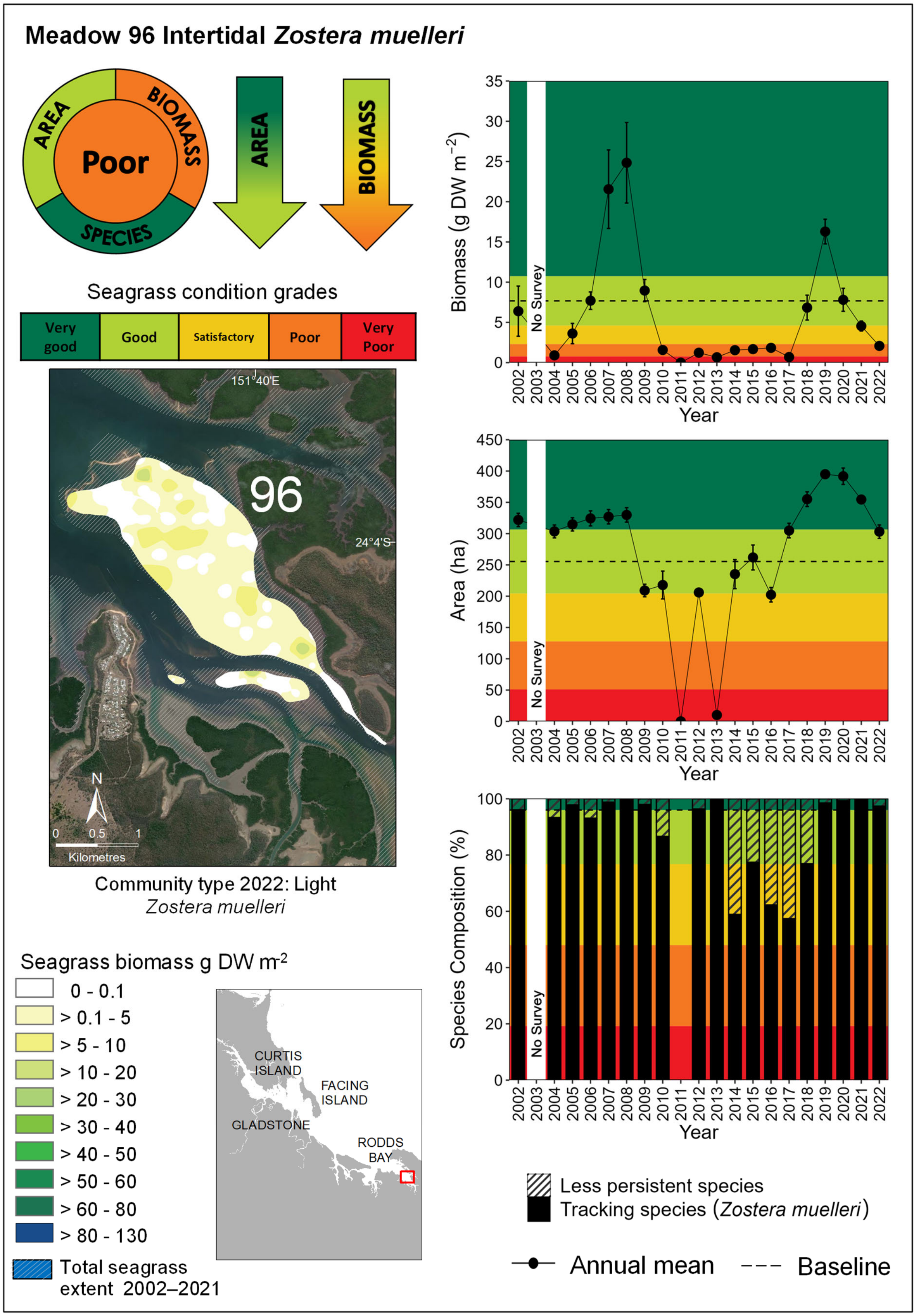


Figure 23. Changes in meadow area, biomass and species composition for Meadow 96, Rodds Bay Zone, 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

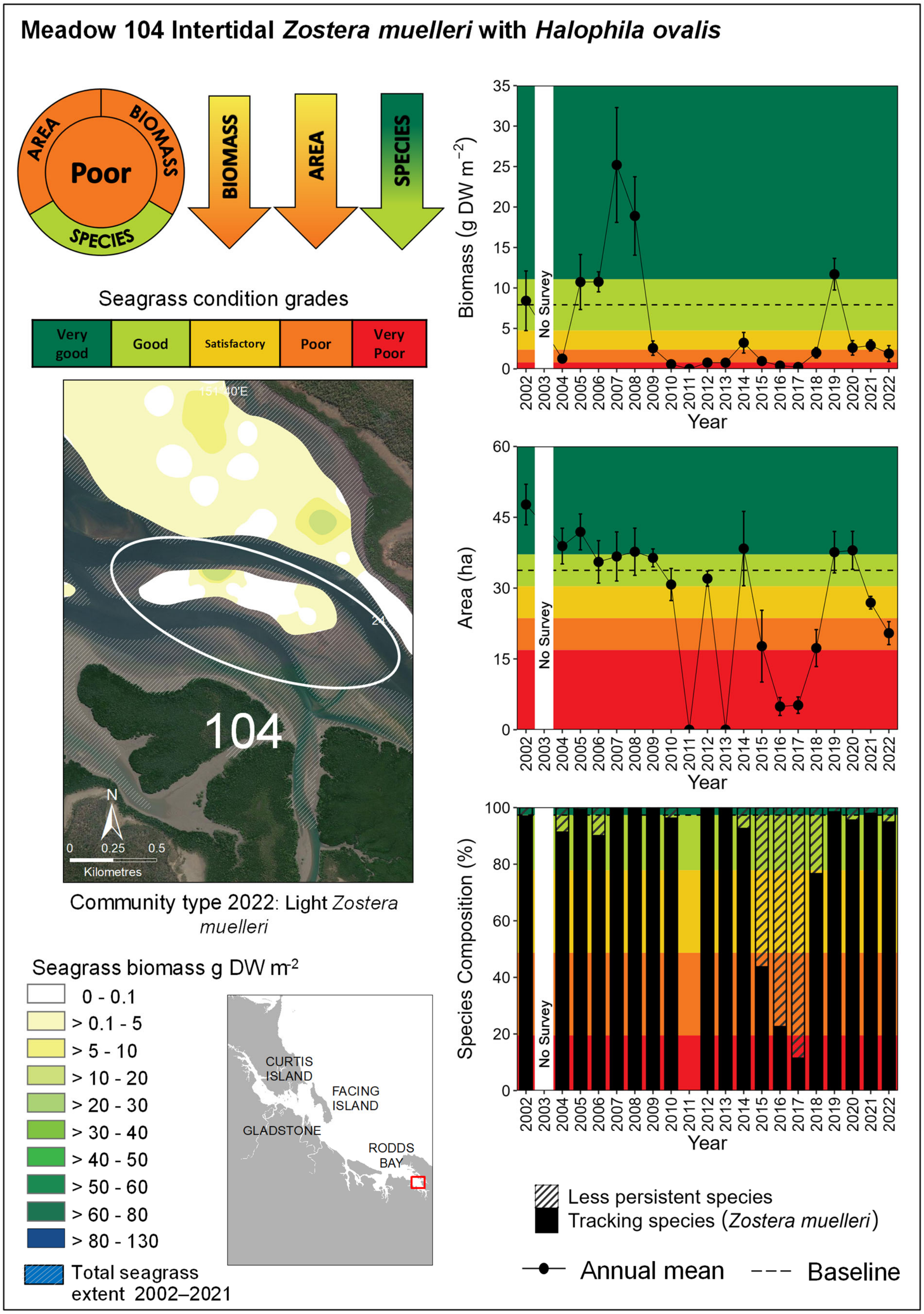
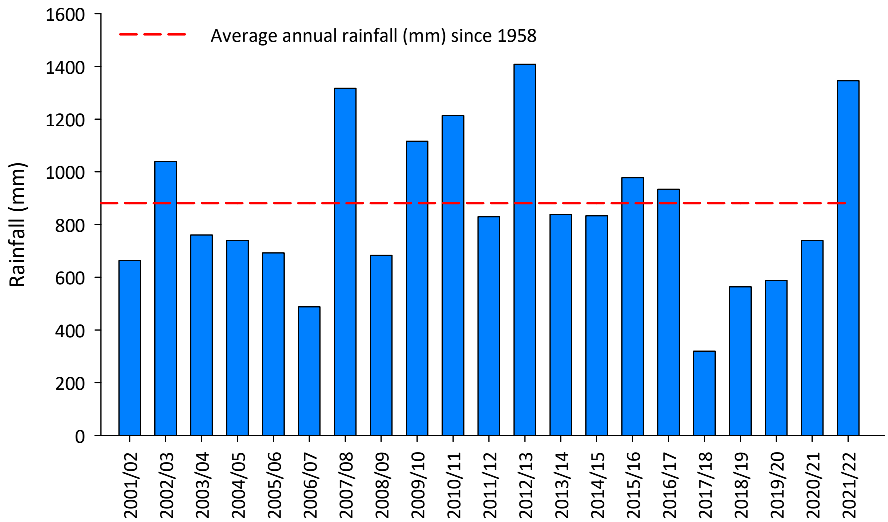


Figure 24. Changes in meadow area, biomass and species composition for Meadow 104, Rodds Bay Zone, November 2002–2022 (biomass error bars = SE; area error bars = "R" reliability estimate).

3.3 Gladstone environmental conditions

Total annual rainfall in the 12 months preceding the November 2022 survey was above average for the first time since 2016/17 (Figure 25a). Monthly rainfall at Gladstone was more than double the monthly average in November 2021 and March, May, July and October 2022 (Figure 29b). River flow from the Calliope River was higher and more consistent than the previous three years when outflow reached 1000 gigalitres in only five months (Figure 26). Between October 2021 and October 2022, river flow exceeded 1000 gigalitres in eight months, and was more than double the average monthly river flow in November 2021 and July 2022. Annual total daytime exposure of intertidal seagrass meadows was below average for the fourth year in a row and one of the lowest on record (Figure 27).

a)



b)

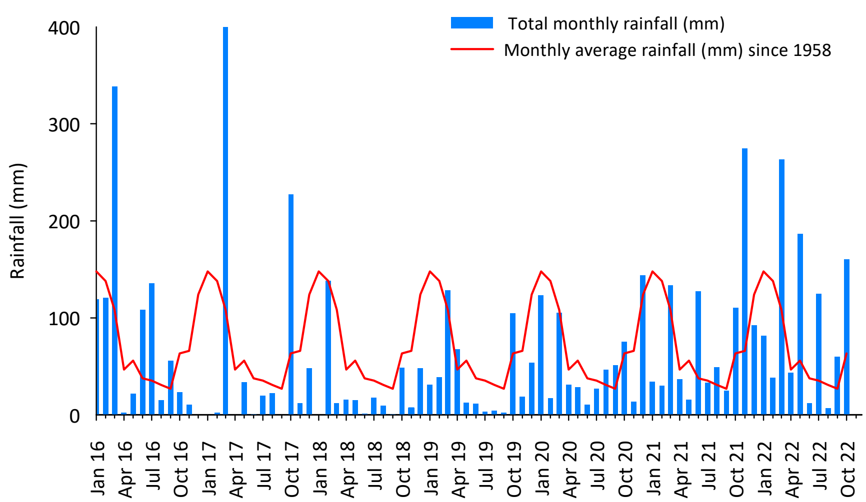


Figure 25. a) Gladstone annual rainfall (mm) and b) monthly rainfall (mm) totals; January 2016–November 2022.

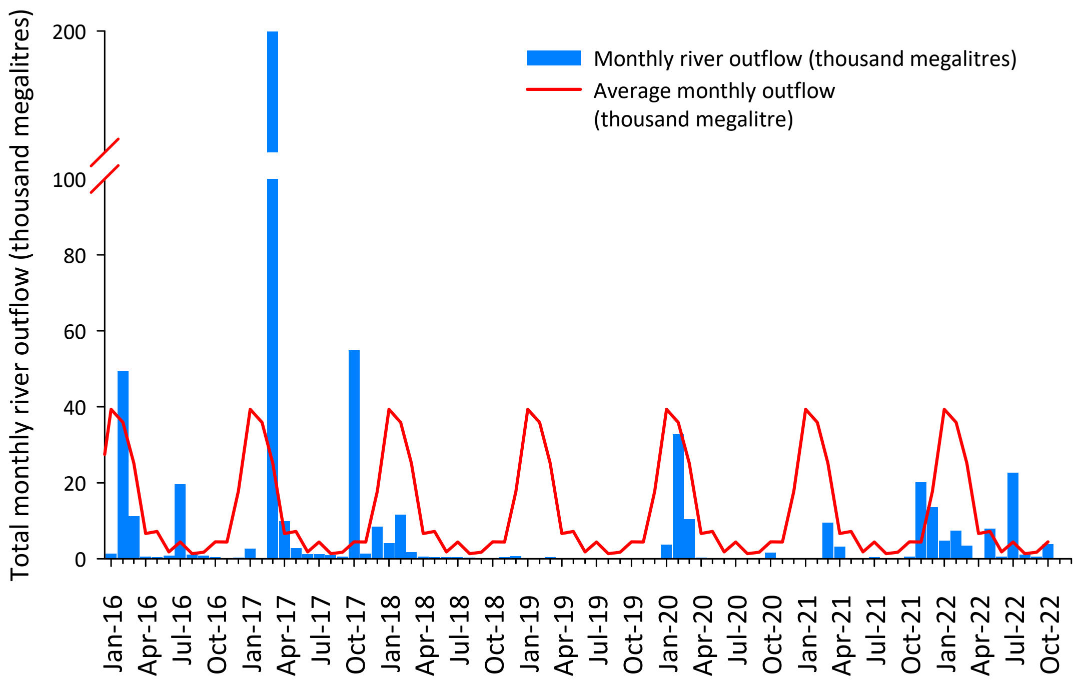


Figure 26. Monthly total river outflow for the Calliope River (thousand megalitres); January 2016–November 2022.

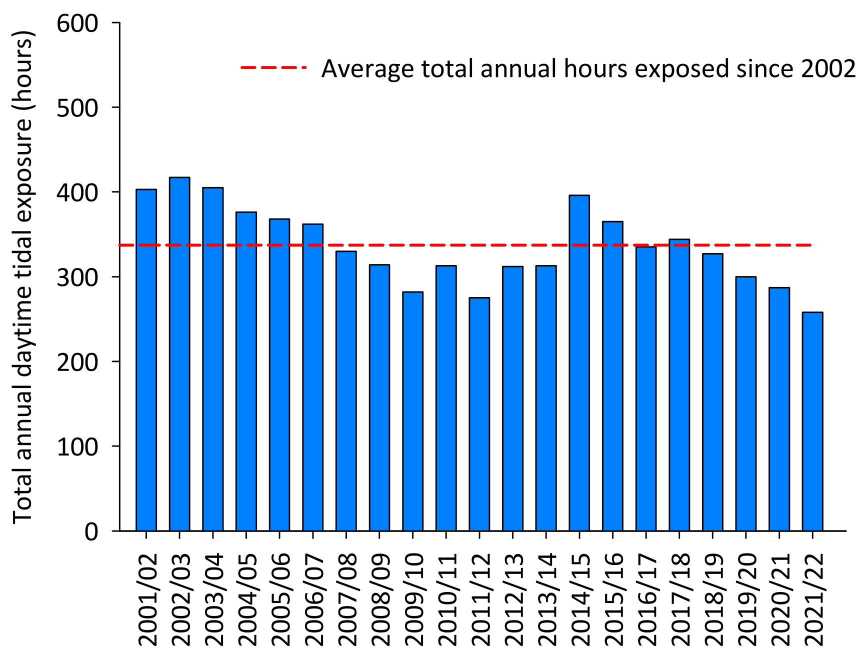


Figure 27. Total annual daytime hours seagrass meadows exposed to air 2001/02 - 2021/22 (daytime hours used 0600 – 1800; <1.0 m below mean sea level).

4 DISCUSSION

4.1 Gladstone seagrass

Seagrass meadows in Port Curtis and Rodds Bay were in an overall satisfactory condition in 2022 after three years of good condition. Half of the seagrass monitoring meadows continued to be in good or very good condition with the majority of these found in the Western Basin and the Narrows, where seagrass biomass continues to be above historical values. Outside the Western Basin and Narrows, all meadows recorded a decrease in meadow biomass that led to declines in meadow condition. Only two of the seven meadows in these regions were in good condition and the remainder were in poor or very poor condition. Monitoring meadows in Rodds Bay are considered reference meadows as they are outside the influence of port operations. All monitoring meadows in Rodds Bay were in poor condition due to low biomass and area, with declines in biomass similar to what was observed in some of the meadows within the port.

Decreases in seagrass biomass and meadow condition in these meadows in 2022 can be attributed to above average rainfall and increased river flow in 2022 relative to the previous four years. Local environmental conditions are a key factor in determining seagrass distribution, biomass and health. Long-term trends in seagrass condition over the past 20 years of annual monitoring reveal a strong relationship with river flow and rainfall in the region. Flow from the Calliope River over the 12 months prior to the survey was higher than any of the previous four years, which were all well below average. Similarly, annual rainfall was the highest in eight years and included significant rainfall events in November 2021, March and May 2022. Seagrass has specific light requirements for photosynthesis and growth (Chartrand et al. 2016; 2018), turbidity associated with rainfall and river outflow reduces benthic light conditions inhibiting seagrass growth and can ultimately lead to plant death. Greater rainfall and river flow in the 12 months preceding the 2022 survey may have led to a reduction in benthic light, poor seagrass growing conditions and ultimately lower seagrass biomass. The low river flow and rainfall conditions between 2018 and 2021 likely led to high benthic light levels allowing seagrass growth and recovery observed over those years. Increases in seagrass biomass, area and species composition in the Western Basin and the Narrows during this period were some of the highest recorded over twenty years of monitoring and provided these meadows with some resilience to the unfavourable growing conditions in 2022. If above average rainfall and river flow conditions continue, seagrass biomass and condition may continue to decrease.

Port dredging operations may alter benthic light conditions which can result in seagrass decline (Chartrand et al. 2016, Wu et al. 2018). The methodology, timing, frequency and duration of dredging operations play a major role in determining what impact, if any, they have on seagrass meadows and careful management of dredging operations can limit these (Chartrand et al. 2016; Wu et al. 2018). Maintenance dredging in Gladstone is carefully managed to ensure minimal reductions in benthic light and subsequent impacts to seagrass meadows (GPC 2019). Dredging occurs over relatively short timeframes that restrict the extent of the dredge plumes, and occurs within the period where local seagrasses tend to have high resilience to light impacts. Meadows in proximity to the maintenance dredging activity in the Western Basin and South Trees Inlet were in good condition or very good condition in 2022 indicating that maintenance dredging was not having any detectable impact on these meadows. The exceptions were subtidal Meadow 7 in the Western Basin and Meadow 58 at the Inner Harbour. Meadow 7 was in satisfactory condition for the third year in a row. Subtidal *Halophila* meadows such as Meadow 7 are highly ephemeral and biomass and area can change rapidly (Rasheed et al. 2014).

Meadow 58 in the Inner Harbour was in very poor condition. This meadow was in poor condition in 2021 and decreased in area by 46% and biomass by 92%. There continues to be a total absence of the foundation species *Z. muelleri* in the meadow, which has been replaced with less persistent *H. uninervis* and *H. ovalis* in recent years. The absence of *Z. muelleri* not only results in a very poor species composition score, but also leads to lower meadow biomass as *Z. muelleri* generally has greater biomass than *H. uninervis* and *H. ovalis*. Prior to 2010 Meadow 58 had higher biomass (5 - 6 g DW m^{-2}) before it underwent severe decline after high rainfall and river flow. During this time, *Z. muelleri* contributed 40-90% of the meadow biomass. Since the meadow was lost in 2010, it has transformed to be predominantly *H. uninervis*/*H. ovalis,* and the ongoing low contributions of *Z. muelleri* to the meadow suggest that it has not been able to re-establish and persist.

The largest seagrass meadow in Port Curtis, Pelican Banks meadow (Meadow 43) is in poor condition after being rated satisfactory in 2021. Pelican Banks is historically the largest, high-biomass seagrass meadow in Port Curtis, but had been in poor condition for the six years prior to 2021. Changes in species composition from the foundation species *Z. muelleri* to less persistent *H. uninervis* and *H. ovalis* during this period contributed to lower meadow biomass and poor meadow condition. In 2021, the contribution of *Z. muelleri* to the meadow biomass improved to 90% resulting in increased meadow biomass. In 2022 the meadow returned to poor condition as *Z. muelleri* decreased across the meadow which had a direct impact on meadow biomass. *Zostera muelleri* has much greater biomass than the other species in the meadow (e.g. *H. uninervis*, *H. ovalis*) and biomass should increase if the contribution of *Z. muelleri* improves. The Pelican Banks meadow typically experiences the best water quality conditions for seagrass meadows in the region based on historical monitoring of benthic light (Chartrand et al. 2016) and therefore meadow condition would be expected to be more consistent or better than those elsewhere in Port Curtis. While patterns of seagrass biomass and condition are similar to elsewhere in the harbour in 2022, the decline in seagrass condition at Pelican Banks over six years prior to 2021 could not be explained by environmental conditions. Megaherbivore (green turtles and dugong) grazing has been suggested as a possible cause of these declines. The Pelican Banks meadow has high levels of herbivory from dugong and turtle with dugong feeding trails regularly observed within the meadow (Rasheed et al. 2017) and direct observations of green turtles also feeding on the meadow (direct observations and Hamann et al. 2016; Limpus et al. 2017). Recent research using herbivore exclusion cages has found the impact of herbivores on both seagrass biomass and canopy height were greater at Pelican Banks than other meadows within Port Curtis and Rodds Bay (Scott et al. 2021a). It has been suggested that megaherbivores target areas of high biomass which may explain high levels of herbivory in the past (Smith et al. 2022, Rasheed et al. 2017) and major meadow losses have occurred in other locations around the world as a direct result of turtle herbivory (Christianen et al. 2014).

Dugong feeding trails were common throughout Pelican Banks as well as other meadows within the survey region in 2022. There is some anecdotal evidence that the dugong population in Gladstone Harbour had increased due to dugongs migrating north from Hervey Bay in search of food after major flooding decimated seagrass meadow in Hervey Bay in early 2022 (York et al. 2022). It is possible that increases in dugong density in Gladstone Harbour and associated increased grazing in seagrass meadows may have contributed to the declines observed in some of the seagrass meadows in Port Curtis and Rodds Bay in 2022.

The declines in seagrass seen at some meadows within the port were also reflected at the out of port reference area in Rodds Bay, with declines occurring in two of the three monitoring meadows and all three rated as being in poor condition in 2022. Biomass and area in the Rodds Bay meadows peaked in 2019-2020 and were considered very good after nine to ten years of being in satisfactory to poor condition. The last two surveys however have seen a general decline in seagrass biomass and area across Rodds Bay. The fact that declines occurred both within and outside of the port point to broader climate related drivers of seagrass change rather than anything specifically related to port activities in 2022.

4.2 Comparisons with Queensland-wide monitoring program

The condition of seagrass meadows in Port Curtis and Rodds Bay reflected local weather-related changes at other monitoring locations along Queensland's east coast between Cairns and Port Curtis. Seagrass in Cairns, Townsville and Clairview were in good condition in 2022 with generally favourable local weather conditions (McKenna et al. 2023; Rasheed et al. 2023; Reason et al. 2023a, b). Seagrass surveys further south at Hervey Bay and the Great Sandy Straits recorded very low seagrass biomass and area following major flooding of the Mary River (York et al. 2022). While there has been a trend of recovery in seagrass meadows over recent years in response to widespread climate associated losses in 2009/10, localised climate events have had a major impact on seagrass outcomes around the state since then. Both Hervey Bay and Port Curtis and Rodds Bay recorded multiple high rainfall events and subsequent decreases in seagrass, whereas both Cairns and Townsville recorded average rainfall and below average river flow and remained in good condition. This is in contrast to severe localised flooding that occurred in the Townsville region in 2019, which led to a decline in seagrass meadows in that year (McKenna et al. 2020). In contrast, Mourilyan Harbour has shown little recovery after complete meadow loss in 2010/2011 and seagrass remains in very poor condition with little prospect of seagrass recovery without some form of restoration (Reason et al. 2023b).

4.3 Implications for port management

Results of this latest annual survey have found seagrasses to be in a satisfactory condition compared with the 20-year monitoring history. All meadows in the Western Basin and the Narrows were in satisfactory to very good condition while those in Rodds Bay, Inner Harbour and the Pelican Banks meadow were in poor or very poor condition. While the majority of meadows had recovered to pre 2010 conditions in the 2021 survey many meadows returned to poor condition in 2022. The seagrass dynamics observed in Port Curtis and Rodds Bay over the past year are consistent with the major climate drivers of seagrass change seen elsewhere in North Queensland and the continued use of the meadows by dugongs and green turtles are signs of a healthy functioning seagrass ecosystem. As recognised indicators of overall marine environmental health (Dennison et al. 1993), the satisfactory condition of seagrasses in 2022 indicates a healthy marine environment for Port Curtis and Rodds Bay.

High biomass and area and the maintenance of foundation species over the previous four sampling years in most Port Curtis and Rodds Bay meadows likely provided some resilience to the less favourable conditions that occurred in 2022. Sustained periods of high biomass can lead to increased reproductive effort and replenish seed banks in the region, particularly for *Z. muelleri.* Larger seed banks further increase seagrass meadow resilience to impacts by increasing their capacity for recovery (Reason et al. 2017b).

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

Over the past decade, seagrass meadows in Port Curtis and Rodds Bay have undergone repeated disturbances from climate, floods, cyclones and anthropogenic activities but have maintained their historical extent and have recovered biomass and species composition to pre disturbance levels following these events. While improvements in biomass and the return of more persistent species to meadows between 2018 and 2021 increased seagrasses resilience to weather events in 2022, future pressures or impacts have the potential to further erode this resilience and increase the susceptibility to further declines.

5 REFERENCES

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

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

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

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

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

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

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

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

Carter, A. B., Coles, R. G., Jarvis, J. C., Bryant, C. V., Smith, T. M., and Rasheed, M. A. 2023. A report card approach to describe temporal and spatial trends in parameter for coastal seagrass habitats. Scientific Reports 13(1),2295

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

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

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

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

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

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

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

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

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

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

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

Gladstone Healthy Harbour Partnership (GHHP) 2022. Technical report, Gladstone Harbour report card 2022, GHHP technical report No. 9, Gladstone Healthy Harbour Partnership, Gladstone. 211 pp

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

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

Hemminga, M. A. and Duarte, C. M. 2000. *Seagrass Ecology*. Cambridge, Cambridge University Press. 298 pp. doi:10.1017/CBO9780511525551

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

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

Limpus, C. J., FitzSimmons, N., Finlayson, K., Harmonn, C., McKinnon, A., Sergeev, J. and Shimada, T. 2017. Increase the understanding of the Green Turtle population in Port Curtis. Brisbane: Department of Environment and Science, Queensland Government. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation Ecosystem Research and Monitoring Program. 28 pp.

Maritime Safety Queensland. 2022. Queensland tide tables, standard port times 2022, State of Queensland, Brisbane, 129 pp. https://www.msq.qld.gov.au/Tides/Tide-Tables

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

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

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

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

McKenna, S. A., Van De Wetering, C., and Wilkinson, J. 2023, Port of Townsville Seagrass Monitoring Program: 2021, James Cook University Publication, Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), Cairns. 56 pp.

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

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

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

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

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

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

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

Rasheed, M. A., van de Wetering, C. and Carter, A. B. 2023 Mackay-Whitsunday-Isaac Seagrass Monitoring 2017-2022: Marine Inshore South Zone (Clairview), Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 23/24. James Cook University, Cairns, 32 pp.

Reason C. L., Smith T. M. and Rasheed M. A. 2021. Seagrass habitat of Cairns Harbour and Trinity Inlet: Cairns shipping development program and annual monitoring report 2020. JCU Publication, Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 21/09, Cairns, 54 pp.

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

Reason, C. L., Rasheed, M. A., Carter, A. B. and Jarvis, J. C. 2017b. Port Curtis seagrass seed bank density and viability studies - Final report. Report produced for the Ecosystem Research and Monitoring Program Advisory

Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 17/40, James Cook University, Cairns, 36 pp.

Reason C. L., York P. H. and Rasheed M.A. 2023a. Seagrass habitat of Cairns Harbour and Trinity Inlet: Cairns shipping development program and annual monitoring report 2022. JCU Publication, Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 23/10, Cairns. 50 pp.

Reason, C.L., York, P.H. and Rasheed, M.A. 2023b, Seagrass habitat of Mourilyan Harbour: Annual monitoring report – 2022, Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 23/11, Cairns, 38pp.

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

Scott A. L, York P. H, Macreadie P. I. and Rasheed M. A. 2021a. Spatial and temporal variability of green turtle and dugong herbivory in seagrass meadows of the southern Great Barrier Reef. Marine Ecology Progress Series 667, 225-231 https://doi.org/10.3354/meps13703

Scott A. L, York P. H. and Rasheed M. A 2021b. Herbivory has a major influence on structure and condition of a Great Barrier Reef subtropical seagrass meadow. Estuaries and Coasts 44, 506-521 https://doi.org/10.1007/s12237-020-00868-0

Scott, A.L., McKenna, S.A., and Rasheed, M.A. 2022. Port of Karumba long-term annual seagrass monitoring 2021, Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 21/70, James Cook University, Cairns, 28 pp.

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

Smith T. M., Chartand K. M., Well J. N., Carter A. B. and Rasheed M. A. 2020. Seagrasses in Port Curtis and Rodds Bay 2019: Annual long-term monitoring and whole of port survey. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 20/64, James Cook University, Cairns, 81 pp.

Smith T. M., Reason C., McKenna S., and Rasheed M. A. 2022. Seagrasses in Port Curtis and Rodds Bay 2021: Annual long-term monitoring. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 21/14, James Cook University, Cairns, 54 pp.

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

Vision Environment. 2021. Compliance water quality monitoring of Port of Gladstone maintenance dredging campaign September to November 2021. Vision Environment ANZ, A Trinity Consultants Australia company, Gladstone Australia, 27 pp.

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

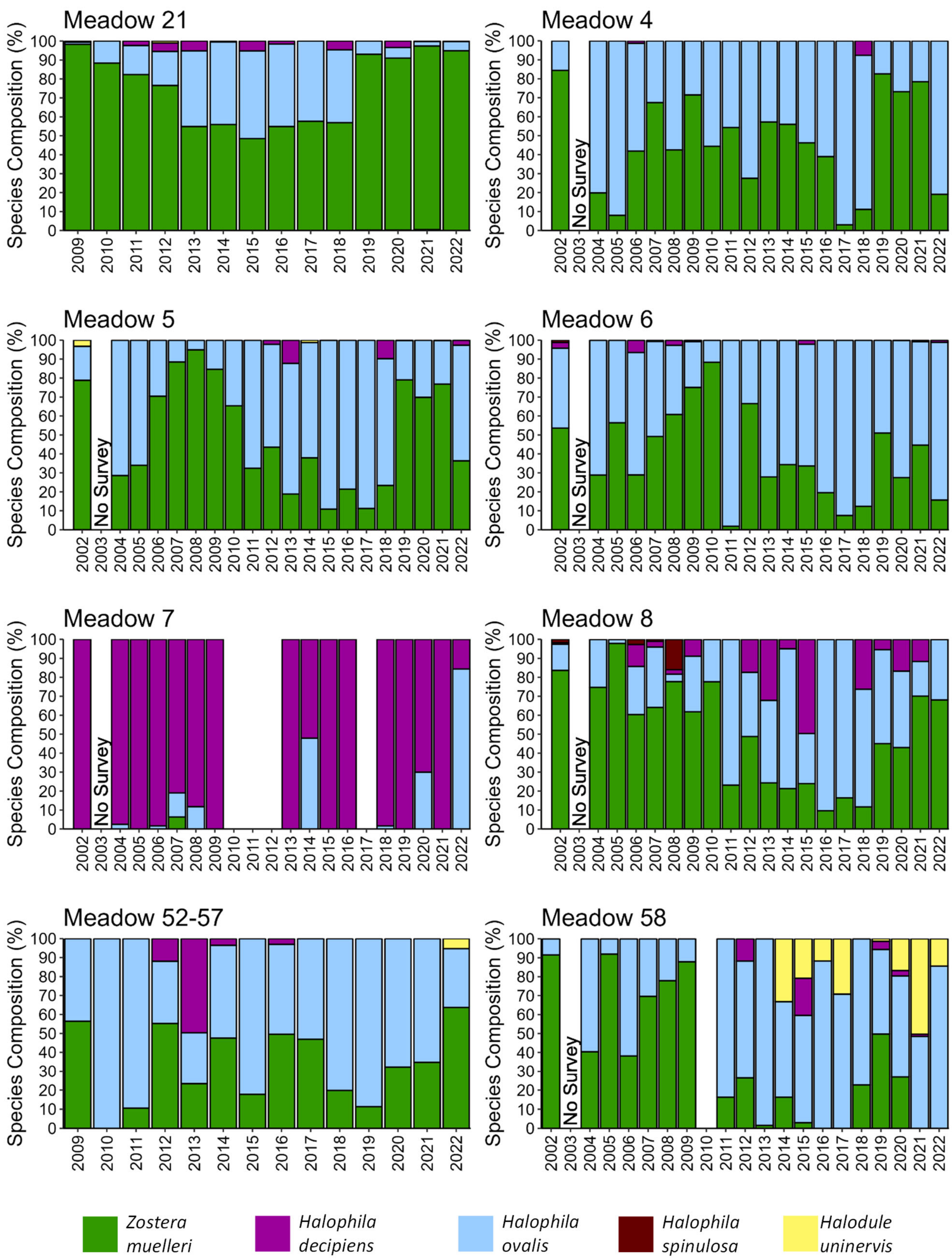
York, P. H., Bryant C. V. and Rasheed M. A. 2022. Post-Flood Seagrass Monitoring in Hervey Bay - May 2022, JCU Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER)Publication 22/31, Cairns. 24 pp.

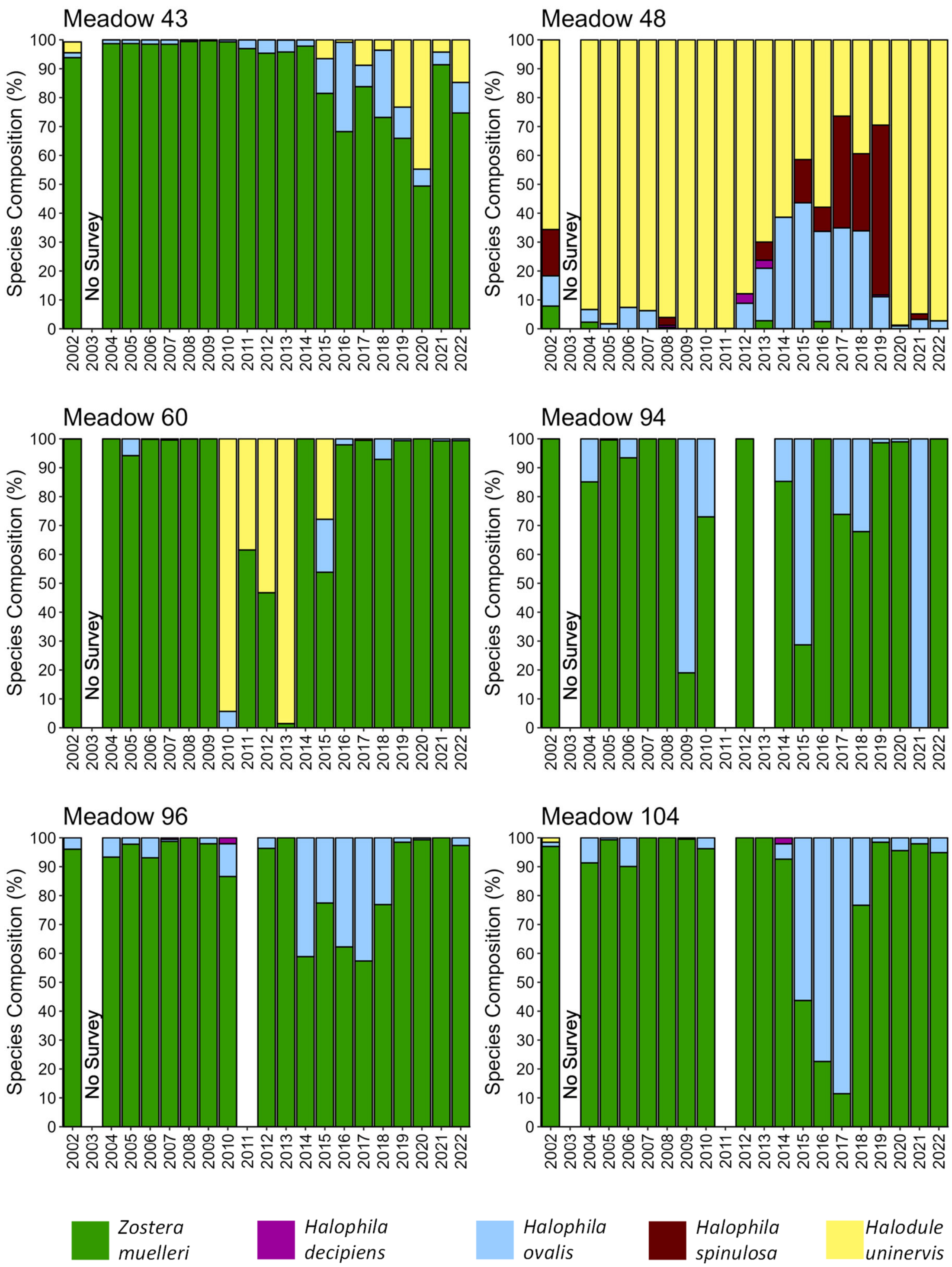
APPENDICES

Appendix 1. Meadow area and above-ground biomass of Port Curtis and Rodds Bay seagrass meadows 2022

Meadow ID	Biomass ± SE (g DW m^{-2})	Area ± R (ha)	Community Type	Landscape Category	Species Present	Zone
21	16.69 ± 2.05	193.52 ± 8.25	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*	The Narrows
4	2.87 ± 0.56	45.30 ± 2.10	Moderate *H. ovalis* with *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*	Western Basin
5	3.37 ± 0.55	158.67 ± 2.92	Moderate *H. ovalis* with *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis, H. uninervis*	Western Basin
6	5.99 ± 0.48	416.87 ± 6.22	Dense *H. ovalis* with mixed species	Aggregated patches	*Z. muelleri, H. ovalis, H. decipiens*	Western Basin
7	0.66 ± 0.39	31.48 ± 2.60	Light *H. ovalis* with *H. decipiens*	Isolated patches	*H. decipiens, H. ovalis*	Western Basin
8	1.68 ± 0.47	175.43 ± 3.19	Light *Z. muelleri* with *H. ovalis*	Isolated patches	*Z. muelleri, H. ovalis, H. decipiens*	Western Basin
52-57	2.04 ± 0.52	52.15 ± 4.30	Light *Z. muelleri* with mixed species	Isolated patches	*Z. muelleri, H. ovalis, H. uninervis*	Western Basin
43	7.93 ± 0.75	648.92 ± 6.87	Light *Z. muelleri* with mixed species	Aggregated patches	*Z. muelleri, H. uninervis, H. ovalis*	Mid Harbour
48	2.27 ± 0.40	259.41 ± 6.87	Moderate *H. uninervis* with *H. ovalis*	Aggregated patches	*H. uninervis, H. ovalis*	Mid Harbour
58	0.17 ± 0.11	25.33 ± 3.20	Light *H. ovalis with H. uninervis*	Isolated patches	*H. uninervis, H. ovalis*	Inner Harbour
60	4.72 ± 0.69	11.87 ± 0.71	Light *Z. muelleri*	Aggregated cover	*Z. muelleri, H. ovalis*	South Trees
94	1.81 ± 0.55	1.45 ± 0.52	Light *Z. muelleri*	Isolated patches	*Z. muelleri, H. ovalis*	Rodds Bay
96	2.08 ± 0.38	303.14 ± 10.76	Light *Z. muelleri*	Aggregated patches	*Z. muelleri, H. ovalis*	Rodds Bay
104	1.89 ± 0.98	20.46 ± 2.44	Light *Z. muelleri*	Isolated patches	*Z. muelleri, H. ovalis*	Rodds Bay

Appendix 2. Detailed species composition for long term monitoring meadows; 2022




Meadow 43
Meadow 48
Meadow 60
Meadow 94
Meadow 96
Meadow 104
Species Composition (%)
No Survey
Zostera muelleri
Halophila decipiens
Halophila ovalis
Halophila spinulosa
Halodule uninervis