Port of Townsville Seagrass Monitoring Program 2024

Report No. 25/02

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Port of Townsville Seagrass Monitoring Program 2024

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CONTENTS

GLOSSARY

Above-ground biomass (gDWm²): The dry weight of seagrass parts above the sediment, used to measure seagrass health.

Colonising: A seagrass life-history strategy with traits including fast shoot turnover and time to sexual reproduction, low physiological resistance (e.g. to low light events), and an ability to rapidly recover from disturbances from seeds in a seed bank, and from lateral expansion and shoot production.

Condition: Relative quantities of characteristics of the seagrass such as biomass, spatial extent and species composition.

Condition index: Composite score of seagrass health based on above-ground biomass (gDWm²), area (ha), and species composition.

Confidence intervals: A range of plausible values for an unknown parameter. Most commonly, and throughout this report, a 95% confidence interval is used.

Deepwater/ deeper water seagrass: In this report deepwater/deeper water seagrass refers to seagrass found in subtidal areas deeper than 8 metres below mean sea level (MSL).

Dry /pre-wet season: The period of the year when the least rainfall and river discharge occurs. The exact time-period can be defined in various ways, but in this report, it refers to May to October.

Ecological function: The role an organism or habitat plays in maintaining ecosystem processes (e.g., dugong feeding trails as evidence of trophic function).

Intertidal: The area between the low tide and high tide levels.

Inverse Distance Weighted (IDW) interpolation: A method used to estimate values across space based on nearby data points.

Kruskal-Wallis test: A non-parametric statistical test to compare among groups.

Meadow footprint: The area (ha) of seabed covered by a seagrass meadow. The footprint of a meadow can change/move intra- and inter-annually.

Meadow/seagrass meadow: A marine habitat that is formed by seagrass plants.

Meadow landscape categories: Classification of seagrass distribution (e.g., isolated patches, aggregated, continuous cover).

Photosynthetically Active Radiation (PAR): An estimate of the quantum of photosynthetically active radiation reaching the benthos based on PAR data collected at the seabed at various sites. It is the light usable by plants for photosynthesis, critical for seagrass growth

R: A free software environment for statistical computing and graphics

Reliability estimate (R (ha)): A statistical measure of the confidence in spatial estimates of seagrass extent/area (ha).

Resilience: The capacity to provide ecological services in the future, based on being able to retain condition and function in the face of disturbances.

Shapiro-Wilk test: A statistical test to assess normality of data.

Species composition: The makeup of different species within a seagrass meadow.

Subtidal: The area below the lowest tide.

Turbidity (NTU): The cloudiness of the waver; a measure of water clarity often affected by suspended particles/sediment in the water column.

Wet season: The period of the year when most of the rainfall and river discharge occurs. The exact time-period can be defined in various ways, but in this report, it refers to November to April.

Zone of Influence (ZOI): Taken from the Townsville Port Expansion Channel Upgrade Project Mechanical Backhoe Dredge Management Plan: ***"****The Zone Of Influence is defined (as per the methods in the AEIS) as the modelled area where dredge plumes would be expected to occur and be detectable with water quality instruments, but the concentration and duration of plumes are not expected to result in any ecological impacts to sensitive receptor environments".*

1 KEY FINDINGS

Seagrass Condition 2024

Poor

LTSMP meadows

Poor

CUSP meadows

This report presents the results of the 18th year of the Long-Term Seagrass Monitoring Program (LTSMP) and the 6th year of the Channel Upgrade Seagrass Program (CUSP; 2019–2024). As this report incorporates monitoring after the completion of the Channel Upgrade Project (the CU Project) the report also includes an analysis of potential impacts from the capital dredging program.

Key findings for the 2024 seagrass assessments and seagrass assessments throughout the CUSP:

- Overall, seagrass condition was poor for the CUSP and LTSMP meadows at the end of 2024. A further downgrade from the previous couple of years. In the LTSMP four of the ten long-term monitoring meadows were in a satisfactory or better condition while six meadows were in poor or very poor condition. For the CUSP, three meadows were in a satisfactory or better condition while seven meadows were in poor or very poor condition.

- The observed decline in most seagrass meadows in recent years is attributable to a combination of simultaneous and successive system-wide meteorological influences rather than attributable to CU Project capital dredging. This is supported by;
    - Models to assess the effects of environmental variables and dredging activity on seagrass above-ground biomass identified photosynthetically active radiation (PAR)) and seabed temperature as significant environmental predictors of seagrass above-ground biomass. Meteorological events that have collectively reduced light availability (PAR) to seagrass and resulted in suboptimal benthic temperature regimes during the CUSP include;
        - Record flooding in January–February 2019.
        - Above-average rainfall and river discharges during the 2018/19, 2021/22, and 2022/23 wet seasons.
        - Extreme temperatures/marine heatwaves:
            - 2019: Australia's hottest year on record (GBRMPA).
            - February 2020: Record high sea surface temperatures (GBR Outlook Report 2024)
            - Summer 2021/2022: sea temperatures above the long-term average (GBR Outlook Report 2024).
            - Summer 2023/2024: high daily means (GBR Outlook Report 2024)
        - Prolonged low light conditions, as evidenced through the CU Marine Water Monitoring Program (CU MWMP) (GHD 2024).
        - Tropical Cyclones:
            - TC Jasper December 2023: Port of Townsville entered Condition Yellow, and CU MWMP water quality instruments were removed.
            - TC Kirrily (January 2024).
    - Analysis comparing season, dredge phase (pre-, during-, post-dredging), meadows and site location (seagrass within or outside the modelled Zone Of Influence (ZOI) from capital dredging) showed no significant differences in seagrass above-ground biomass trends that could be attributed to the CU Project capital dredging. This is supported by:

  - Seagrass above-ground biomass declines were observed at assessment sites inside and outside the ZOI.
  - Seagrass declines across dredge phases inside the ZOI were not significantly different, but at seagrass meadows beyond the ZOI declines were significant across dredge phases.
  - The inshore Strand meadow (15), one of the meadows closest to capital dredging activity was the only LTSMP meadow in a very good condition at the end of 2024.
  - The Townsville region/Bay wide scale of seagrass declines suggests system-wide influences rather than localised impacts from dredging activities.
  - Results from the CU MWMP also support this: exceedances of water quality monitoring thresholds (e.g., PAR and turbidity), generally occurred concurrently and consistently at reference, sentinel and compliance locations, indicating system-wide influences.

- While an extensive seagrass footprint remained at the end of 2024, declines in meadow above-ground biomass and/or area between October 2023 to October 2024 were recorded across most meadows.

- The fact that seagrasses in Townsville still had satisfactory spatial coverage, good species composition and the presence of higher light requiring species in subtidal meadows provides a good foundation for future recovery. Considering the poor condition of Townsville seagrass at the end of 2024, Port of Townsville have commissioned a post-wet season 2025 assessment of seagrass, to update seagrass meadow condition in the area.

2 IN BRIEF

The Port of Townsville Long-term Seagrass Monitoring Program (LTSMP) was established in 2007. Seagrass in the region has been monitored annually since then. In 2019, the LTSMP was enhanced to a fit-for-purpose program to address regulator conditions outlined for the Channel Upgrade Project (CU Project): the Channel Upgrade Seagrass Program (CUSP). This specified monitoring program builds on the LTSMP and is designed to assess and monitor seagrass habitat biannually before, during and after planned capital dredging works. The CUSP includes the monitoring meadows that form the LTSMP and expanded areas of seagrass in assessments to meet regulatory requirements and conditions associated with the CU Project (Figure 1; Table 1). At the end of each year all seagrasses within the broader port limits are surveyed (Figure 1).

This report presents the results of the 18th year of the LTSMP and the 6th year of the CUSP. As this report incorporates monitoring after the completion of the CU Project, the report also includes an analysis of potential impacts from this capital dredging program.

Seagrass in the Port of Townsville were in an overall poor condition at the end of 2024. In the LTSMP four of the ten long-term monitoring meadows were in a satisfactory or better condition while six meadows were in poor or very poor condition (Figure 2). The inshore meadow along the Strand (Meadow 15), a meadow near the capital dredging location, was the only meadow that was in very good condition at the end of 2024 for all condition indicators (Figure 2). For the CUSP, three meadows were in a satisfactory or better condition while seven meadows were in poor or very poor condition (Table 3), noting that most meadows between the LTSMP and CUSP are common to each other (Figure 1). The degradation in meadows was mostly driven by declines in the seagrass above-ground biomass condition indicator (Figure 2, 3). The area of meadows was mostly satisfactory or better (Figure 2) however the total area of the LTSMP meadows has been below the long-term average for two years now (Figure 3). The species composition of seagrass meadows ranged between satisfactory and very good condition (Figure 2).

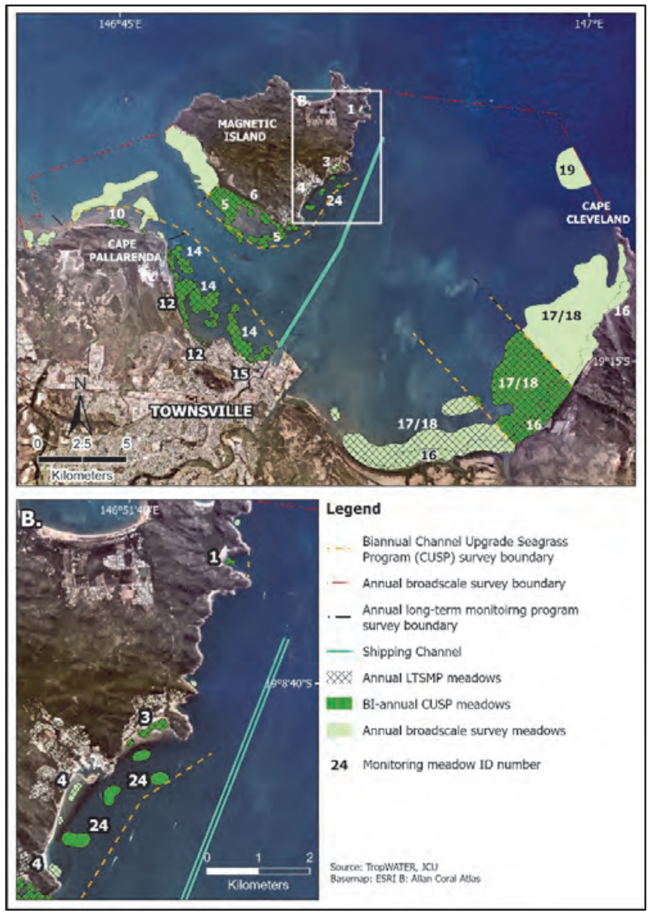


Figure 1. Location and survey extent of meadows assessed in annually surveyed LTSMP meadows, biannually surveyed CUSP meadows, and at the annual broadscale scale survey. Seagrass meadows represented are September/October 2024 meadows.

Seagrass was found across 8,046 ha in the annual broadscale survey boundary in 2024 (Figure 1). The long-term monitoring meadows (LTSMP) covered 4,564 ha of this (Figure 3), and the CUSP meadows covered 2,987 ha.

The loss of seagrass condition was most likely due to a range of cumulative climate event related influences across the Townsville region over the past six years (2019–2024) and not capital dredging activity. This is supported through analysis and models in this study investigating seagrass above-ground biomass with environmental parameters, dredge phase (pre- during- and post-dredging), location (seagrass assessment sites and meadows inside versus outside the modelled Zone Of Influence (ZOI), season (see section 5.5).

Models to assess the effects of environmental variables and dredging activity on seagrass above-ground biomass identified photosynthetically active radiation (PAR)) and seabed temperature as significant environmental predictors of seagrass above-ground biomass. During the CUSP (2019–2024) there were many periods when environmental conditions were not favourable for seagrass growth and persistence. Meteorological events that have collectively reduced light availability (PAR) to seagrass and resulted in suboptimal benthic temperature regimes during the CUSP include (see also section 5.6);

- Record flooding in January–February 2019.
- Above-average rainfall and river discharges during the 2018/19, 2021/22, and 2022/23 wet seasons.
- Extreme temperatures/marine heatwaves (MHW):
  - 2019: Australia's hottest year on record (GBRMPA).
  - February 2020: Record high sea surface temperatures (GBR Outlook Report 2024)
  - Summer 2021/2022: sea temperatures above the long-term average (GBR Outlook Report 2024).
  - Summer 2023/2024: high daily means (GBR Outlook Report 2024)
- Tropical Cyclones:
  - TC Jasper December 2023: Port of Townsville entered Condition Yellow, and CU MWMP water quality instruments were removed.
  - TC Kirrily (January 2024).

Most of these events caused elevated turbidity (NTU) through riverine discharges and wind/wave driven resuspension of seabed sediment into the water column, and in turn prolonged low light (PAR) conditions (Table 5; GHD 2024). This is supported and evidenced through the CU Marine Water Monitoring Program (CU MWMP) (GHD 2024). The CU MWMP affirmed that turbidity conditions in the Bay are strongly correlated with elevated wind and wave driven events, and that turbidity is strongly correlated with PAR. The CU MWMP reported patterns of decreasing PAR at most locations, including those far beyond the predicted ZOI of the dredge (i.e., Reference location Paluma Shoal), indicating the influence of broadscale prevailing meteorological pressures rather than the influence of the capital dredging Project.

Analysis comparing seagrass above-ground biomass with season, dredge phase (pre-, during-, post-dredging), and location (meadows and seagrass assessment sites within or outside the ZOI) further support that seagrass above-ground biomass loss in Townsville were not attributable to the capital dredging Project. This is evidenced through;

- Trends in seagrass above-ground biomass declines were consistently observed at assessment sites and seagrass meadows inside and outside the ZOI.
  - Seagrass assessment sites outside of the ZOI included those in the far east of Cleveland Bay, well beyond the predicted ZOI of the dredge.
- Seagrass above-ground biomass declines across dredge phases (pre-, during- and post-dredging) inside the ZOI were not significantly different, but above-ground biomass declines beyond the ZOI were statistically significant across dredge phases.
- The inshore Strand meadow (15), one of the meadows closest to capital dredging activity was the only monitoring meadow in a very good condition at the end of 2024.

Given that trends in seagrass above-ground biomass and PAR declines, and suboptimal temperatures (the two environmental parameters identified as predictors of seagrass above-ground biomass) were recorded at the Townsville region/Bay wide scale, the observed declines are considered natural occurrences indicative of system-wide pressures rather than localised impacts from capital dredging activities.

The pattern of seagrass decline extended beyond Townsville, with annual seagrass monitoring at Abbot Point also recording declines in seagrass above-ground biomass and/or area between 2022 and 2024 (McKenna et al. 2024; TropWATER in prep). Declines in seagrass cover were also recorded in the Great Barrier Reef Marine Park Authority Marine Monitoring Program (GBRMPA MMP). Seagrass monitoring at Shelley Beach recorded

0% seagrass cover at the end of 2024 (www.seagrasswatch.org/burdekin/). On Magnetic Island, the intertidal site MI1 recorded its lowest seagrass cover since 2016, while MI2 had 17.8% cover, and the subtidal site (MI3s) recorded 4.7% cover of seagrass. The intertidal sites on Magnetic Island were dominated by the colonising species *Halophila ovalis* (McKenzie et al. 2024). At Bushland Beach, seagrass cover at the end of 2024 was the lowest recorded since 2011.

The fact that seagrasses in Townsville still had satisfactory spatial coverage, good species composition and the presence of higher light requiring species in subtidal meadows provides a foundation for future recovery. The presence of dugong feeding trails in some meadows, also indicates ongoing ecological function, despite degraded conditions. Considering the poor condition of Townsville seagrass at the end of 2024, Port of Townsville (PoTL) have commissioned a post-wet season 2025 assessment of seagrass, to update seagrass meadow condition in the area.

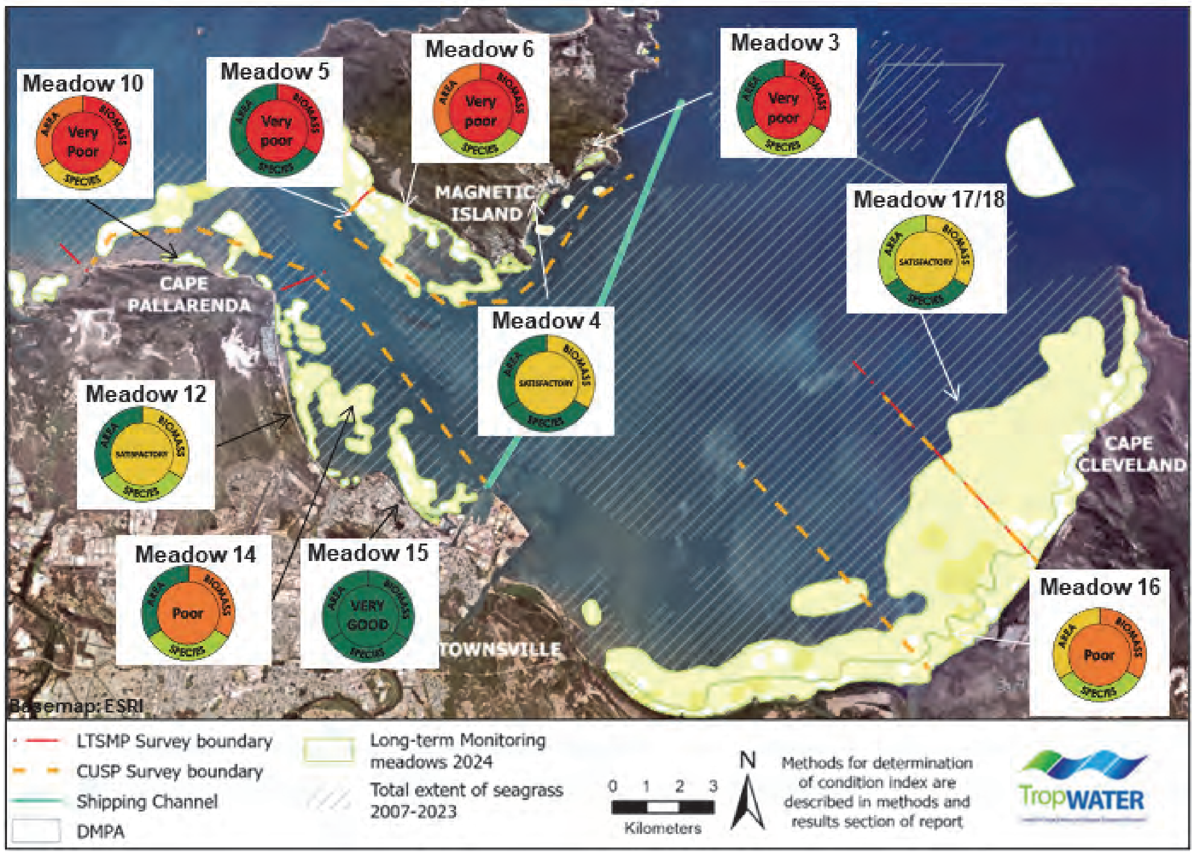


Figure 2. Seagrass condition for meadows monitored as part of the Long-Term Seagrass Monitoring Program (LTSMP) September/October 2024. For CUSP meadow condition see results section 5.2.

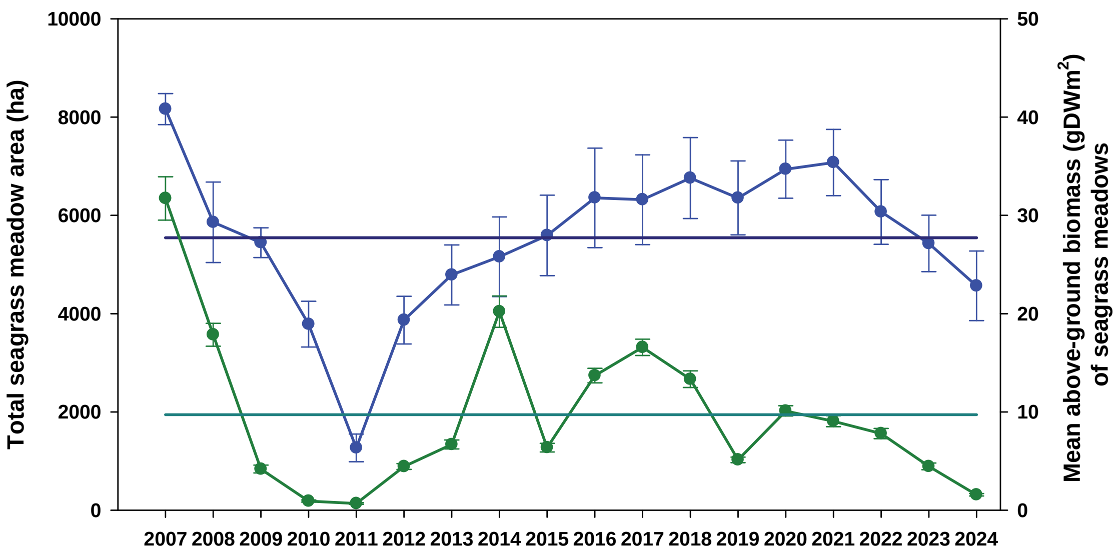


Figure 3. Total area (ha) of the Long-Term Seagrass Monitoring Program (LTSMP) seagrass meadows 2007–2024 (blue line) (error bars = R (reliability estimate), dark blue solid line = long term mean of total area (ha) 2007–2024). Mean meadow above-ground biomass (gDWm^2) of all LTSMP meadows combined 2007–2024 (dark green line) (error bars = standard error, green solid line = long term mean of meadow above-ground biomass (gDWm^2)).

3 INTRODUCTION

Seagrasses are one of the most productive marine habitats on earth and provide a variety of important ecosystem services (Barbier et al. 2011; Costanza et al. 2014). These services include the provision of nursery habitat for economically important fish and crustaceans (Coles et al. 1993; Heck et al. 2003), and food for grazing marine megaherbivores like dugongs and sea turtles (Heck et al. 2008; Scott et al. 2018). Seagrasses also play a major role in the cycling of nutrients (McMahon and Walker 1998), sequestration of carbon (Fourqurean et al. 2012; Lavery et al. 2013; York et al. 2018, Rasheed et al. 2019), stabilisation of sediments (James et al. 2019), and the improvement of water quality (McGlathery et al. 2007).

Globally, seagrasses have been declining due to natural and anthropogenic causes (Dunic et al. 2021; Waycott et al. 2009). Explanations for seagrass decline include natural disturbances such as storms and cyclones, disease and overgrazing by herbivores, and anthropogenic stresses including direct disturbance from coastal development, dredging and trawling, coupled with indirect effects through changes in water quality due to sedimentation, pollution, and eutrophication (Short and Wyllie-Echeverria 1996). In the Great Barrier Reef (GBR) coastal region, the hot spots with the highest threat exposure for seagrasses all occur in the southern two thirds of the GBR, in areas where multiple threats accumulate including urban, port, industrial and agricultural runoff (Grech et al. 2011). These hot spots arise as seagrasses occur in the same sheltered coastal locations where ports and urban centres are established (Coles et al. 2015). In Queensland this has been recognised and a strategic monitoring program of these high-risk areas has been established to aid in their management (Coles et al. 2015).

3.1 Queensland Ports Seagrass Monitoring Program

A long-term seagrass monitoring and assessment program is established in most Queensland commercial ports. The program was developed by James Cook University's Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) in partnership with the various Queensland port authorities. While each location is funded separately, a common methodology and rationale is used providing a network of seagrass monitoring locations throughout Queensland (Figure 4).

Figure 4. Location of Queensland port seagrass monitoring sites.

This strategic long-term assessment and monitoring program for seagrasses provides port managers and regulators with key information on seagrass habitat and ecosystem function. 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 habitats. The program has also provided significant advances in the science and knowledge of tropical seagrass and habitat ecology. This includes the development of tools, indicators and thresholds for the protection and management of seagrass, and an understanding of some of the drivers of seagrass change.

For more information on the program and reports from the other monitoring locations see: https://www.tropwater.com/themes/seagrass-habitats

3.2 Port of Townsville Seagrass Monitoring Programs

3.2.1 The Long-Term Seagrass Monitoring Program (LTSMP)

The Townsville port is managed by Port of Townsville Limited (PoTL). The port is situated in the Great Barrier Reef World Heritage Area, outside of the Great Barrier Reef Marine Park, and supports a diverse range of habitats including significant and productive seagrass meadows and reefs that begin in the intertidal zone and extend to the deeper areas of Cleveland Bay. Townsville seagrass meadows are a connectivity hot spot in the central GBR (Grech et al. 2018).

As part of their commitment to the environmental health of the port and surrounding areas, PoTL in partnership with James Cook University's TropWATER established a seagrass monitoring program in 2007 to assess and monitor the seagrass habitat surrounding Townsville and Magnetic Island; the Long-term Seagrass Monitoring Program (LTSMP). Detailed baseline surveys were conducted in 2007 and 2008 to provide information on the distribution, abundance and seasonality of seagrasses within the broader port limits (Rasheed and Taylor 2008). From these baseline surveys representative meadows (currently 10 meadows; Figure 5) were selected for annual monitoring, with broadscale mapping occurring in some years (2007, 2008, 2013, 2016, annually from 2019–2024). The areas selected for annual monitoring represent the range of seagrass communities within the port, and include meadows considered most likely to be influenced by port activity and development, along with areas outside the zone of influence of port activity and development. The LTSMP has mapped up to 25,000 ha (2007; Figures 31, 32) of coastal and deep-water seagrass in the broader Townsville area.

The program provides a regular assessment of seagrass condition and resilience in the area and provides an annual update on the marine environmental health of Cleveland Bay to inform port management. The monitoring program forms part of Queensland's network of long-term monitoring sites of important fish habitats in high-risk areas. Information from the program also provides key input into the condition and trend of habitats for the Dry Tropics Partnership for Healthy Water reporting (www.drytropicshealthywaters.org).

3.2.2 The Channel Upgrade Seagrass Program (CUSP)

The Port of Townsville Limited upgraded the approach channel between 2022 and early 2024 as part of their Port Expansion Project: The Channel Upgrade Project (CU Project). The CU Project involved capital dredging-related activities of the Platypus and Sea channels, and the construction of a reclamation area and temporary offloading facility. Capital dredging for the CU Project was finalised in March 2024 (see https://www.townsville-port.com.au/Projects-development/channel-upgrade/ for more information on the CU Project).

To address regulator conditions outlined for the Project, a fit-for-purpose seagrass program was established in 2019; the Channel Upgrade Seagrass Program (CUSP). This specified monitoring program built on the established LTSMP and was designed to assess and monitor seagrass habitat biannually in the Townsville region pre-, during- and post- planned capital dredging works. The CUSP included the monitoring meadows that form the LTSMP and expanded areas of seagrass in assessments to meet regulatory requirements and conditions associated with capital dredging for the CU Project (Table 1; Figure 5). The CUSP involved:

- Establishing baseline conditions of seagrass habitats before CU Project works began.
- Monitoring the condition of seagrass habitats pre-, during- and post-dredging.
- Assessing seagrass condition at selected monitoring meadows biannually and at the broadscale survey extent annually.
- Determining if any changes in seagrass habitat were attributable to CU Project capital dredging, climate/weather events or natural background changes.

This report presents the results of the 18th year of the LTSMP and the 6th year of the CUSP. As this report incorporates monitoring after the completion of capital dredging for the CU Project, the report also includes an analysis of potential impacts from dredging.

4 METHODS

4.1 Sampling approach

Survey and monitoring methods for assessing seagrass in the Townsville region follow those of the established techniques for Townsville and JCU TropWATER's Queensland-wide seagrass monitoring programs. The application of standardised methods in Townsville and throughout Queensland allows for direct comparison of local seagrass dynamics with other seagrass monitoring programs in the broader Queensland region.

Detailed methods and sampling approach for the LTSMP and CUSP are in previous reports (McKenna et al. 2022; Wells and Rasheed 2017). Briefly, the Townsville LTSMP has assessed and monitored ten seagrass meadows annually in the Townsville region since 2007 (Figure 5). Seagrass assessments for the LTSMP occur annually between September–November. In 2007, 2013 and 2016 the survey scope for the LTSMP increased to the broadscale survey extent (Figure 5). Assessing seagrass at the broadscale survey extent ensures trends observed in the monitoring meadows represent the broader Townsville area, and conversely the changes in seagrasses in the broader area add important perspective and confidence to any changes seen in the monitoring meadows. It is at this broadscale survey extent that the deeper water (>8 m) highly variable seagrasses between Cleveland Bay and Magnetic Island (Meadow 19) are assessed (Figure 5).

In preparation for the CU Project, in 2018, seagrass meadows that form the LTSMP were assessed to determine if the monitoring meadows were appropriate (i.e., location, species composition, meeting approval conditions etc.) to assess and monitor as sensitive receptors throughout the CU Project. Rather than changing the array of LTSMP meadows; as it was important to keep the LTSMP dataset continuing for ambient monitoring beyond the CU Project, a parallel program and selection of meadows was developed; the CUSP. While there are many seagrass meadows common to both the LTSMP and the CUSP, differences include (Table 1; Figure 5):

- The CUSP survey scope is completed biannually whereas the LTSMP survey scope is completed annually.
- Meadow 4 at Nelly Bay is not included in the CUSP but is included in the LTSMP.
- Only a section of LTSMP Meadows 16 and 17/18 are surveyed in the CUSP.
- Meadow 1 in Florence Bay, Magnetic Island was added to the CUSP and is not included in the LTSMP.
- Broadscale survey frequency was increased from every 3 years to annually.

In the original CUSP design, seagrass meadows were assigned as reference or impact meadows based on EIS and AEIS modelled zones of impact and influence from the CU Project capital dredging works. With the change dredge method and scope (i.e., from Trailor Suction Hopper Dredge to mechanical backhoe dredging and refined plume modelling), the nomination of reference/impact meadows changed to seagrass/seagrass meadows within the Zone Of Influence (ZOI) and seagrass/seagrass meadows outside the ZOI (Table 1; Figure 6). The seagrass meadows in the ZOI are seagrasses between the Strand/Breakwater Marina wall and Cape Pallarenda (Meadows 12, 14, 15). These meadows have sections that are inside and outside the ZOI (Figure 6).

During capital dredging for the CU Project, the broadscale survey assessments were completed at the end of each year between 2019–2024 rather than every third year as they had been with the LTSMP. This scope of survey will revert to every three years at the completion of the CU Project.

The CUSP was implemented in parallel with the Coral Monitoring Program and the Channel Upgrade Marine Water Monitoring Program (CU MWMP) as part of an integrated and complementary monitoring approach through the CU Project. CU MWMP water quality monitoring stations were positioned within or adjacent to some key seagrass meadows to be able to compare light and temperature with known seagrass condition.

(Figure 7). Data collected through the CU MWMP during dredging provided an early warning indication of change in water quality for sensitive receptors, such as seagrass, based on known impact pathways.

Table 1 provides details on which meadows are assessed biannually or annually, meadows described as reference/impact meadows according to the original EIS and AEIS modelling and the change in meadow location type (meadows within or outside the ZOI) based on updated plume modelling because of a change in capital dredge method.

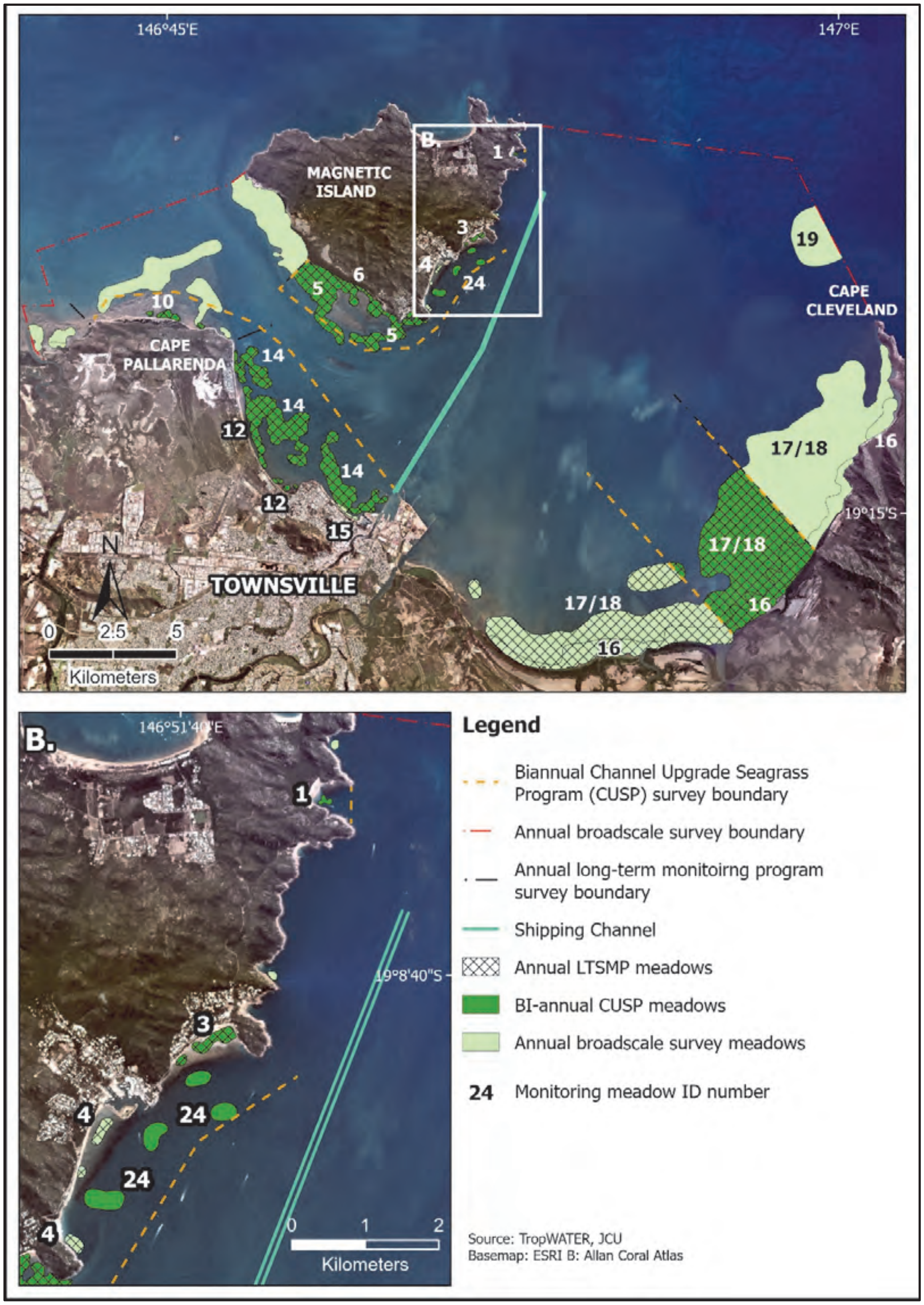


Figure 5. Location and survey extent of LTSMP meadows assessed annually, CUSP meadows assessed biannually, and meadows assessed annually at the broadscale survey extent. Seagrass meadows shown are September/October 2024 meadows.

Table 1. The seagrass meadows that make up the LTSMP and CUSP, their monitoring location type, survey frequency, and what species are present in the meadows.

Monitoring location (Meadow ID)	Monitoring location type based on original EIS & AEIS	Monitoring location type based on updated dredge plume modelling	Survey frequency for CU Project	Common to CUSP & LTSMP	Seagrass Meadow Depth	Seagrass meadow type (dominant species)*	Species present in meadow*	Monitoring History
Magnetic Island								
Florence Bay (1)	Impact	Reference	Biannually	N	Intertidal/shallow subtidal	HU	HU	2007, 08, 16, 19-24
Geoffrey Bay (3)	Impact	Reference	Biannually	Y	Intertidal	HU	HU, HO, CS	Detailed Annual >10 years
Nelly Bay (4)	Impact	Reference	Annually	N	Intertidal/shallow subtidal	HU	HU, HO, CS	Detailed Annual >10 years
Geoffrey Bay (24)	Impact	Reference	Biannually	N	Subtidal	HS	HS	2013, 16, 19-24
Cockle/Picnic Bay (5)	Impact	Reference	Biannually	Y	Intertidal/shallow subtidal	HU	CS, HU, HO, HS, HD	Detailed Annual >10 years
Cockle Bay (6)	Impact	Reference	Biannually	Y	Intertidal	ZM	ZM, HU, HO	Detailed Annual >10 years
Strand to Cape Pallarenda / Shelley Beach								
Shelly Beach (10)	Reference	Reference	Biannually	Y	Intertidal	ZM	ZM, HU, HO	Detailed Annual >10 years
Rowes Bay (12)	Impact	Gradient (inside & outside the Zone Of Influence)	Biannually	Y	Intertidal/shallow subtidal	HU	HU, HO, HD, ZM, HS, CS	Detailed Annual >10 years
Pallarenda inc. Virago Shoal) (14)	Impact	Gradient (inside & outside the Zone Of Influence)	Biannually	Y	Shallow subtidal	HS	HS, HU, HO, HD, CS	Detailed Annual >10 years
Strand (15)	Impact	Inside the Zone Of Influence	Annually	N	Intertidal/shallow subtidal	HU	HU, HO, HD, ZM, HS	Detailed Annual >10 years
Cleveland Bay (east side of bay)								
Cleveland Bay (16)	Reference	Reference	Biannually	Y	Intertidal	ZM	ZM, HU, CS	Detailed Annual >10 years
Cleveland Bay (17/18)	Reference	Reference	Biannually	Y	Subtidal	HU/CS/HS	HU, CS, HD, HS	Detailed Annual >10 years

*HU – *Halodule uninervis*, HO - *Halophila ovalis*, HD - *Halophila decipiens*, HS – *Halophila spinulosa*, HT – *Halophila tricostata*, ZM – *Zostera muelleri*, CS – *Cymodocea serrulata*

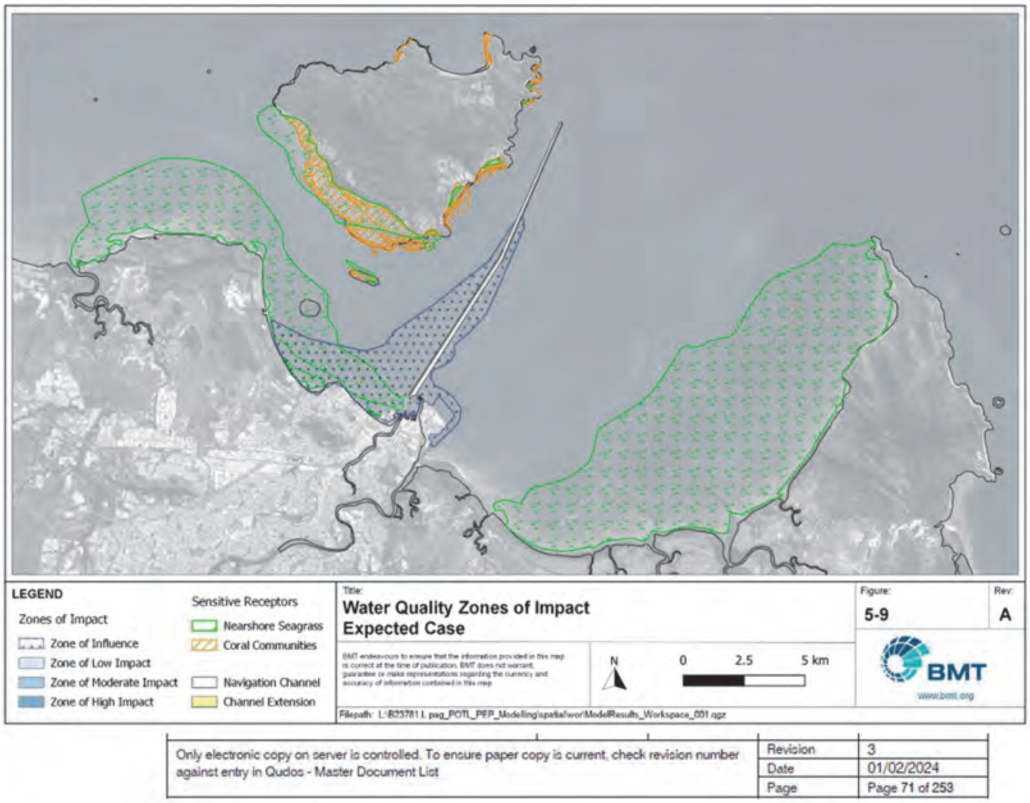


Figure 6. Figure 21 from the Townsville Port Expansion Channel Upgrade Project Mechanical Backhoe Dredge Management Plan showing Zone Of Impact output from the re-modelling for the CU Project. The expected case scenario only results in a Zone Of Influence (ZOI) (where plumes may be noticeable, but unlikely to have any ecological effects).The CU Project DMP can be found here: https://s3-ap-southeast-2.amazonaws.com/os-data-2/townsville-port-2/bundle24/20240201_pot_2095_-_cu_dmp_mechanical_dredge_r3.pdf

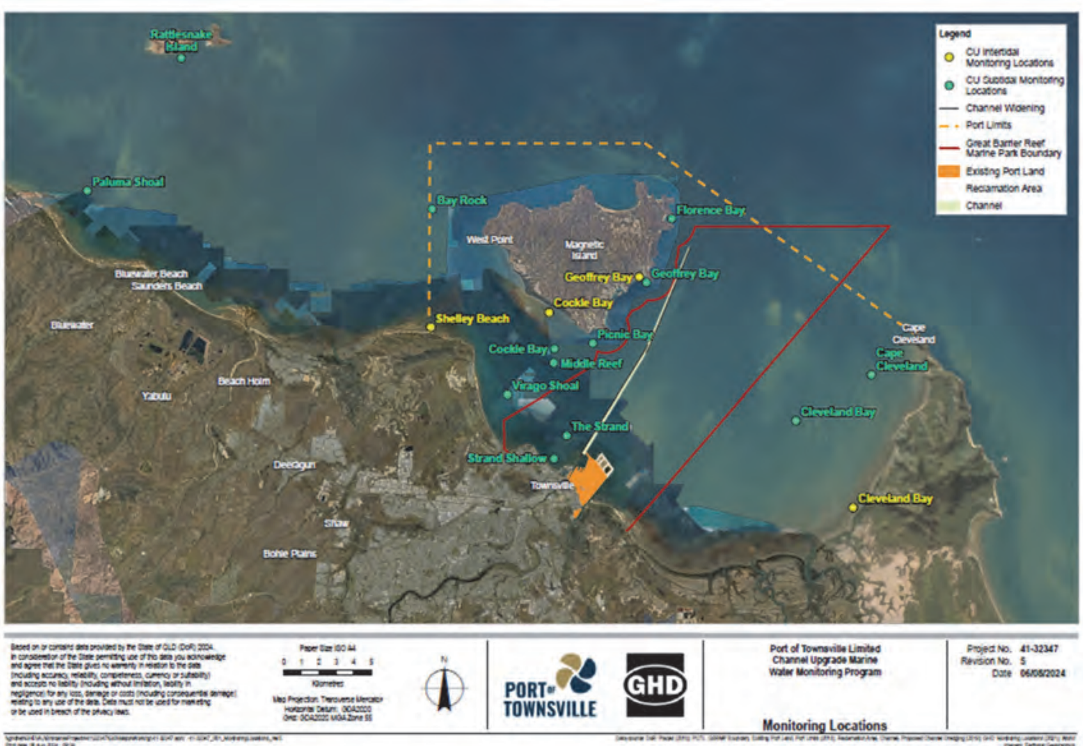


Figure 7. Water quality monitoring locations. Figure from the GHD Annual Synthesis Report 2023 Channel Upgrade - Marine Water Monitoring Program (GHD 2024).

4.2 Seagrass indicators and sampling methods

Three principal indicators of seagrass condition are assessed at each survey: seagrass above-ground biomass (grams dry weight per metre square (gDWm^2)), species composition and meadow area (ha). These are fundamental indicators used to answer questions surrounding seagrass condition, i.e., is seagrass present? What is the spatial footprint of the meadow? How dense is the seagrass? What species define the meadow?

Sampling methods include (Figure 8):

1. *Intertidal seagrass*: helicopter survey of exposed banks during spring low tide – sites were scattered throughout the seagrass meadow and sampled by a trained observer when the helicopter was in a low hover (<1 m) from the substrate.
2. *Shallow subtidal seagrass*: boat-based video camera vertical drops – A high-definition camera with wide-angle lens was attached to a 'drop' frame. Footage was relayed to a screen on the vessel for real-time data analysis and footage also recorded where required/needed. Assessment sites were sampled haphazardly within survey boundaries approximately every 50-200 m or where major changes in bottom topography and seagrass community type occurred. Assessment sites extended to the offshore edge of seagrass meadows or 'hard' survey boundaries.
3. *Deep-water seagrass*: boat-based towed video camera transects – Towed video transects used a high-definition camera with wide-angle lens. The camera and a net were attached to a sled and towed for approximately 100 m at drift speed. Footage was relayed to a screen on the vessel for real-time data analysis and footage also recorded where required/needed. Surface benthos was captured in the towed net and used to confirm seagrass species observed on the real-time screen. The technique ensured that a large area of seafloor was surveyed and integrated at each site so that patchily distributed seagrass and benthic life typically found in deep-water habitats was detected.

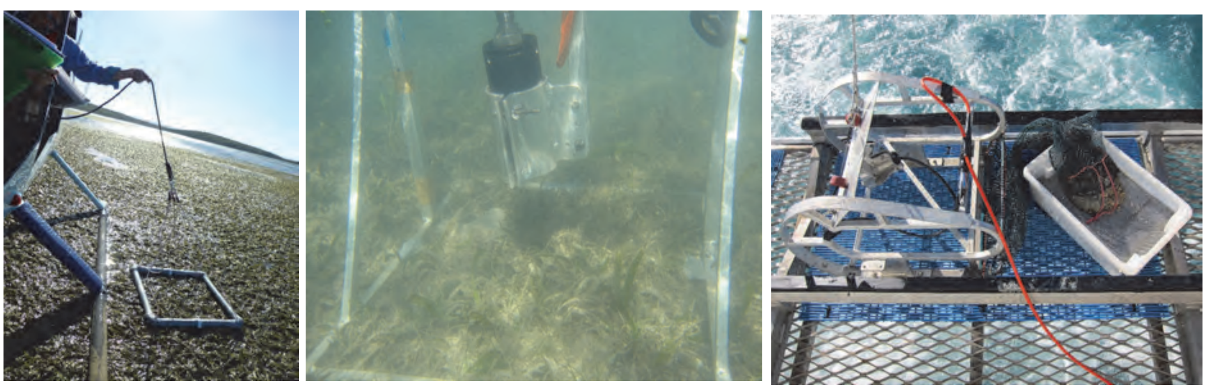


Figure 8. The different seagrass monitoring techniques: helicopter aerial surveillance, boat based digital, live feed camera systems.

Seagrass above-ground biomass was determined using a visual estimate of biomass technique (see Kirkman, 1978; Mellors, 1991). Seagrass percent covers were estimated using cover standards (www.seagrasswatch.org/manuals).

Above-ground biomass and species change calculations for Meadows 3 and 4 on Magnetic Island were performed excluding the contribution of *Cymodocea serrulata.* The focus of monitoring at these meadows is to track changes in *Halodule uninervis,* however the presence of the much larger *C. serrulata* in some isolated patches had the potential to mask changes to *H. uninervis* between years. This was due to the haphazard site locations occasionally falling on one of these isolated patches. Similarly, *Enhalus acoroides* has been excluded from meadow above-ground biomass calculations in Meadows 5 and 6 at Magnetic Island.

4.3 Seagrass condition assessments, index, and meadow baselines

A condition index was developed for seagrass monitoring meadows based on changes in mean above-ground biomass, total meadow area and species composition relative to a 10-year baseline (see Carter et al. 2023 for full details on the development of the condition index). 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 was the lowest indicator score where this is above-ground biomass or area. Where species composition was the lowest score, it contributes 50% of the overall meadow score, and the next lowest indicator (area or above-ground biomass) contributes the remaining 50% (Carter et al. 2023).

We have previously established baseline conditions for seagrass meadow above-ground biomass, area, and species composition at the ten LTSMP meadows. For CUSP meadows that are also LTSMP meadows (Table 1), these baseline conditions are the same. The baseline condition for the CUSP sub-section of the Cleveland Bay meadows (Meadows 16 and 17/18) was extracted from the historical data available and calculated for the CUSP section (10 years of baseline data). For the two CUSP meadows that are not part of the LTSMP (Meadows 1 and 24; Table 1) we have developed an interim baseline condition using the data available at the time of this report (nine years for Meadow 1 and eight years for Meadow 24). Baseline conditions for these meadows will continue to be added to and adjusted with additional years of monitoring data as appropriate until 10 years of data has been incorporated into the baseline analysis.

4.4 Habitat mapping and Geographic Information System

All survey data were entered into the Port of Townsville Limited Geographic Information System (GIS) database using ArcPro®. GIS layers were created to describe spatial features of the region: a site layer, seagrass meadow layers, and seagrass above-ground biomass interpolation layers.

- *Site Layer:* The site (point) layer contains data collected at each site, including:
    - Unique site number.
    - Temporal details – survey date and time.
    - Spatial details – latitude and 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 above-ground biomass standard error (SE); percent cover of seagrass, algae, and open substrate; presence/absence of dugong feeding trails (DFTs).
    - Sampling method and any relevant comments.

- *Meadow layers:* The meadow (polygon) layer provides summary information for all sites within each meadow, including:
    - Temporal details – survey date.
    - Habitat information – depth category (intertidal/subtidal), mean meadow above-ground biomass + standard error (SE), meadow area (hectares) + reliability estimate (R), number of sites within the meadow, seagrass species present, meadow density and community type, meadow landscape category.
    - Meadow identification number – a unique number assigned to each monitoring meadow to allow comparisons among surveys.
    - Sampling method and any relevant comments.

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

Seagrass meadow community type, meadow density (light, moderate, dense) and meadow landscape categories (isolated seagrass patches, aggregated patches, and continuous cover) were described using a standard nomenclature system developed for Queensland's seagrass meadows. Details of this approach are in previous reports (see McKenna et al. 2022).

Seagrass 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), depth contours and aerial photographs taken during helicopter surveys. Meadow area was determined using the calculate geometry function in ArcPro®. Meadows were assigned a mapping precision estimate (in metres) based on mapping methods used for that meadow (Table 2). 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.

Table 2. Mapping precision and methodology for seagrass meadows in Townsville, 2024.

Mapping precision	Mapping methodology
3-20 m	• Intertidal meadows completely exposed or visible at low tide. • Inshore meadow boundaries determined from helicopter. • Offshore meadow boundaries determined from helicopter and/or free diver/camera. • Relatively high density of mapping and survey sites. • Recent aerial photography aided in mapping.
20-50 m	• Meadow boundary interpreted from free diver/camera surveys. • Most meadows partially-completely subtidal. • Moderate density of survey sites. • Recent aerial photography aided in mapping.
100 m	• Subtidal meadow boundaries determined from free diving/camera/grab/distance between survey sites/ presence/absence of seagrass. • Meadows subtidal. • Moderate – sparse density of survey sites. • Deepwater meadows determined from camera tows

4.5 Environmental data

4.5.1 Local climate/weather conditions

Data for time series plots for rainfall (mm), air temperature and wind speed are publicly available from Australian Bureau of Meteorology website (http://www.bom.gov.au/climate/data/) and are presented in section 5.6. Data from Townsville Airport (station #032040) were used. Wind speed data was also obtained from the Australian Institute of Marine Science (AIMS) Cleveland Bay weather station. River flow data for time series plots in section 5.5 were obtained from the Queensland Governments Water Monitoring Information Portal https://water-monitoring.information.qld.gov.au/. Tidal data used in tidal exposure time series plots in section 5.6 were provided by Maritime Safety Queensland (MSQ) for Townsville Berth 1 Pumphouse (MSQ station #100447).

4.5.2 Light and temperature at seagrass meadows

Before capital dredging for the CU Project began, benthic light (Photosynthetically Active Radiation (PAR)) and temperature loggers (among other parameters) were deployed and maintained through the Channel Upgrade

Marine Water Monitoring Program (CU MWMP). These loggers were positioned within or adjacent to some key seagrass meadows to be able to compare light and temperature with known seagrass condition. Photosynthetically active radiation (PAR) and temperature data discussed, referred to or presented in this report have been provided by the CU MWMP. Reports with results from the CU MWMP can be found at https://www.townsville-port.com.au/Projects-development/channel-upgrade/environmental-monitoring/.

PAR (mol photons m^2 day^1) and temperature (°C) data for analyses against seagrass condition was provided from data collected and analysed from at least 10 logging stations, appropriate for use in informing seagrass condition. Data between December 2018 and November 2024 was used in this report.

4.6 Statistical approach and methods for the CUSP

4.6.1 Statistical approach

The CUSP was developed for the CU Project to contribute to PoTL's compliance of Project approval conditions. Surveys (survey event) specific to the CUSP were conducted between 2019–2024. Seagrass surveys were conducted biannually; post-wet season (April–June) and dry/pre-wet season (September–November) of each year. In July 2022 (mid-year), an additional survey event was conducted at a select group of meadows (Magnetic Island meadows 1, 3, 5, 6 and 24; Cape Pallarenda–Strand meadows 12 and 14; Figure 5) to capture any potential delayed response of seagrass stress/loss due to the March 2022 marine heat wave.

The LTSMP and long-term baselines for seagrass condition indicators (above-ground biomass ($gDWm^2$), area (ha), and species composition) developed through the LTSMP were used to inform statistical analysis and models and interpret results. Seagrass above-ground biomass was the primary indicator used for statistical analysis and models as this was the most sensitive condition indicator, that varied significantly over the CUSP study period: 2019–2024. The area and species composition of seagrass meadows mostly stayed in satisfactory or better condition against historical baselines.

The original CUSP design and proposed analysis was based on EIS and AEIS capital dredge plume modelling that included zones of impact. With the change in dredge method (to mechanical backhoe) and scope, updated modelling demonstrated that seagrass meadows were no longer in a zone of impact, only a Zone Of Influence (ZOI) (for expected case and worst case capital dredge plume modelling scenarios). Seagrass meadows that fell within the ZOI occurred between the Strand/Breakwater Marina wall and Cape Pallarenda (Meadows 12, 14, 15). Meadows 12 and 14 have sections that are inside and outside the ZOI (Figure 9).

As such the statistical approach to determine if capital dredging had an impact on seagrass focussed on analysing seagrass that occurred within the ZOI and seagrass that was located outside the ZOI (column 3 Table 1). Seagrass above-ground biomass was analysed against dredge phases (pre- during- and post-capital dredging) and analysed against environmental parameters. Statistical analysis approach was structured as the following:

- First determine if there were seasonal (post-wet, mid-year (2022 only) and pre-wet/dry season) differences in seagrass above-ground biomass.
    - If seasonal differences found, data from between year and within year survey events analysed separately.
    - If seasonal differences not found, data pooled according to dredge phase (pre-, during- and post-dredging).
- Compare and analyse seagrass assessment sites in any/all survey events that were within and outside the modelled ZOI polygon (for both worst case and expected case scenarios) (Figure 9);
    - 'Impact' sites were located within the modelled ZOI polygon (for both worst case and expected case scenarios) in any survey event.
    - 'Reference' sites were located outside of the modelled ZOI polygon (for both worst case and expected case scenarios).
- Compare and analyse seagrass assessment sites within and outside the ZOI against dredge phases:

  - Pre-dredging (seagrass assessments conducted 2019–2021; n=6 survey events),
  - During-dredging (seagrass assessments conducted 2022–2023; n=5 survey events) and
  - Post-dredging (seagrass assessments conducted in 2024; n=2 survey events).
- If capital dredging was found not to be the driver of seagrass change between 2019–2024, assess seagrass against environmental parameters to determine if meteorological/environmental parameters could be attributed to change.
- Data was analysed using quantitative methods and modelling.

Statistical analysis was conducted on original EIS AND AEIS nominated reference/impacts meadows (based on column 2 in Table 1) and are presented in Appendix 2 for interest.

4.6.1.1 Seagrass above-ground biomass vs season, Zone Of Influence and dredge phase

Using R (R Core Team 2024), normality of the six years' worth of CUSP data (13 survey events) was assessed by conducting Shapiro-Wilk tests on multiple variables. Results indicated a significant departure from normality ($p < 0.05$) for several variables, suggesting that the data were not normally distributed, therefore non-parametric tests were applied.

Kruskal-Wallis tests were used to determine whether there were statistically significant differences in seagrass above-ground biomass between seasons (post-wet season, mid-year (only in 'during' dredge phase at a select group of meadows) and dry season), among dredge phases within individual meadows, and the ZOI. This non-parametric approach was chosen due to its robustness against violations of normality assumptions, providing reliable results for our dataset.

To analyse the relationship between seagrass above-ground biomass, season, dredge phase, meadows and ZOI Generalised Linear Models (GLMs) were used. The GLMs were used in a multilevel approach to show trends in seagrass above-ground biomass between seasons, treatment (inside/outside the ZOI) and dredge phases (pre-, during-, post-dredging):

- First model examined seagrass above-ground biomass in relation to seasonality (post-wet season, mid-year (July 2022 only and only at 7 of the monitoring meadows) and dry/pre-wet season) across dredging phases.
  - This analysis was conducted to determine if there were any differences between seasons.
  - This analysis was conducted on pooled data across the study period: post-wet season pooled data (n=2489), the one-off mid-year survey July 2022 (n=255) and pre-wet/dry season data (n=2463).
  - This analysis was also conducted at the individual meadow scale pooled according to dredge phases.
  - If no differences were detected, all data were pooled across survey events according to dredge phase for analysis to increase the number of data points for the following models.
  - If significant differences were detected, only the data that showed no significant difference was pooled while the rest was removed from the GLM's and subsequent post-hoc analysis.
- Second model assessed seagrass above-ground biomass in relation to whether assessment sites were located inside or outside the expected and worst-case modelled ZOI for turbidity (Figure 9).

Each GLM used appropriate error structures and link functions to account for the distribution of above-ground biomass data, providing a robust framework for identifying potential effects of dredging on seagrass above-ground biomass. A significant interaction in these terms (inside/outside the ZOI, and dredge phases), specifically a reduction in seagrass above-ground biomass at sites within the ZOI relative to sites outside the ZOI, was interpreted as an impact related to dredging.

Post-hoc testing was performed using the emmeans package (Lenth 2025) to identify which assessment sites and dredging phases showed significant changes in above-ground biomass. Pairwise comparisons were conducted across levels of the categorical variables, allowing us to pinpoint specific combinations of site conditions (inside/outside the ZOI) and dredge phases where above-ground biomass was significantly higher or lower.

The long-term mean meadow above-ground biomass baseline (see section 4.3) for each meadow was displayed on figures at the meadow scale. These baseline means incorporate the variability and history of change for Townsville seagrass meadows. Displaying the baseline means for each meadow helps to visualise the 2019–2024 data in relation to historical data and helps place any changes that occurred in the meadows between 2019–2024 relative to historical data and variability.

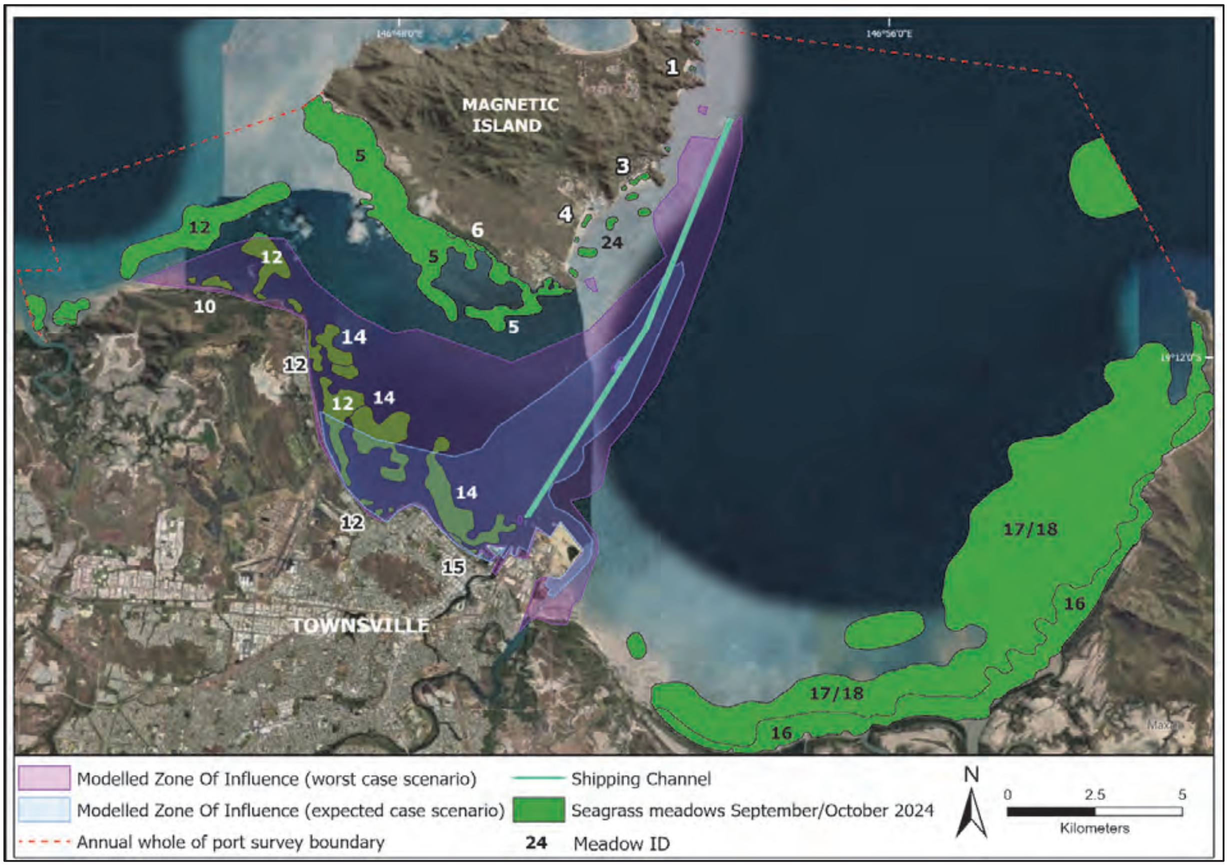


Figure 9. Seagrass meadows within and outside the modelled Zone Of Influence (expected case and worst case scenarios). Seagrass meadows shown are 2024 meadow polygons.

4.6.1.2 Seagrass above-ground biomass vs meteorological /environmental parameters

Data from the CU MWMP has consistently shown that PAR—a key driver of seagrass survival and persistence—is strongly influenced by a suite of interrelated environmental conditions. These include high wind and wave events that increase turbidity, rainfall, and periods of high cloud cover (GHD 2024). These factors often occur sequentially, compounding their impact and leading to extended periods of low benthic light available to sensitive receptors such as seagrass (GHD 2024). Time series analysis and correlation statistics confirm that turbidity is tightly linked to wind-driven wave activity, and that periods of reduced PAR consistently align with elevated turbidity levels (GHD 2024). Additionally, exceedances of light thresholds (i.e., during the 2023 monitoring period) were closely associated with high cloud cover, strong winds, increased wave heights, and rainfall—further reinforcing the role of these environmental drivers in limiting light availability to seagrass (GHD 2024).

Given the strong correlations between turbidity and other environmental variables that directly influence PAR, turbidity was not included as a standalone predictor in our assessments. Instead, to evaluate the effects of environmental conditions and capital dredging on seagrass above-ground biomass, we focused on PAR, temperature, wind, rainfall, and river flow.

A series of generalized additive mixed models (GAMMs) were developed to assess the effects of environmental variables and dredging activity on seagrass above-ground biomass. Environmental predictors (PAR, temperature, wind, rainfall and river flow) were summarized using rolling windows of 7, 14, 30, 60, and 90 days prior to each sampling event. For most variables (temperature, PAR, wind, and rainfall), running means were calculated, while for river discharge, total flow over each window was used. Temperature and PAR data were obtained from meadow-specific loggers, with secondary sources used when necessary. To reduce redundancy and improve interpretability, predictors were grouped by environmental type, and only one rolling window per group was retained for further analysis. The dataset was split into intertidal and subtidal data points for model fitting, GAMMs, and predictive modelling.

A two-stage model selection process was employed to address multicollinearity and streamline model construction. In the first stage, univariate GAMs were fit to each rolling window per variable group, selecting the best-performing version of each predictor. A second iterative process then tested combinations of these selected variables across models to identify those with the greatest explanatory power. Correlations were further assessed visually using ggpairs(), and when high multicollinearity was detected, the less theoretically relevant variable was excluded. All models used a negative binomial distribution to handle zero-inflated and over dispersed above-ground biomass data (common to seagrass data), and smooth terms were constrained to a basis dimension of 10 to prevent overfitting.

To enhance computational efficiency, we optimised the GAM fitting workflow. This included preprocessing to remove missing values and scale predictors, restricting predictor combinations to a maximum of 500 models, and utilising parallel processing to reduce runtime. We also switched from REML to faster fitting methods (e.g., fREML), cutting model selection time from several hours to 5–15 minutes. Only models with sufficient data (≥20 complete observations) and successful convergence were retained for evaluation.

The final multivariate GAMM incorporated both fixed and random effects, including dredging phase (pre-, during-, post-), spatial location (latitude × longitude), and meadow identity (intertidal/subtidal). Model performance was ranked using AIC, and the best-fitting model was interpreted using chi squared statistics, p-values, and partial effect plots. This allowed us to identify the most influential environmental drivers of seagrass above-ground biomass across intertidal and subtidal meadows, providing insight into both short- and long-term ecosystem responses. The relationship between environmental variables and the above-ground biomass of intertidal and subtidal seagrass systems were predicted based on the model of best fit.

5 RESULTS

5.1 Seagrass presence and species throughout Townsville

In 2024 two monitoring surveys were conducted in the Port of Townsville. The May–June survey monitored CUSP meadows only, with the September–October survey monitoring seagrass throughout the broadscale survey extent.

Key findings of the 2024 surveys include:

- May–June 2024; post-wet season CUSP survey:
  - A total of 586 sites were assessed for seagrass condition with seagrass present at ~37% of sites.
  - The CUSP seagrass meadow footprint covered 2,351 ha. This was a 35% decrease from the October 2023 CUSP meadow extent.
  - Deep-water meadows (e.g., Meadow 19 in the middle of Cleveland Bay) are not surveyed at this time of year (i.e., in the post-wet season survey).

- September–October 2024; pre-wet/dry season broadscale survey that encompassed the LTSMP and CUSP monitoring meadows, and all seagrass within the broadscale survey extent (Figure 5):
  - A total of 1,150 sites were assessed for seagrass condition with seagrass present at 39% of sites.
  - The broadscale survey seagrass footprint covered 8,046 ± 1,047 ha. This was an 18% decrease in footprint from the same time and survey extent in 2023. Of the broadscale footprint:
    - CUSP meadows covered 2,987 ± 448 ha: a 27% increase from the May–June 2024 survey.
    - LTSMP meadows covered 4,564 ± 709 ha: a 16% decrease in footprint from the same time in 2023.
    - The deep-water *Halophila* meadow (Meadow 19) covered 312 ± 72 ha.
  - For most meadows, meadow above-ground biomass was the lowest it has been since 2010/11 when Townsville meadows were significantly impacted by Tropical Cyclone Yasi (Jan/Feb 2011) and associated La Niña conditions.

Eleven seagrass species have historically been identified in the monitoring program (Figure 10). Except for *Syringodium isoetifolium*, *Cymodocea rotundata* and *Halophila tricostata* all species (eight) were present at assessment sites or noted in the area in the 2024 surveys (Figure 10). *Syringodium isoetifolium* was last found in the program in 2015 while *C. rotundata* was last present in monitoring meadows in 2021. *Halophila tricostata* was last present in the deepwater meadow in 2022 (Meadow 19).

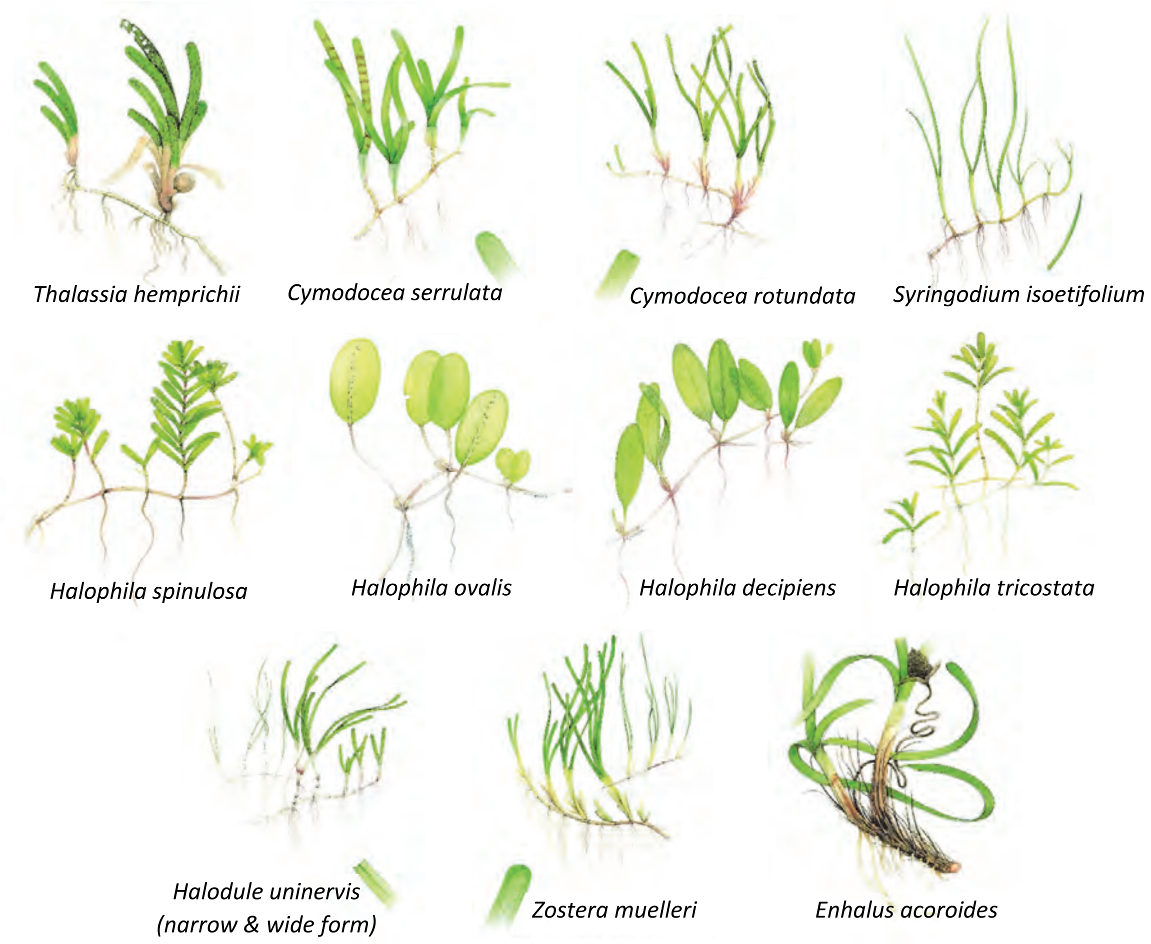


Figure 10. Seagrass species identified in the Townsville seagrass monitoring program since 2007. Pictures are not to scale.

5.2 Seagrass condition in Townsville

Townsville seagrass meadows were in an overall poor condition in 2024 between the two monitoring programs: LTSMP and CUSP (Table 3). This was primarily driven by low seagrass above-ground biomass in most of the meadows. Despite the low above-ground biomass across the region, the extent of most of the meadows across both programs was in satisfactory or better condition, and the species composition of all monitoring meadows was in satisfactory or better condition (Table 3).

the LTSMP four of the ten long-term monitoring meadows were in a satisfactory or better condition while six meadows were in poor or very poor condition (Table 3). The inshore meadow along the Strand (Meadow 15), a meadow near the capital dredging activity (within the ZOI), was the only meadow that was in very good condition for all condition indicators at the end of 2024 (Table 3). For the CUSP, three meadows were in a satisfactory or better condition while seven meadows were in poor or very poor condition (Table 3), noting that most meadows between the LTSMP and CUSP are common to each other (Figure 5).

For most meadows, meadow above-ground biomass was the lowest it has been since 2010/11 when Townsville meadows were significantly impacted by Tropical Cyclone Yasi (Jan/Feb 2011) and associated La Niña conditions.

Individual monitoring meadow area ranged from 1.33 ha in the subtidal *H. uninervis* Florence Bay meadow (Meadow 1; Figure 11, 15) to 2,436 ha for the subtidal Cleveland Bay meadow (Meadow 17/18; Figure 11, 27).

Monitoring meadow above-ground biomass ranged from 0.04 gDWm^2 in the intertidal *Zostera muelleri* meadow at Shelley Beach (Meadow 10) to 2.73 gDWm^2 in the subtidal Cleveland Bay *Halodule uninervis* meadow (Figure 29).

Table 3. Grades and scores for seagrass indicators (above-ground biomass (gDWm^2), area (ha), and species composition) for the Long-Term Seagrass Monitoring Program (LTSMP) and Channel Upgrade Seagrass Program (CUSP) meadows in Townsville; September–October 2024 survey.

Meadow	Region	LTSMP/CUSP	Above-ground Biomass (gDWm^2)	Area (ha)	Species Composition	LTSMP Overall Meadow Score	CUSP Overall Meadow Score
1	Magnetic Island	CUSP	0.69	0.85	1.0		0.69
3	Magnetic Island	LTSMP & CUSP	0.05	0.85	0.77	0.05	0.05
4	Magnetic Island	LTSMP	0.52	0.90	1.0	0.52	
5	Magnetic Island	LTSMP & CUSP	0.24	1.0	0.95	0.24	0.24
6	Magnetic Island	LTSMP & CUSP	0.15	0.28	0.65	0.15	0.15
24	Magnetic Island	CUSP	0.16	0.65	0.61		0.16
10	Cape Pallarenda - Strand	LTSMP & CUSP	0.01	0.32	0.52	0.01	0.01
12	Cape Pallarenda - Strand	LTSMP & CUSP	0.60	0.95	0.78	0.60	0.60
14	Cape Pallarenda - Strand	LTSMP & CUSP	0.45	0.57	0.95	0.45	0.45
15	Cape Pallarenda - Strand	LTSMP	0.85	0.99	0.99	0.85	
16	Cleveland Bay	LTSMP	0.28	0.56	0.79	0.28	
16 (CUSP meadow section)	Cleveland Bay	CUSP	0.27	0.88	0.82		0.27
17/18	Cleveland Bay	LTSMP	0.50	0.73	0.96	0.50	
17/18 (CUSP meadow section)	Cleveland Bay	CUSP	0.50	0.69	0.97		0.50
					LTSMP - Overall Score for the Port of Townsville 2024	**0.37**	
					CUSP - Overall Score for the Port of Townsville 2024		**0.31**

= very good condition = good condition = satisfactory condition

= poor condition = very poor condition

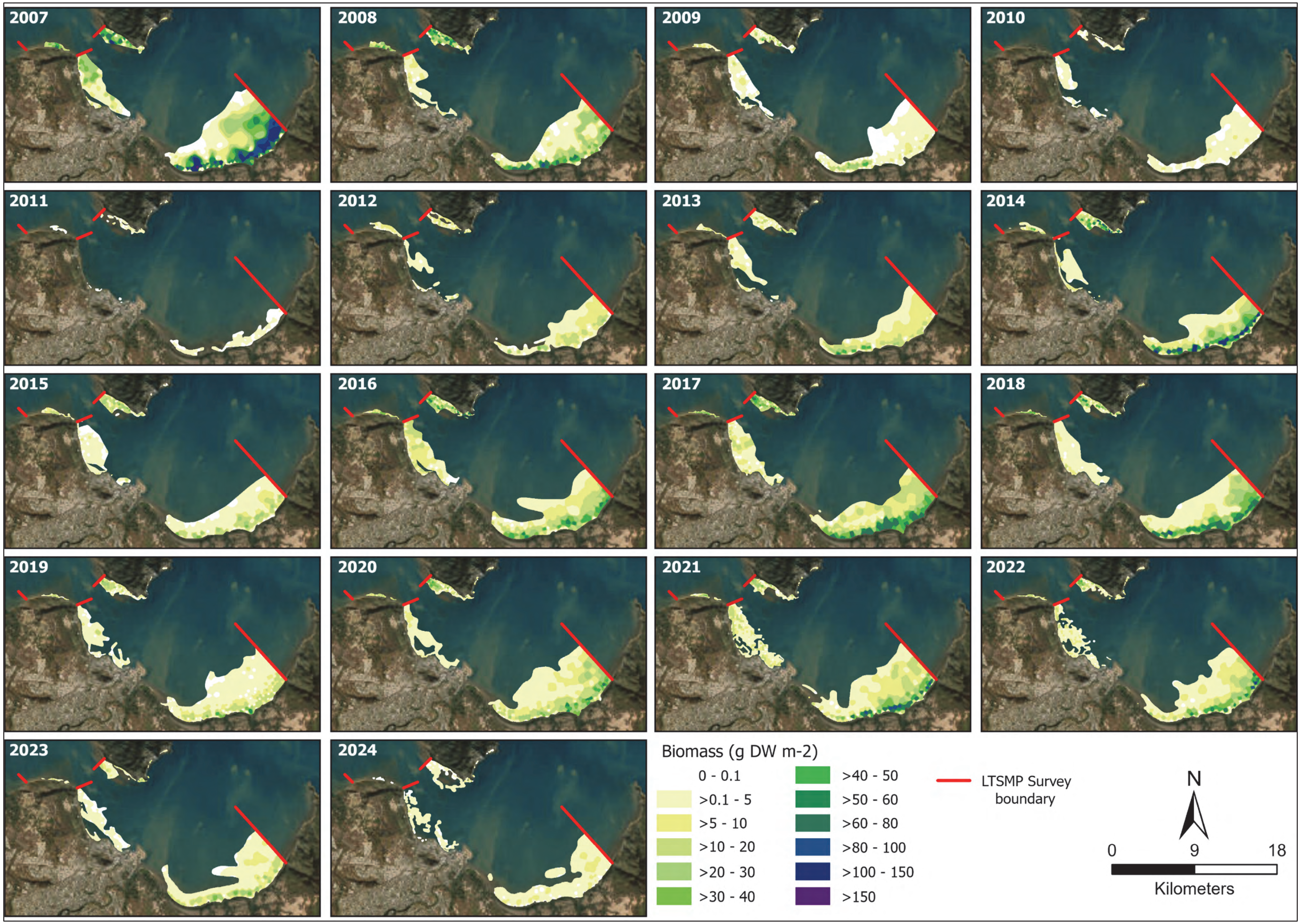


Figure 11. Long-Term Seagrass Monitoring Program (LTSMP) meadow above-ground biomass (gDWm^2), location, and spatial extent of meadows from 2007 – 2024. Note: deepwater meadow (19) in the middle of the bay not displayed.

5.2.1 Magnetic Island seagrass meadows

Between the LTSMP and CUSP there are six monitoring meadows around Magnetic Island (Meadows 1, 3, 4, 5, 6, 24) (Figures 15-20). These meadows range from intertidal to deeper water (>8 m below MSL) meadows. Two of the six meadows were of satisfactory or better condition at the end of 2024, while the other four meadows were in very poor condition measured against their long-term baselines (Table 3). Condition indicators (above-ground biomass, area, and species composition) for each meadow ranged from very poor to very good (Table 3).

The Geoffrey Bay intertidal *H. uninervis* meadow (3) was degraded from 'poor' (2023) to 'very poor' this survey due to a further decline in overall meadow above-ground biomass (Figure 16). The extent of the meadow and the species composition of the meadow remained in very good and good condition respectively. Above-ground biomass in the meadow increased between the October 2023 survey and the May 2024 survey, but then decreased again by the September 2024 survey. The cover of seagrass in this meadow has become very sparse (i.e., most assessment sites had <5% cover of seagrass) and seagrass shoots are very short. Small declines in area and species composition were measured, however not to a degree to reduce the condition grade for these indicators (Figure 16).

The subtidal *Halophila* meadow (24) that spans the deepwater areas between Geoffrey Bay and Nelly Bay degraded from poor condition (2022 and 2023) to very poor condition at the end of 2024. This was due to meadow above-ground biomass scoring very poor against its baseline value (Table 3; Figure 20). The area of this meadow has been on a downward trajectory after peaking in 2020. Despite this decline, the extent of the meadow was still considered to be in good condition against its historical baseline (Table 3; Figure 20). Species composition of the meadow shifted from very good in 2023 to satisfactory in 2024. This was due to the meadow having a higher presence of *H. decipiens* in the meadow, rather than that meadow being dominated by *H. spinulosa*. Seagrass was found to 9.4 m below MSL in this meadow, similar to the same time last year, the deepest seagrass in the LTSMP and CUSP 2024 monitoring surveys. Seagrass has previously been found to 11.2 m below MSL in this meadow. The baseline for all condition indicators for this meadow is still being developed, as ten years of data has not yet been collected, on which baseline values for condition indicators are set (see section 4.3). Moving forward, some of these condition scores may therefore change.

The other two monitoring meadows on the eastern side of Magnetic Island (Meadows 1 and 4) were in satisfactory or better condition in October 2024, similar to the same time in 2023 (Figures 15, 17). After being at its highest density in October 2023 since monitoring began, the Nelly Bay meadow (4) underwent a significant decline in above-ground biomass by October 2024 to satisfactory condition. This was due to the loss of above-ground biomass 'hot spots' of *H. uninervis* (wide morphology) that have been present in the meadow for the last couple of years. The Florence Bay meadow (1) was in good condition.

On the southwestern side of the Island, the Cockle Bay monitoring meadows were in very poor condition in October 2024 (Figures 18, 19). Both the intertidal *Z. muelleri* meadow (6) and the intertidal-subtidal *H. uninervis* monitoring meadow (5) declined in above-ground biomass from 2023 to 2024 degrading the condition of both meadows to very poor. In contrast, the area of Meadow 5 significantly increased in 2024 to the largest seagrass extent recorded in the LTSMP for this meadow. The area of this monitoring meadow had been on a downward trajectory since 2013, with much of the decline in extent occurring on the meadow's seaward edges. In the May 2024 survey, there was an increase in the extent of the meadow, and by October 2024 the meadow had again expanded. Most of this gain occurred along the seaward edges of the meadow and was a mix of *H. ovalis* and *H. uninervis*. We have not recorded seagrass in these southeastern edges since 2015 (Figure 11). We recorded a significant increase in *H. ovalis* across this reef top with significant numbers of dugong feeding trails present (Figure 12).

Figure 12. Significant numbers of dugong feeding trails (meandering lines in images) found throughout the Cockle Bay reef top monitoring meadow (Meadow 5), in *Halophila ovalis* dominated areas of the meadow in the September–October 2024 survey.

The Cockle Bay *Z. muelleri* meadow (6) continued to be in very poor condition, with not very much *Z. muelleri* recorded in this section of the Island (Figure 19). The majority of seagrass here is now *H. ovalis*, with small, isolated patches of *Z. muelleri* spread throughout a very small stretch of mangroves. The reduction in *Z. muelleri* was also recorded across the whole meadow (at the broadscale survey extent). No *Z. muelleri* was recorded in the portion of the meadow beyond the LTSMP survey boundary (i.e., from the LTSMP survey boundary to West Point) like there has been in previous years. This meadow has been variable in its extent from year to year throughout the program (Figure 19). Much of this variability is because of the variable presence and inclusion, then the absence (and therefore exclusion) of isolated patches of *Z. muelleri* when aerially mapping the boundary of the meadow on the seaward side of the meadow.

5.2.2 Cape Pallarenda-Strand seagrass meadows

There are four monitoring meadows that make up the Cape Pallarenda – Strand/Breakwater Marina region (Meadows 10, 12, 14, 15) (Figures 21–24). The condition of monitoring meadows in this region ranged from very poor (Meadow 10) to very good (Meadow 15) at the end of 2024. The most significant change was in the intertidal Shelley Beach *Z. muelleri* meadow (10). The presence of *Z. muelleri* in this area of Townsville has been on a downward trajectory since at least 2017 (Figure 21). The only other *Z. muelleri* found in this stretch of coast is towards the Bohle River. Only four of the eleven assessment sites in this meadow had *Z. muelleri* present, the other sites that made up this meadow were dominated by *H. uninervis* resulting in the species composition indicator degrading from very good condition (2023) to satisfactory condition (2024) (Table 3; Figure 13). Seagrass cover in this area was only 1–2% (Figure 14). Unlike previous surveys where the *H. uninervis* meadow (12) has abutted and formed the seaward boundary of Meadow 10, *H. uninervis* was absent on most of the Cape Pallarenda to Bohle River intertidal bank (Figure 29).

In the 2023 annual seagrass report (McKenna et al. 2024) we conveyed that field observations by multiple seagrass experts working on different research and monitoring Projects noted that there had been a large sediment shift in the Cape Pallarenda/Shelley Beach area from the area being dominated by mud, which *Z. muelleri* prefer to grow in, to coarser sand. In the October 2024 survey, researchers also noted much scouring of sediment in the area, with sites that had seagrass present recorded as having rhizomes and roots exposed to the air. There were many locations in this area where only exposed rhizomes remained of the plant, indicating there had been significant scouring in the area or sediment shift. Wolanski and Hopper's recent paper (2025; Article In Press), suggest that the Pallarenda coast, north of the mouth of Three Mile Creek started eroding severely in 2020 with sand cliffs developing in late 2022. While Wolanski and Hopper did not look beyond Cape Pallarenda, some of this sediment activity/migration may extend between Cape Pallarenda and the Bohle River where have seen sediment shift/scouring in the Shelley Beach seagrass meadow/sand bank.

Another notable change was the lack of dugong feeding trails in the area. Compared to previous survey years, we did not record any dugong feeding trails in this area in the October 2024 survey. In the past the seagrass meadows around Cape Pallarenda and Shelley Beach have been a high use area for dugongs.

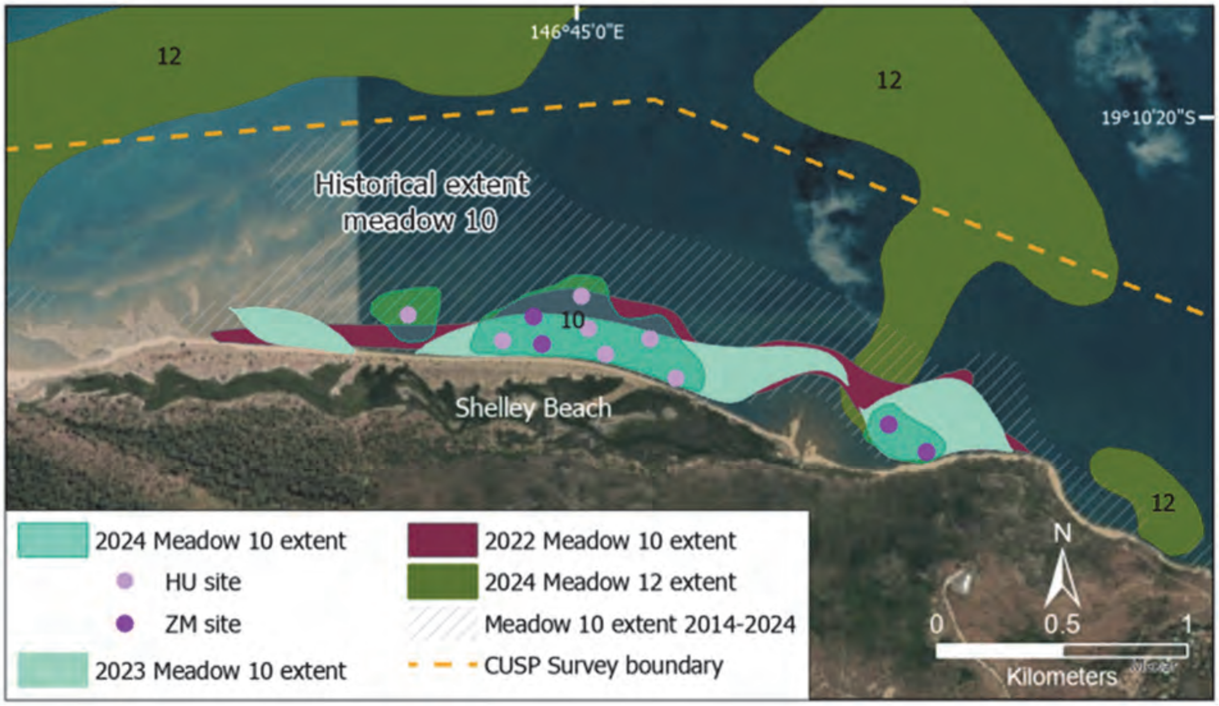


Figure 13. Seagrass spatial extent and footprint in the Shelley Beach meadow (Meadow 10) (2014–2024) showing the retraction of seagrass and species change recorded in 2024. Sites that had no seagrass in 2024 are not displayed.

Figure 14. Example of low cover of *Z. muelleri* at assessment sites at Shelley Beach in the September–October 2024 survey.

For the meadows within the modelled ZOI (expected case scenario); Meadows 12, 14 and 15, the condition of Meadow 14 remained the same (poor) between 2023 and 2024 annual surveys; Meadow 15 increased in condition from good to very good; and Meadow 12 decreased in condition from good in 2023, to satisfactory in 2024 (Table 3; Figures 22–24). For Meadow 12, this downgrade in condition score was due to a very small decrease in the above-ground biomass score between years: 2023 = 0.65, 2024 = 0.60, which was enough to push Meadow 12 into the satisfactory condition category.

While the subtidal Meadow 14 remained in poor condition (2023 and 2024) due to consecutive years of a poor above-ground biomass score, the species composition of the meadow has been in very good condition. In 2024, the meadow consisted mostly of *H. uninervis* with *H. ovalis* and *H. decipiens* making up the rest of the species mix (Figure 23; Appendix 1). *H. spinulosa*, historically one of the dominant species of the meadow, was not present at any of the assessment sites in Meadow 14 in the September–October 2024 survey. Seagrass was found to 4.95 m (below MSL) in the September–October 2024 survey, similar to previous years.

The above-ground biomass in Meadow 15, which extends between the Mariners North rock wall, northwest to the second sea groyne, increased between the 2023 and 2024 annual surveys, pushing the meadow into very good condition (Figure 24). Seagrass above-ground biomass, area and species composition indicators were all in very good condition at the end of 2024.

5.2.3 Cleveland Bay seagrass meadows

There are two monitoring meadows in Cleveland Bay: the intertidal *Z. muelleri* meadow (Meadow 16) and the shallow subtidal *H. uninervis* meadow (Meadow 17/18) (Figures 25–28). These meadows are the largest continuous coastal meadows in Townsville (Figure 11). For the CUSP, only a section of these large meadows is monitored biannually (Figures 5, 26, 28).

In 2023, both monitoring meadows (16 and 17/18) were in a satisfactory condition. In 2024 the subtidal *H. uninervis* meadow (17/18) remained in the same condition while Meadow 16, like all the other *Z. muelleri* meadows in the Townsville region degraded to a poor condition, driven by a decline in meadow above-ground biomass (Figures 25–28). The density of this meadow (16) has been quite variable and seems to fluctuate between peaks and troughs every three to four years. The area of the meadow (16) is not as variable as above-ground biomass, but it has been on a downward trajectory since 2018 (Figure 25). Contrasting to this trend, in the CUSP section of Meadow 16 there was an increase in meadow area that was significant enough to raise the condition score for CUSP (16) area from satisfactory in 2023 to very good in 2024 (Table 3; Figure 26).

The notable change in this intertidal meadow has been the reduction in high-density seagrass 'hotspots' across the meadow over the last couple of years (Figure 11). In 2022, above-ground biomass 'hotspots' of up to 100 $gDWm^2$ were recorded in the meadow (Figure 11). In the same area in 2023 these 'hotspots' reduced to ~34 $gDWm^2$. In 2024 these 'hotspots' only consisted of seagrass up to 9 $gDWm^2$. Seagrass cover in the meadow ranged from 1–30% at assessment sites.

At the adjacent subtidal *H. uninervis* meadow (Meadow 17/18), meadow above-ground biomass has been in a satisfactory condition for two years now, following a three-year rebound into good condition after the 2019 Townsville floods (Table 3; Figures 27, 28). The area of the meadow fell just below the long-term baseline for the first time in eight years but remains in good condition. The species composition in the meadow has been in very good condition since 2014. The only notable change in the September–October 2024 survey was the reduction in the presence of *C. serrulata* in the meadow. This species has consistently been in the meadow for the last 9 years (Figure 27; Appendix 1). In 2024, only two assessment sites had *C. serrulata* present. *Halophila ovalis* and *H. decipiens* made up the rest of the above-ground biomass in the meadow (Figure 27; Appendix 1). The lack of *C. serrulata* in the meadow would contribute to a loss in overall meadow above-ground biomass.

5.2.4 Cleveland Bay deep-water seagrass meadow

The Cleveland Bay deep-water meadow (Meadow 19) is extremely variable in its presence, distribution, and footprint. The above-ground biomass of the meadow is relatively stable as the meadow only ever has a light density and low cover of *Halophila* species when present (Figures 30–32).

In 2019, the extent of this variable deep-water meadow was the largest recorded since 2007; 8,023 ha (Figures 30–32). In 2020, this area decreased by nearly 67% to 2,329 ha, and the meadow became fragmented. In 2021, the meadow increased again to 5,405 ha. In 2023, the meadows' footprint only measured 163 ha. In 2024 this meadow was only present in a small area on the northeastern side of the survey boundary.

In 2021 *H. tricostata* was recorded in this meadow. This species had not been recorded in the LTSMP until then, although has previously been recorded in the region. *Halophila tricostata* has not been present at assessment sites since 2021.

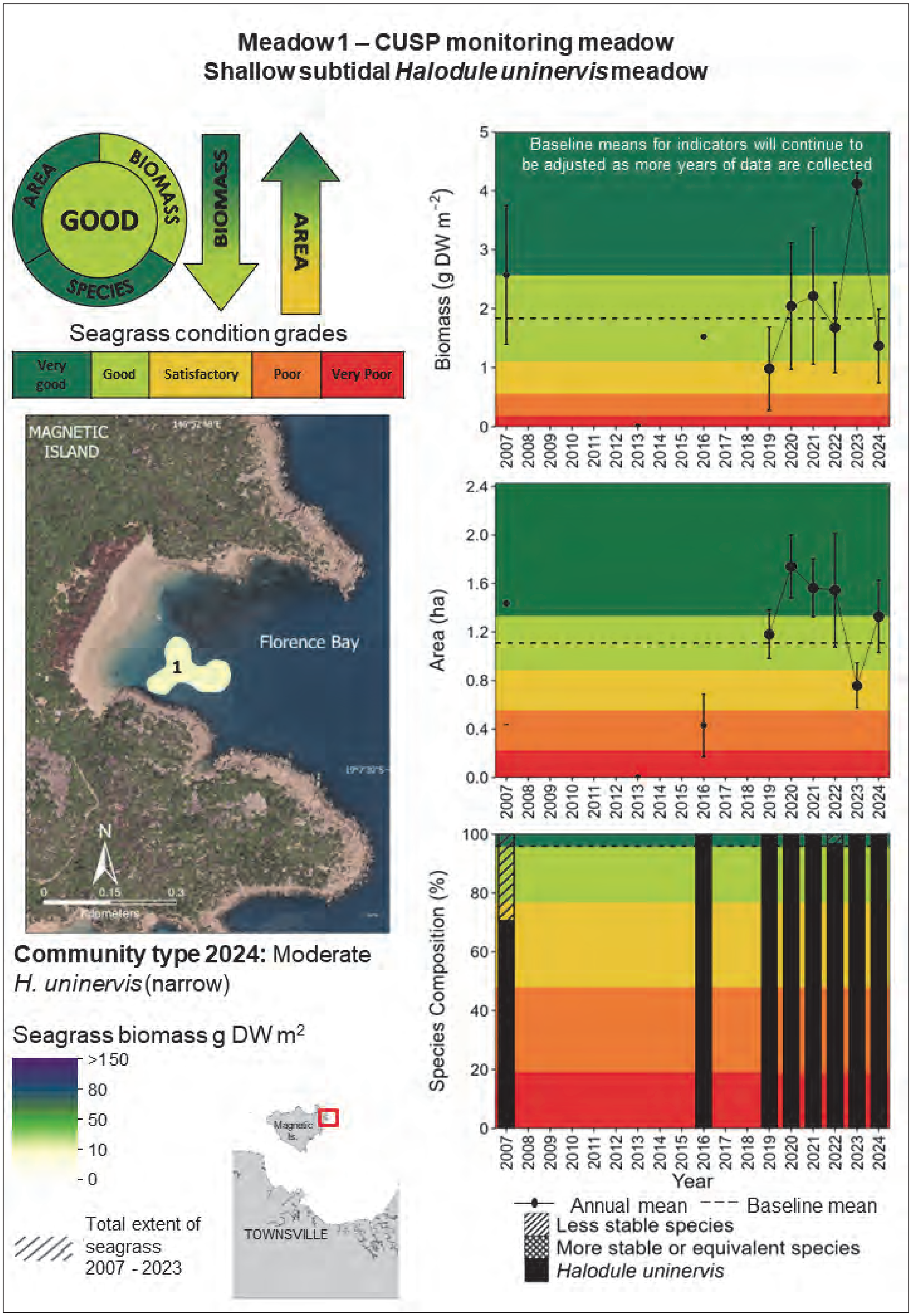


Figure 15. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for seagrass Meadow 1 at Magnetic Island, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

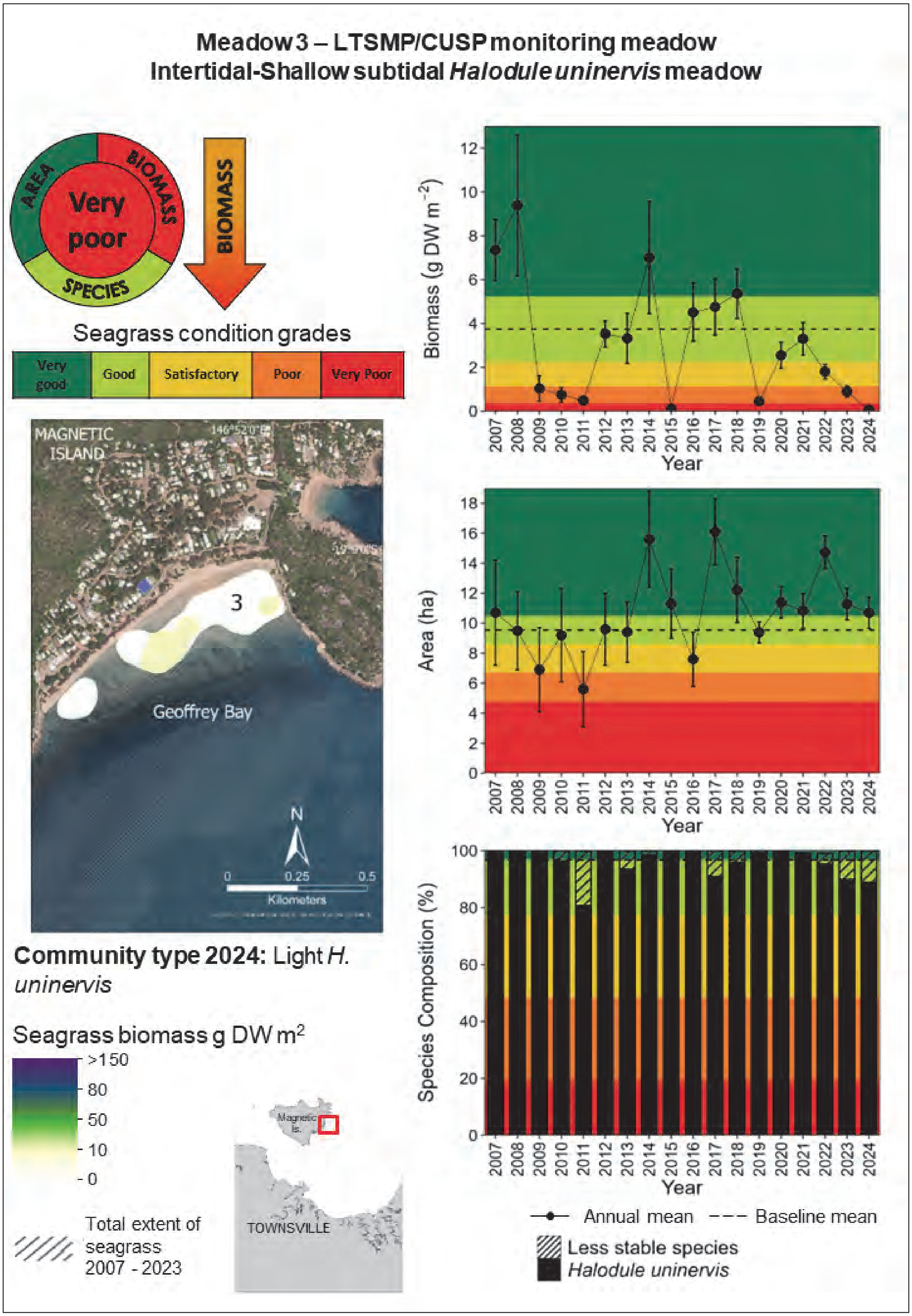


Figure 16. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for seagrass Meadow 3 at Magnetic Island, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

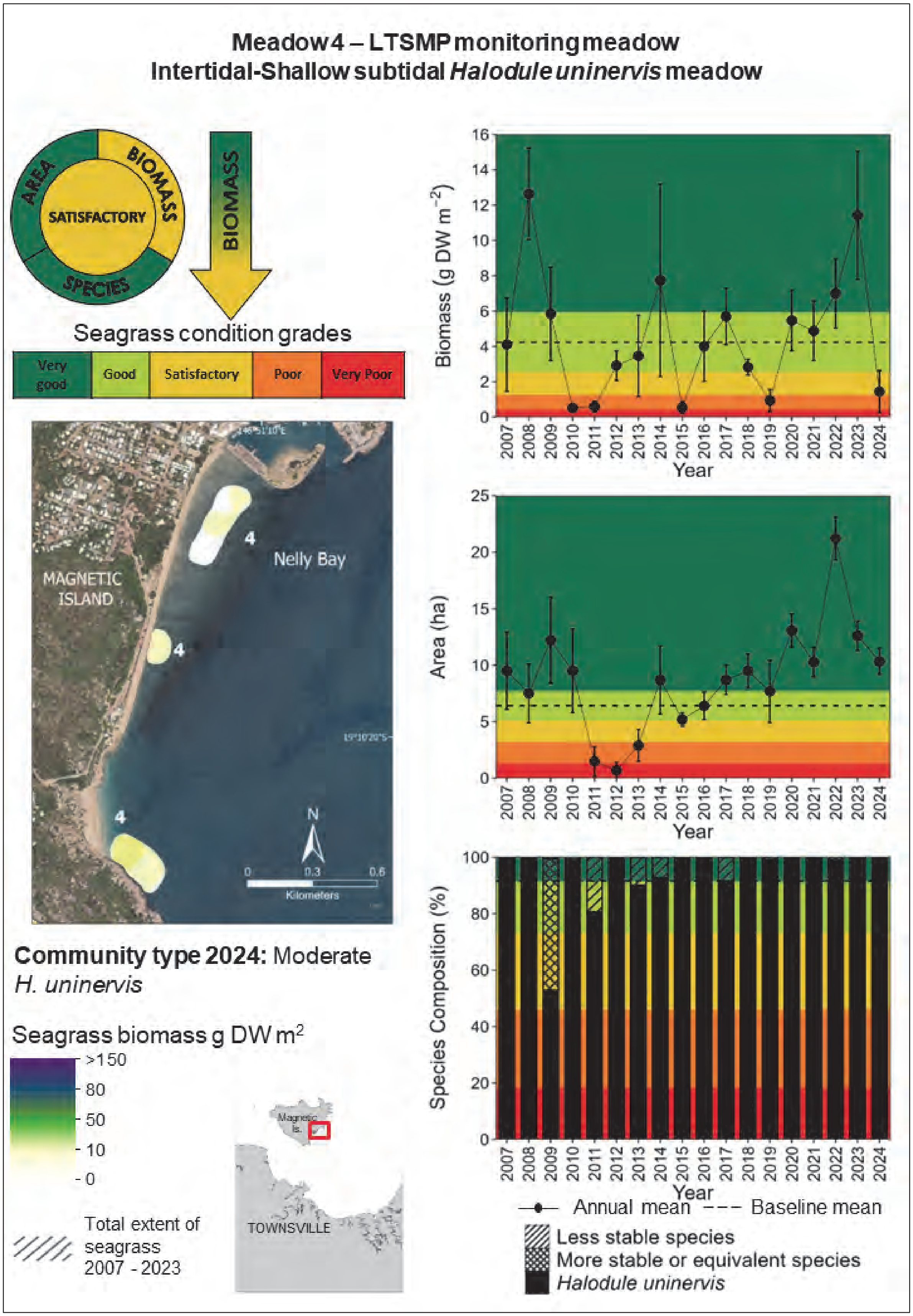


Figure 17. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for LTSMP seagrass Meadow 4 at Magnetic Island, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

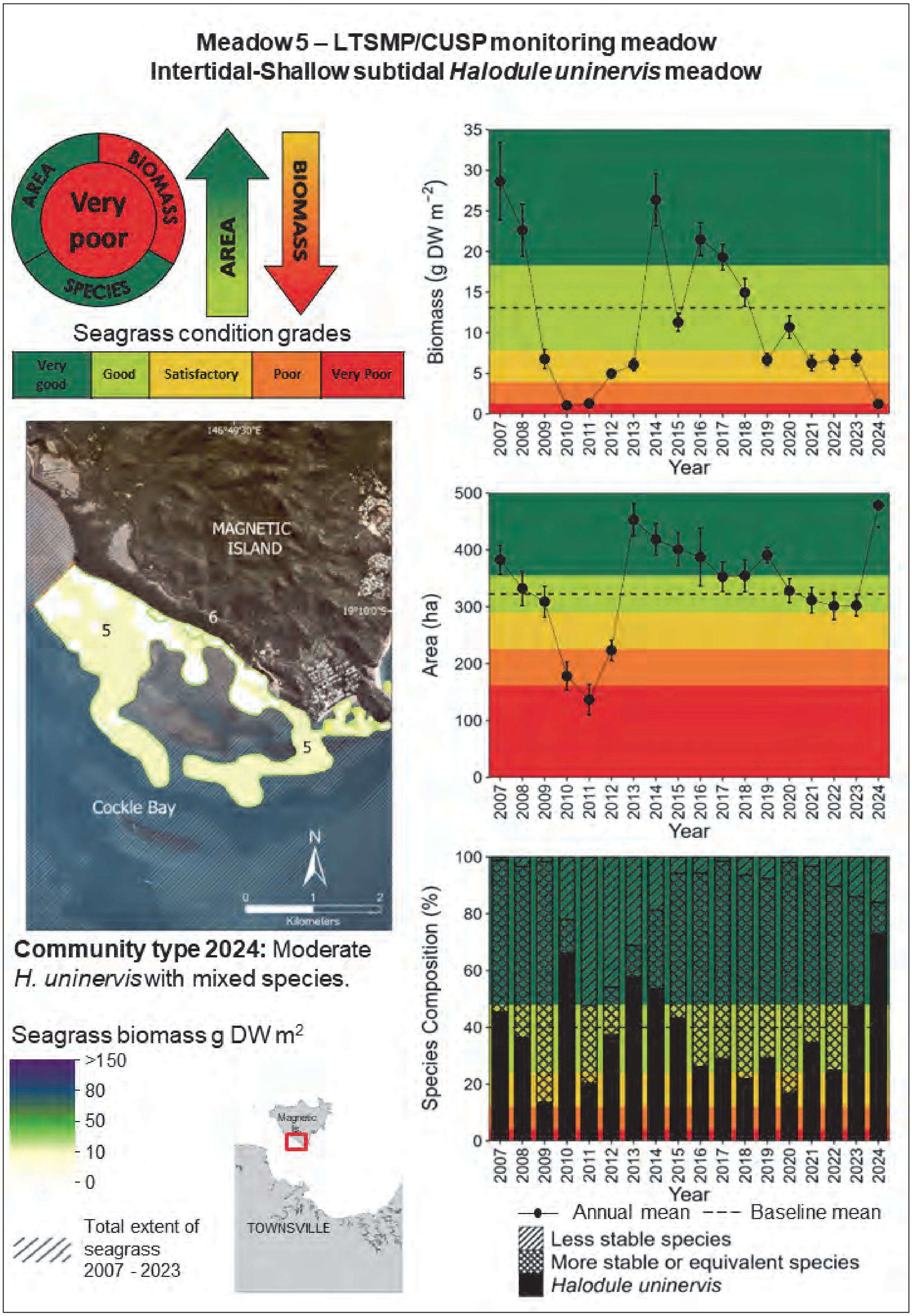


Figure 18. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for LTSMP seagrass Meadow 5 at Magnetic Island, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

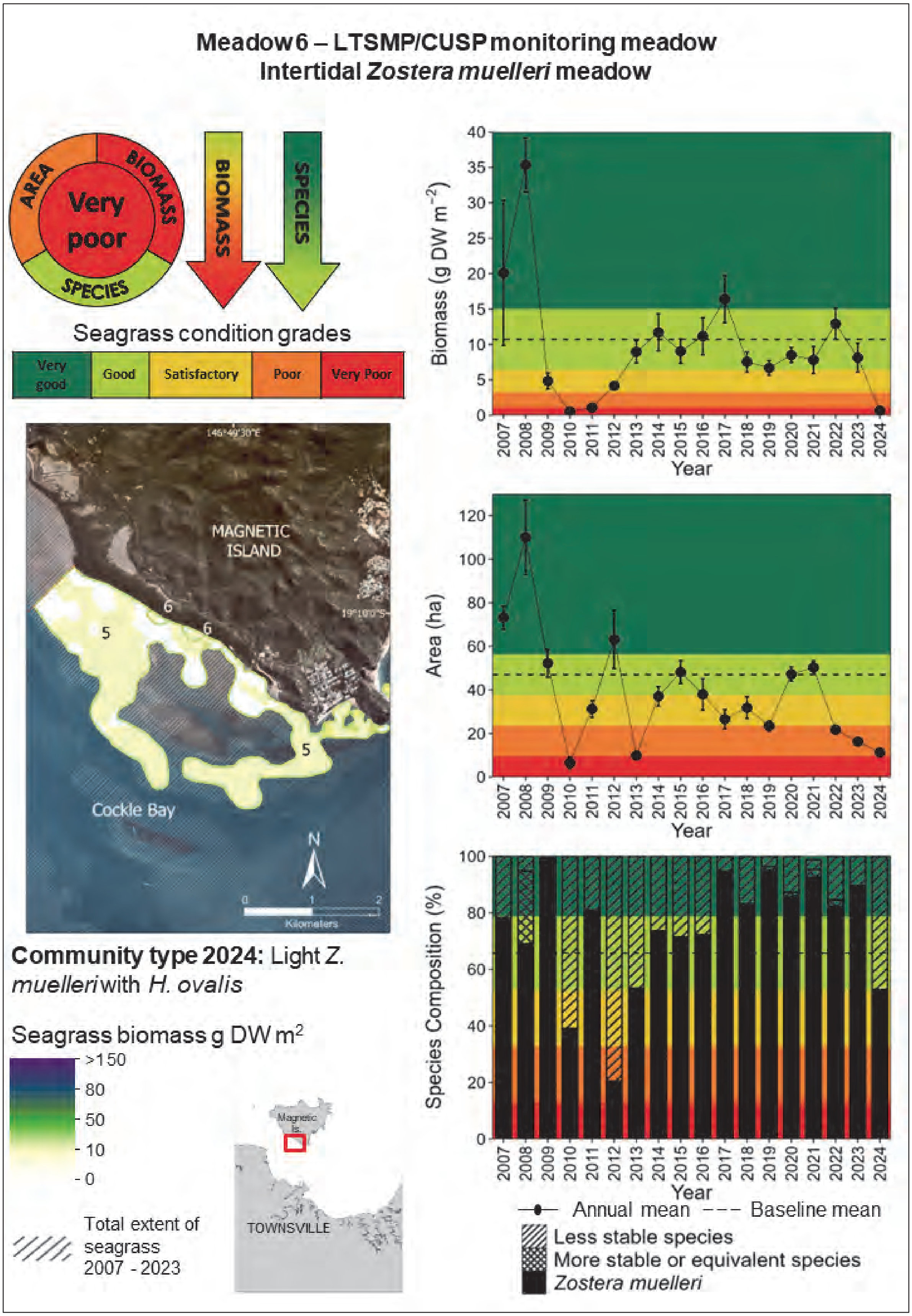


Figure 19. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for LTSMP seagrass Meadow 6 at Magnetic Island, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

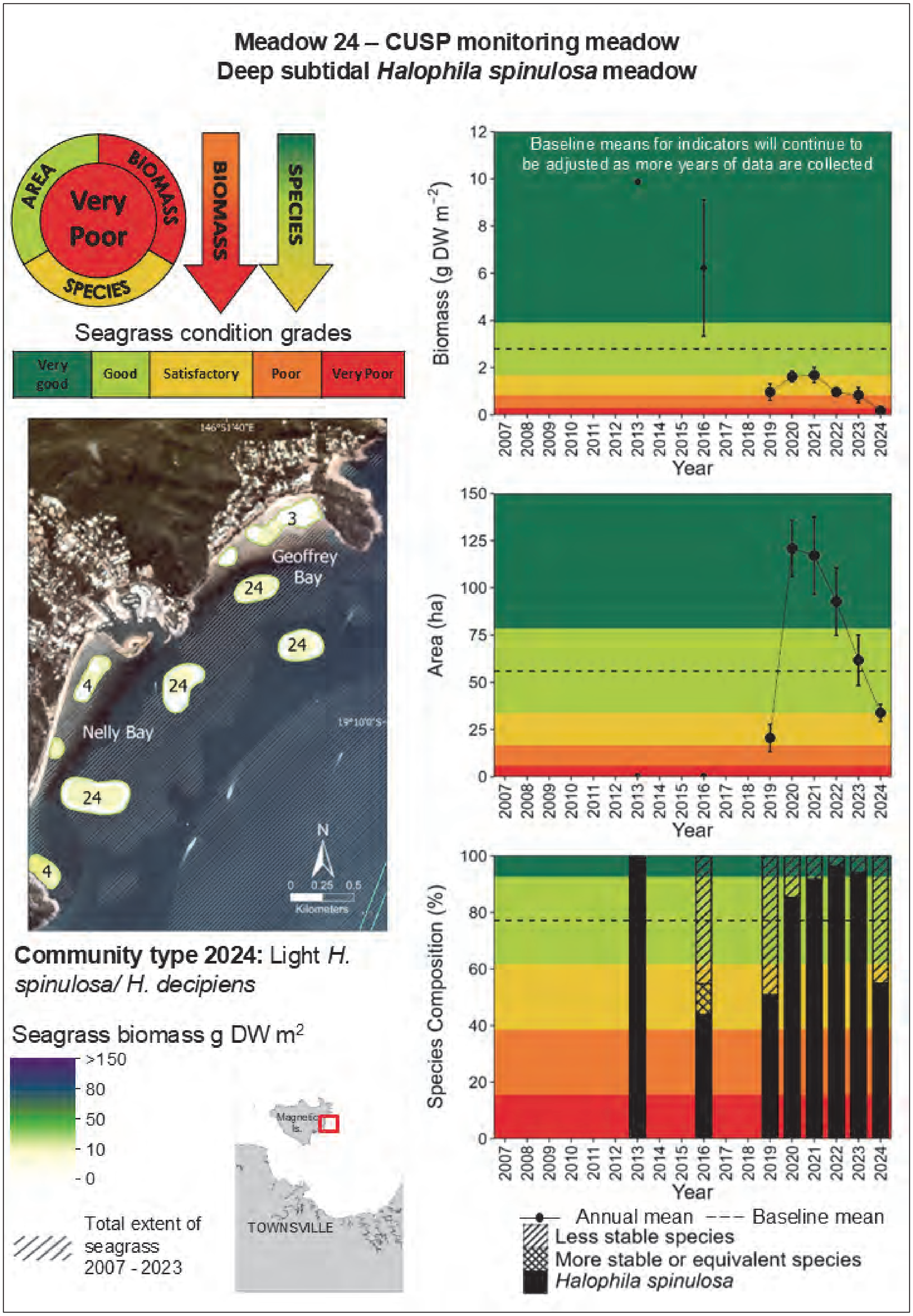


Figure 20. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for LTSMP seagrass Meadow 24 at Magnetic Island, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

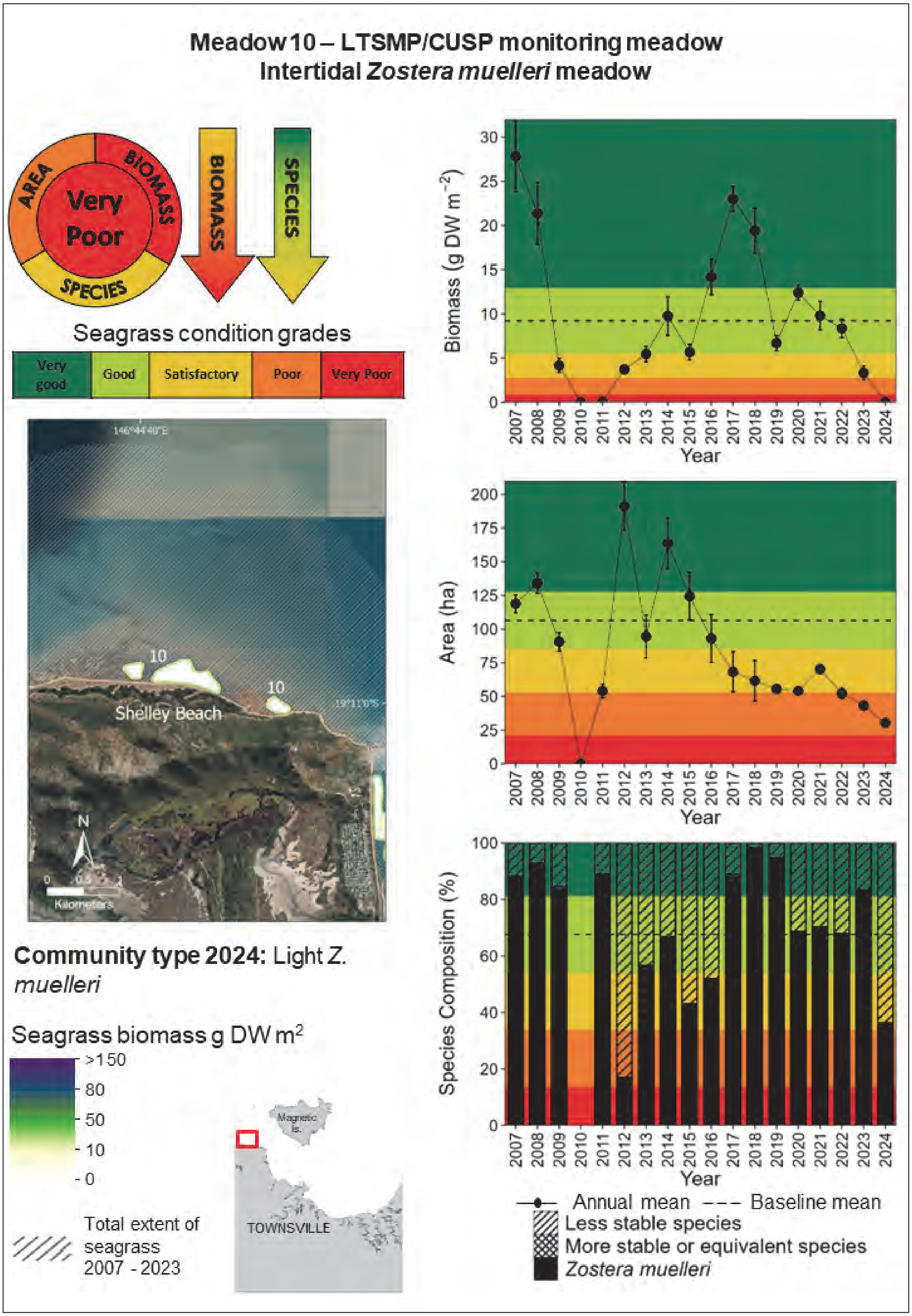


Figure 21. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for LTSMP seagrass Meadow 10 at Shelley Beach, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

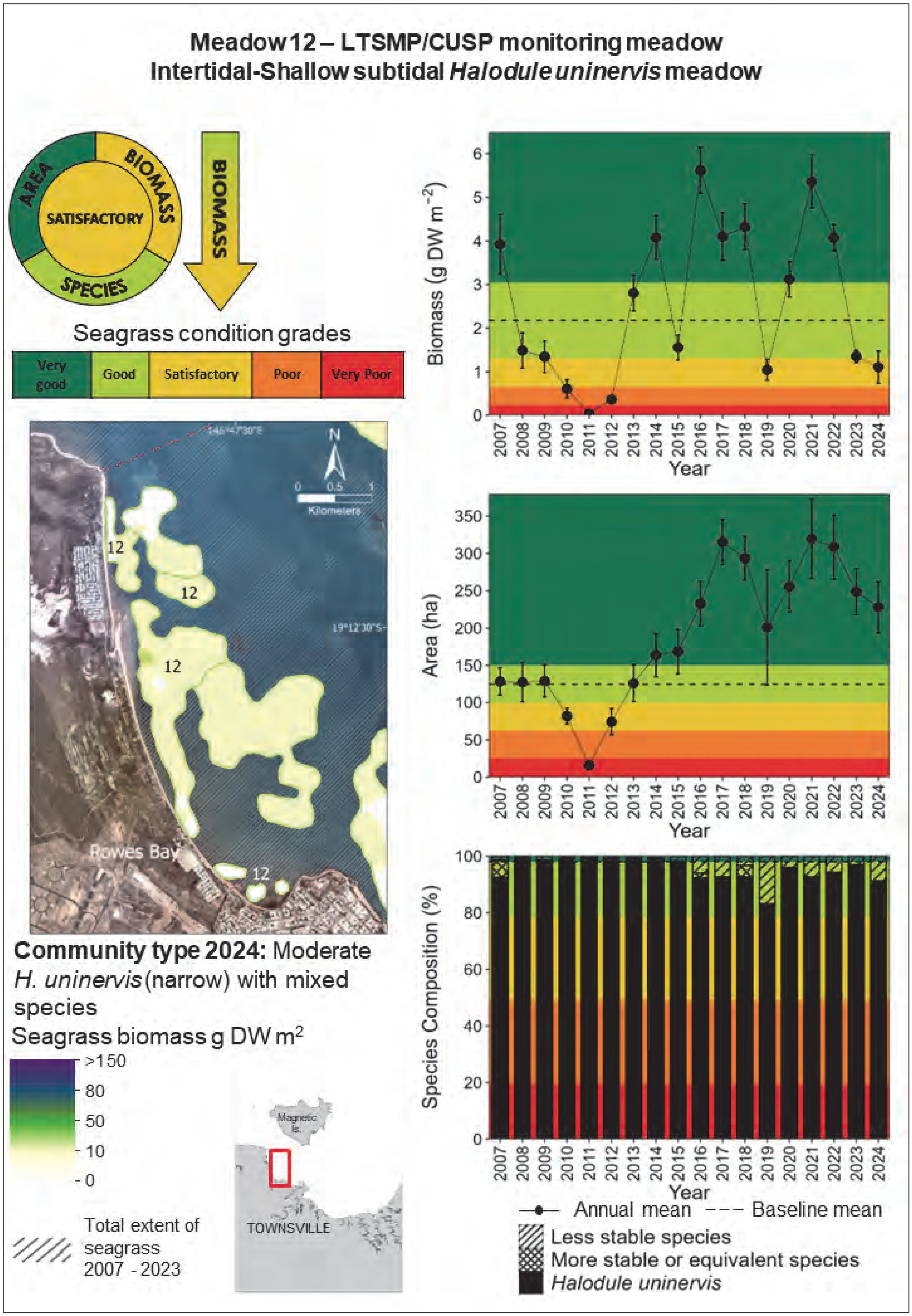


Figure 22. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for LTSMP seagrass Meadow 12, at Rowes Bay to Cape Pallarenda, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

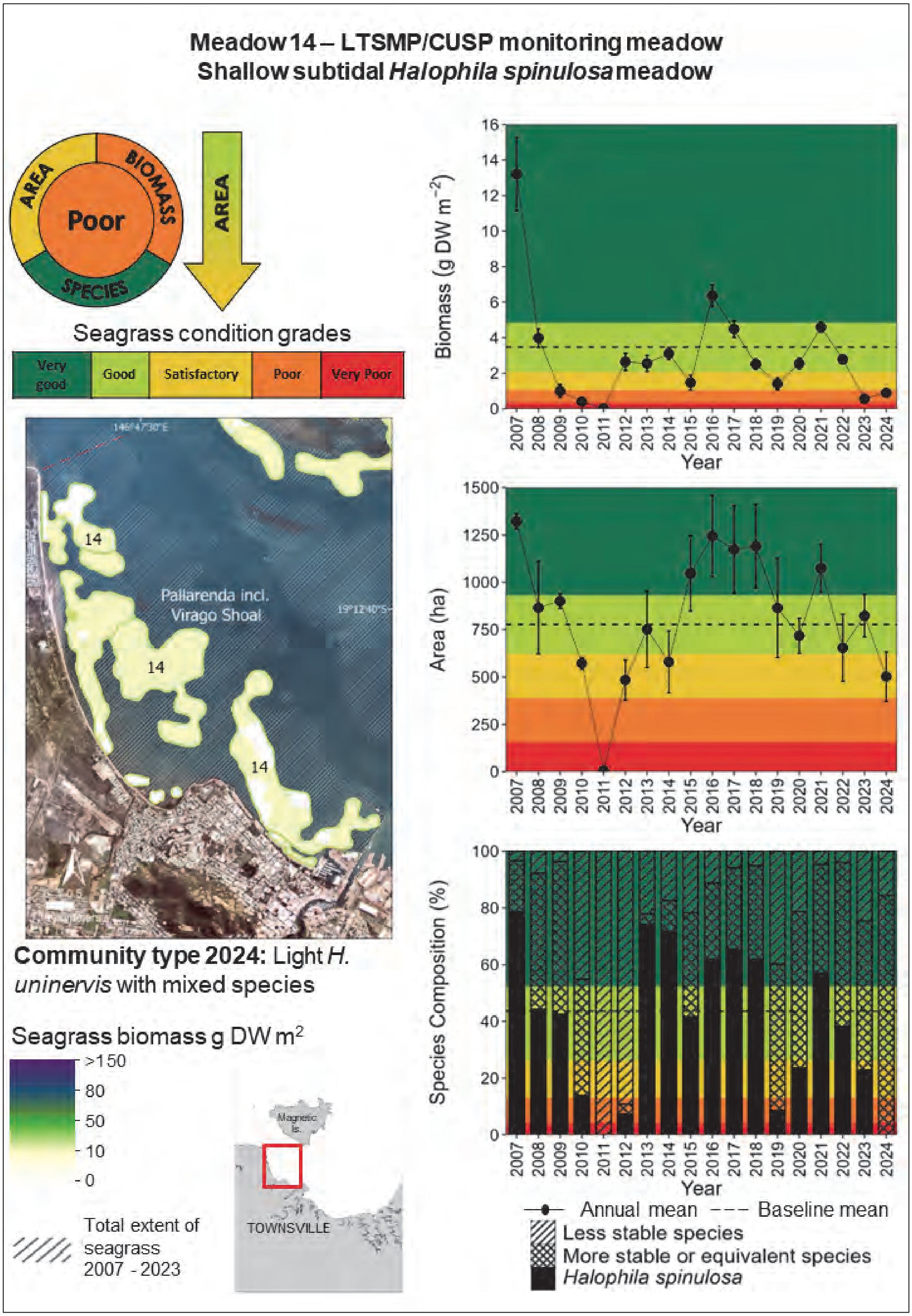


Figure 23. Changes in meadow area (ha), above-ground biomass (gDWm[2]), and species composition for LTSMP seagrass Meadow 14 at the Strand to Cape Pallarenda, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

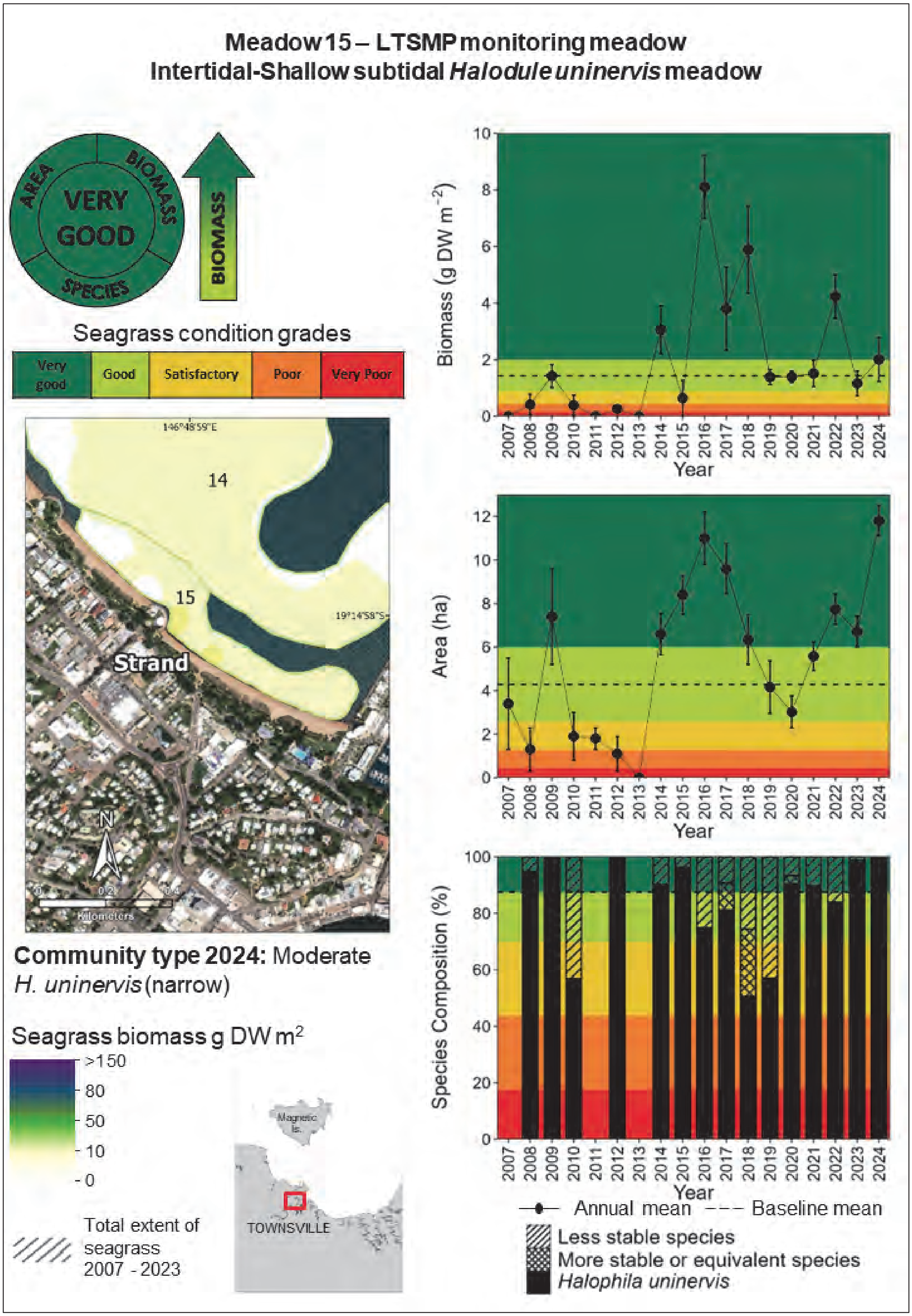


Figure 24. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for LTSMP seagrass Meadow 15 at the Strand, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

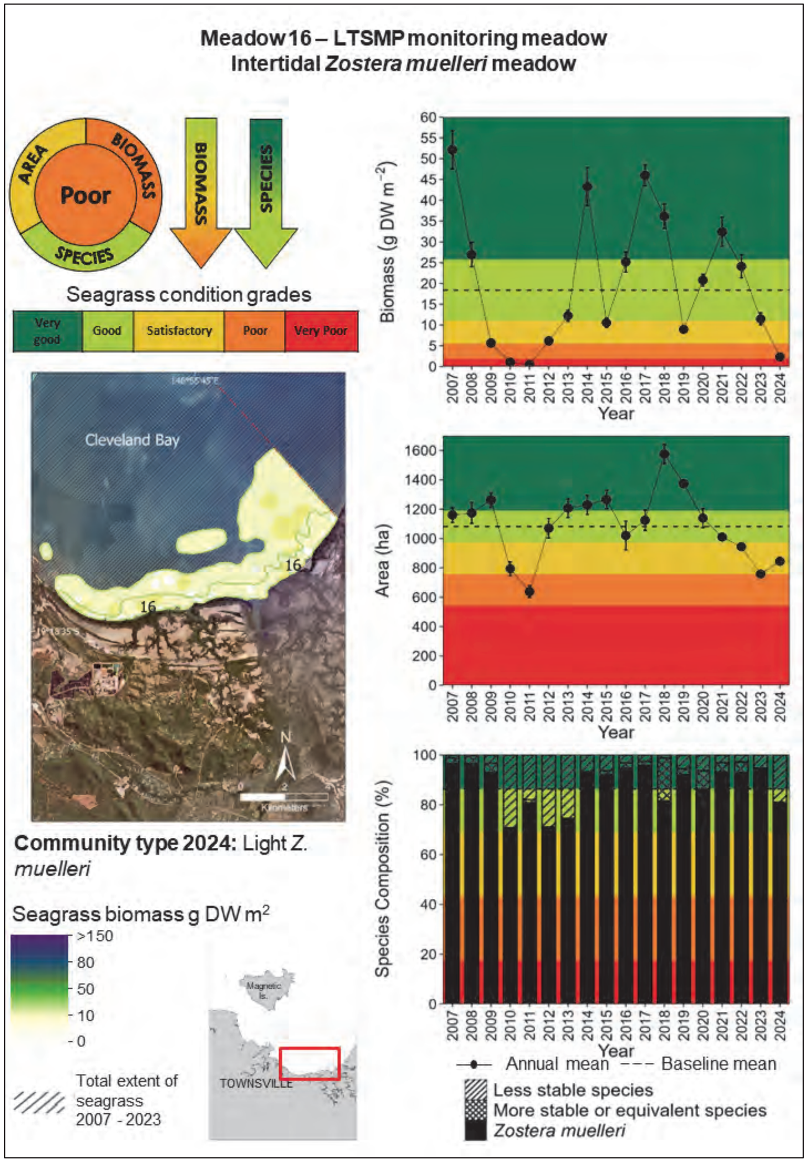


Figure 25. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for LTSMP seagrass Meadow 16 in Cleveland Bay, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

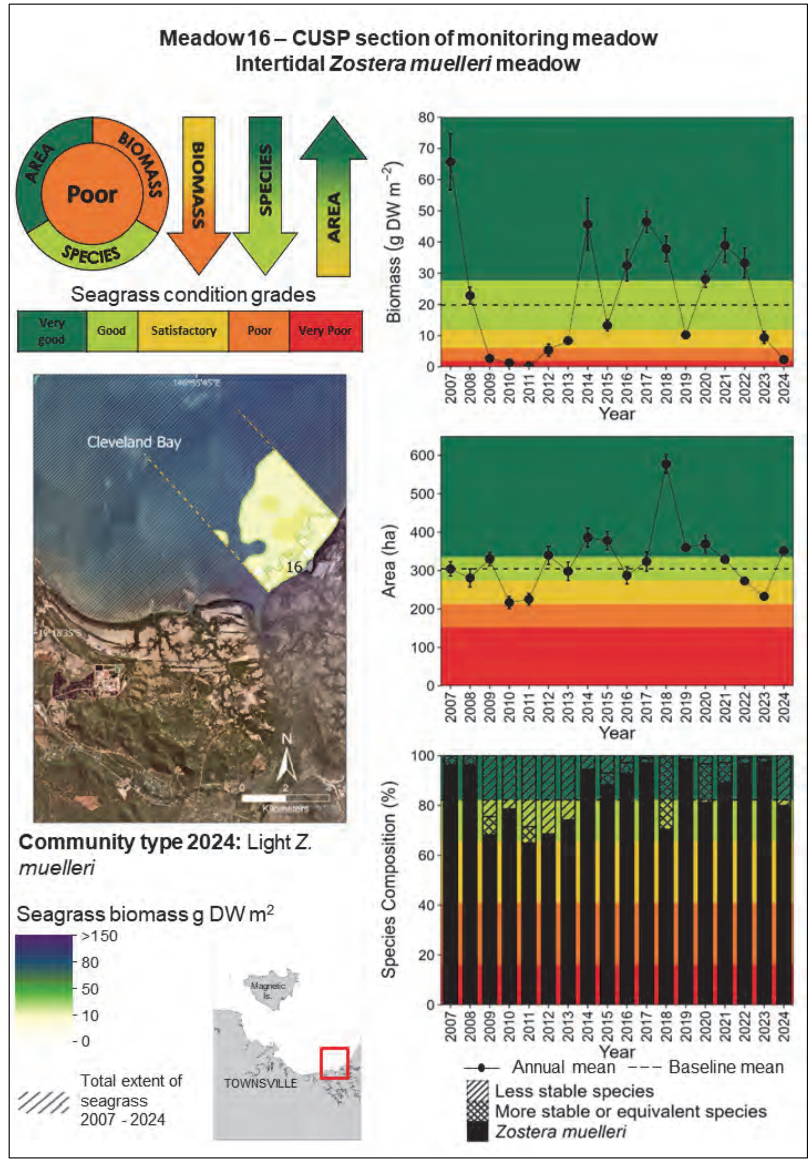


Figure 26. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for CUSP meadow section in Meadow 16 in Cleveland Bay, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

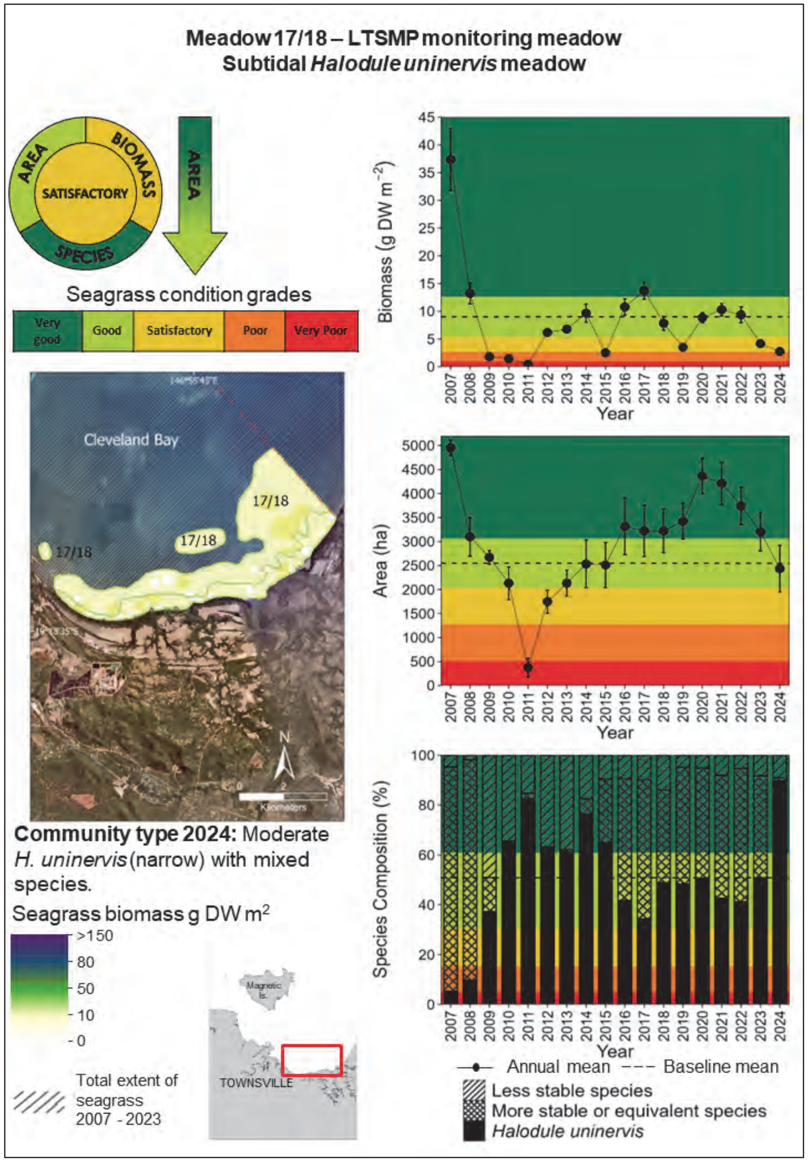


Figure 27. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for LTSMP seagrass Meadow 17/18 in Cleveland Bay, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

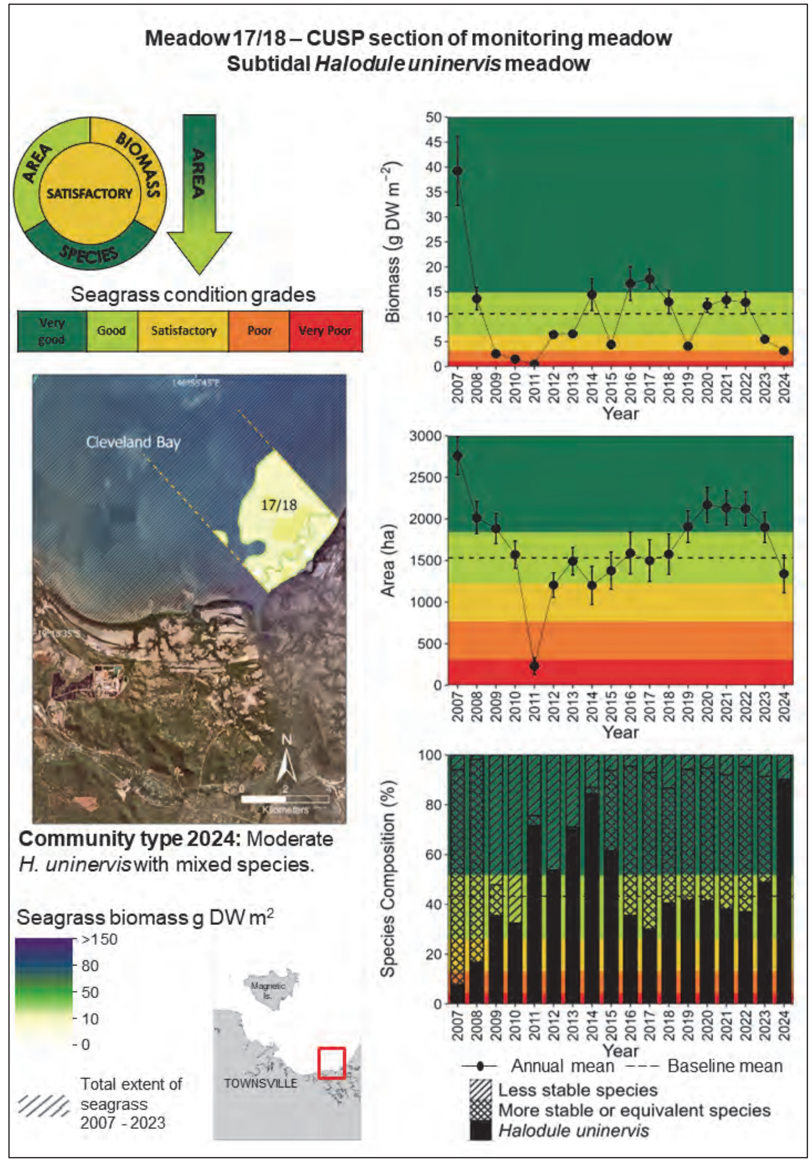


Figure 28. Changes in meadow area (ha), above-ground biomass (gDWm^2), and species composition for CUSP meadow section Meadow 17/18 in Cleveland Bay, 2007–2024. (Above-ground biomass error bars = SE; area error bars = R (reliability estimate)).

5.3 Seasonal comparisons of Townville CUSP meadows

Seagrass meadows that form the CUSP are surveyed biannually (Table 1; Figure 5). Biannual surveys in tropical Queensland help track the condition of seagrass pre-wet season and post-wet season, and seasonality (if any) in seagrass meadows and provide more frequent sampling for the CU Project.

Analysis of six years of seagrass above-ground biomass between post-wet season data (n=2489), the one-off mid-year survey July 2022 (n=255) and pre-wet/dry season data (n=2463) found that seagrass above-ground biomass did not change significantly between seasons in Townsville between 2019 and 2024 ($\chi^2 = 3.4$, $p = 0.18$). See section 5.5.1 for more analysis of seasonal data. The direction of change between post-wet and pre-wet/dry season surveys for both area and above-ground biomass tend to vary at the individual meadow scale. Seagrass meadows in Townsville have historically been highly variable.

For Magnetic Island CUSP meadows, meadow above-ground biomass increased between the May 2024 survey and the October 2024 survey in the subtidal Geoffrey Bay meadow (24), decreased in the Florence Bay meadow, Geoffrey Bay intertidal meadow (3) and intertidal Cockle Bay meadow (6) and remained the same for the larger Cockle Bay intertidal-subtidal meadow (5) (Figures 29, 30). Area increased in between the two 2024 surveys in Meadows 1, 24 and 5 but decreased in the intertidal Meadows 3 and 6 (Figures 29, 30).

Between Cape Pallarenda and the Strand, all CUSP monitoring meadows (10, 12, 14) increased in area between the May 2024 survey and the October 2024 survey (Figures 29, 30). The two meadows closest to the shore (10 and 12) decreased in above-ground biomass between surveys while the subtidal Meadow 14 increased in above-ground biomass.

Over in Cleveland Bay, the above-ground biomass and area of intertidal *Z. muelleri* meadow increased between 2024 surveys, while for the subtidal meadow (17/18), above-ground biomass increased slightly, and area decreased by ~139 ha (Figures 29, 30).

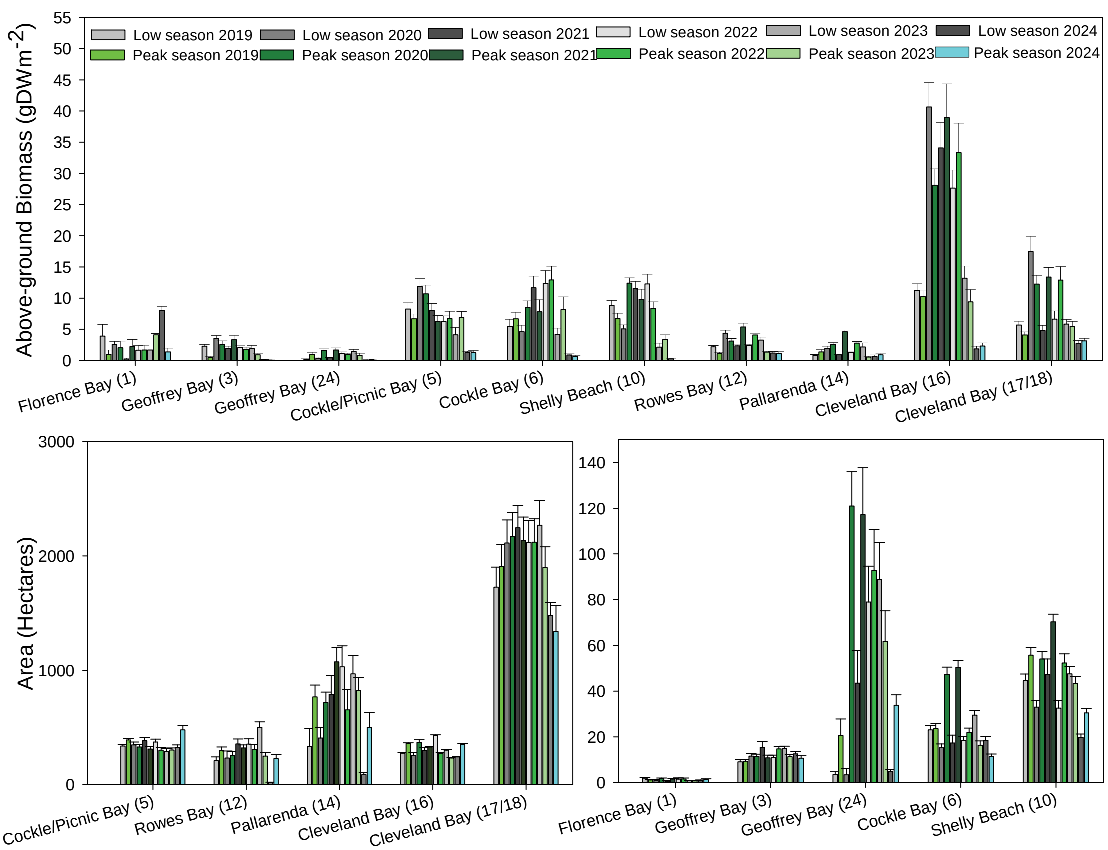


Figure 29. Seasonal meadow above-ground biomass and area in April–June and September–November surveys 2019–2024.

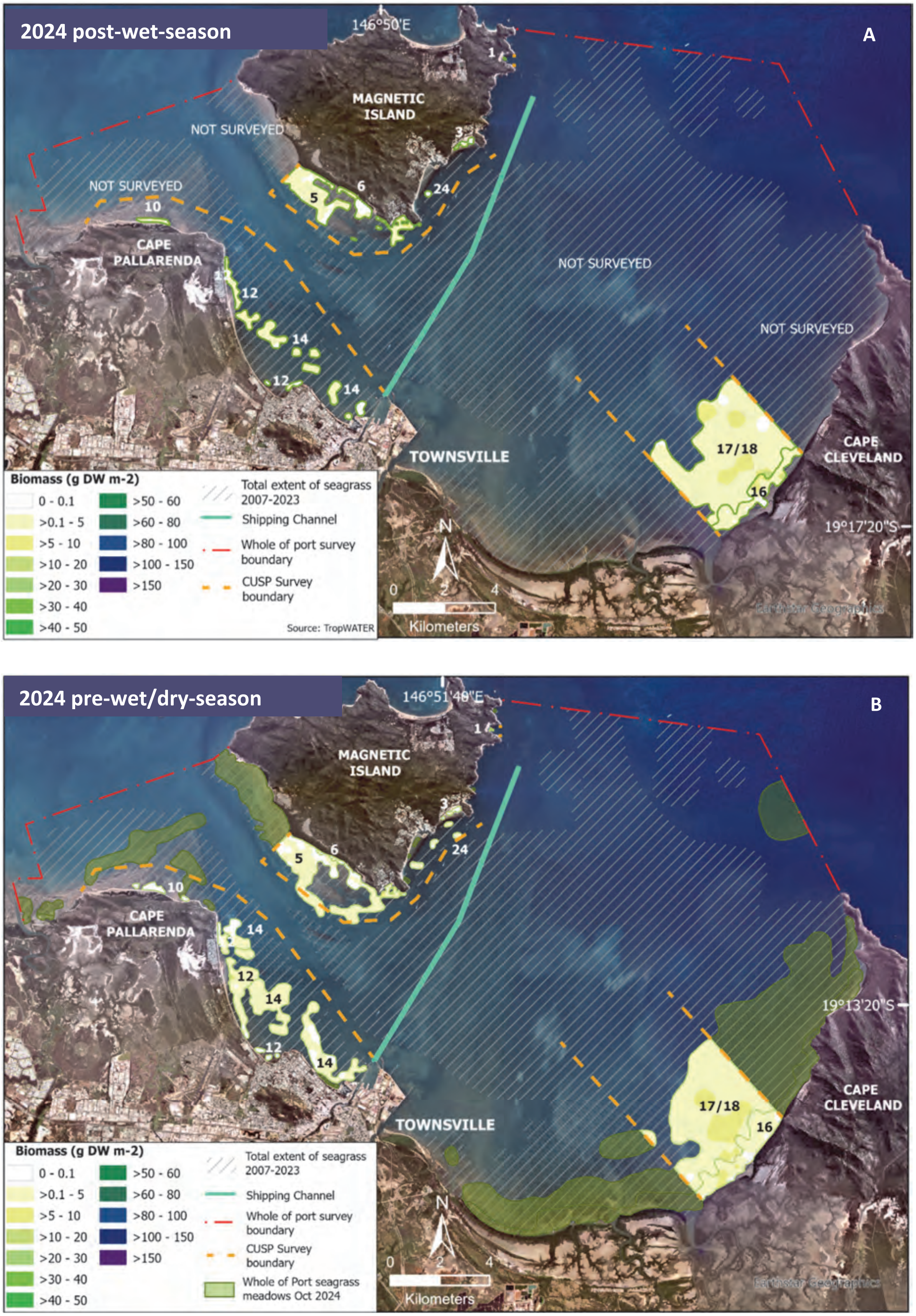


Figure 30. Seagrass density (above-ground biomass gDWm^2) and distribution in the 2024 A) post-wet and B) pre-wet/dry season.

5.4 Broadscale comparisons of Townsville seagrass

Dry season broadscale surveys have been conducted nine times since the LTSMP program was established in 2007: 2007, 2013, 2016, 2019–2024. Seagrass meadow location and species composition has generally been similar around the port in each of these surveys.

A total of 1,150 sites were assessed for seagrass condition as part of the September–October 2024 broadscale seagrass surveys, with seagrass present at 39% of sites. The broadscale survey seagrass footprint covered 8,046 ± 1,047 ha (Figures 31, 32). This was an 18% decrease in footprint from the same time in 2023. Most of the spatial footprint decrease was due to a reduction in area of the Cleveland Bay meadows and the Cape Pallarenda to Strand meadows (Figure 31, 32).

Mean seagrass above-ground biomass has varied between each of the broadscale surveys (Figures 31, 32). In 2019, above-ground biomass was the lowest for the program across all monitoring regions of Townsville. The seagrass above-ground biomass across all regions in 2024 is now lower than what it was in 2019.

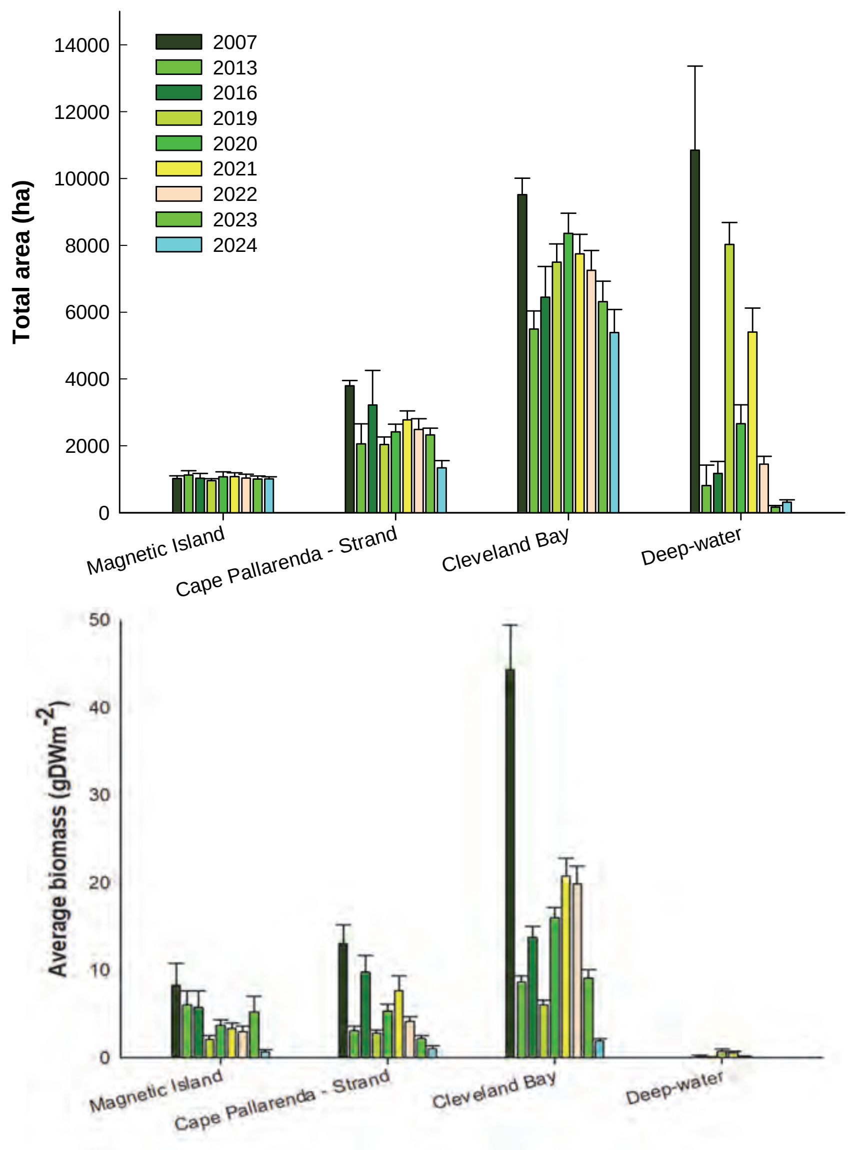


Figure 31. Comparison of broadscale survey extent meadow area (ha) and above-ground biomass (gDWm^2) in the four Townsville survey regions: 2007, 2013, 2016, annually 2019–2024. (Average biomass error bars = SE; area error bars = R (reliability estimate)).

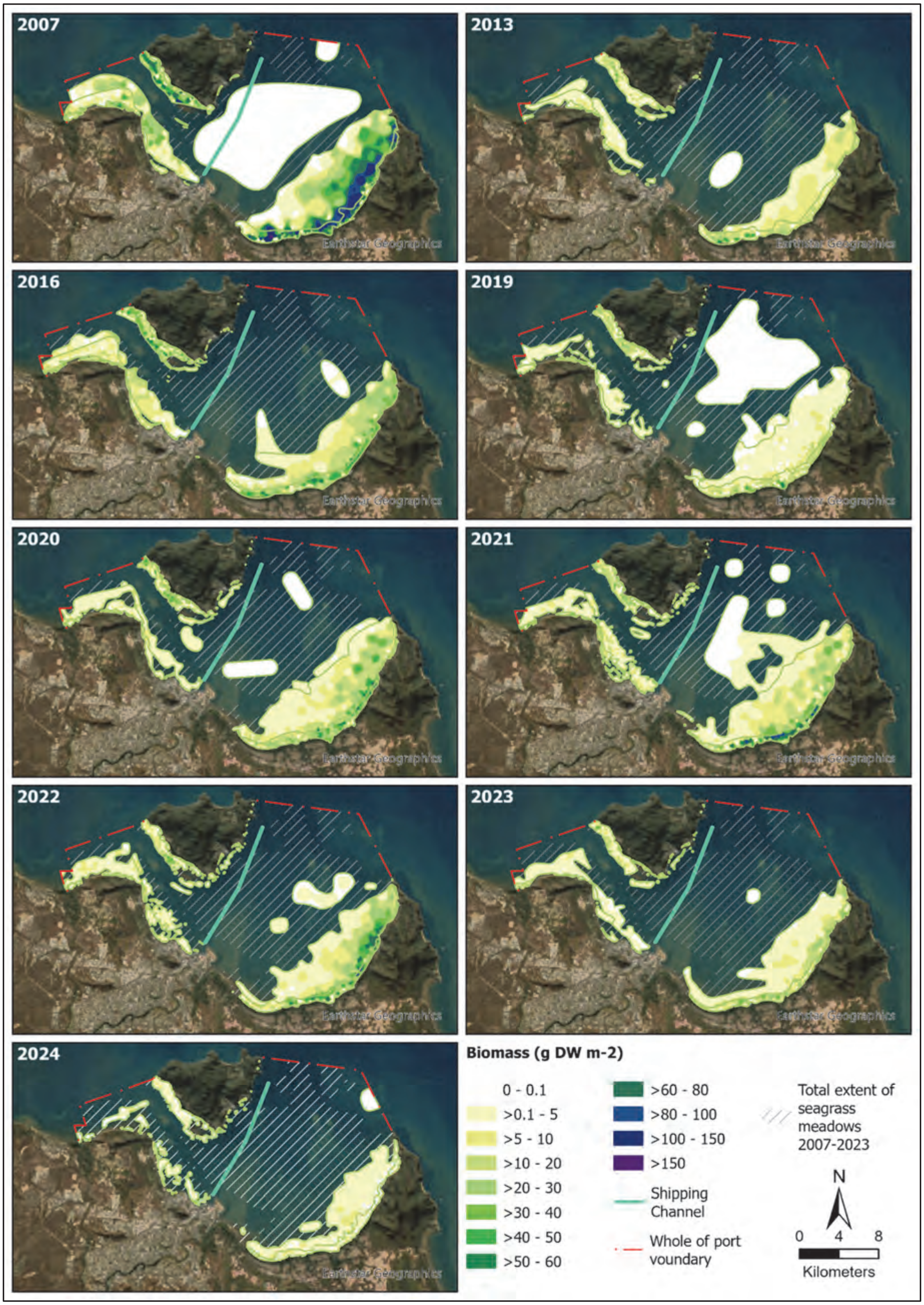


Figure 32. Comparison of broadscale survey seagrass above-ground biomass (gDWm^2) and meadow extent; October 2007, 2013, 2016, 2019–2024.

5.5 Assessing potential impacts of dredging on Townsville seagrass

Seagrass above-ground biomass ($gDWm^2$) was the primary indicator used for statistical analysis as this was the most sensitive condition indicator, that varied significantly over the 2019–2024 period and in 2024 was in poor or very poor condition at most monitoring meadows (see Table 3). Area and species composition of monitoring meadows mostly remained in satisfactory to very good condition during the program.

5.5.1 Seagrass above-ground biomass and seasonality

To determine if seasonality needed to be factored into models to assess above-ground biomass data against dredge phases (pre-, during and post-dredging), analysis of seagrass above-ground biomass and season (post-wet, mid-year and pre-wet/dry season) was conducted. Models of seagrass above-ground biomass between post-wet season pooled data (n=2489), the one-off mid-year survey July 2022 (n=255) and dry season pooled data (n=2463) showed that above-ground biomass was not significantly different between these times in Townsville between 2019 and 2024 ($\chi^2 = 3.4$, $p = 0.18$).

Analysis at the meadow scale found that Meadows 3, 12, and 14 showed significant differences in above-ground biomass between seasons but that the season that was significantly different in these meadows was only the mid-year survey event. The mid-year survey event was a one-off survey conducted in July 2022 (during-dredge phase) to determine any potential impacts to seagrass from the March 2022 marine heat wave. This survey event was only conducted at seven of the ten monitoring meadows (Figure 33).

Seagrass above-ground biomass in Meadow 3 was significantly different between seasons ($F = 5.99$, $p <0.01$). Specifically, seagrass above-ground biomass in the mid-year 2022 sampling event was significantly higher than both post-wet season ($t = 2.94$, $p < 0.01$) and dry season ($t = 3.46$, $p < 0.01$) survey events (Figure 33).

For Meadow 12 that spans between Rowes Bay and Cape Pallarenda, seagrass above-ground biomass was significantly different ($F = 4.99$, $p < 0.01$) between seasons. The mid-year 2022 survey event also drove these differences: mid-year vs post-wet season survey events ($t = 2.60$, $p <0.01$).

For Meadow 14 that spans the subtidal areas between the Breakwater Marina and Cape Pallarenda, adjacent to Meadow 12, above-ground biomass was significantly different between all sampling periods ($F = 55.4$, $p <0.01$). Post hoc analysis showed that above-ground biomass differences occurred between dry season survey events and the mid-year 2022 survey event ($t = 2.90$, $p < 0.01$), and the post-wet season and the mid-year 2022 survey event ($t = 7.0$, $p < 0.01$). But also, between the dry season and post-wet season survey events ($t = 9.2$, $p <0.01$).

Because seagrass above-ground biomass in the mid-year July 2022 survey event was different to all other events, the July 2022 data was excluded for the following GLM's and post hoc analyses. As most assessment sites within meadows did not show a significant relationship between seagrass above-ground biomass and season (post-wet and dry season) we combined seagrass assessment sites from multiple survey events into dredge phase categories: pre-dredge (n = 2689), during dredge (n = 1796), and post-dredge (n = 467) for the below models.

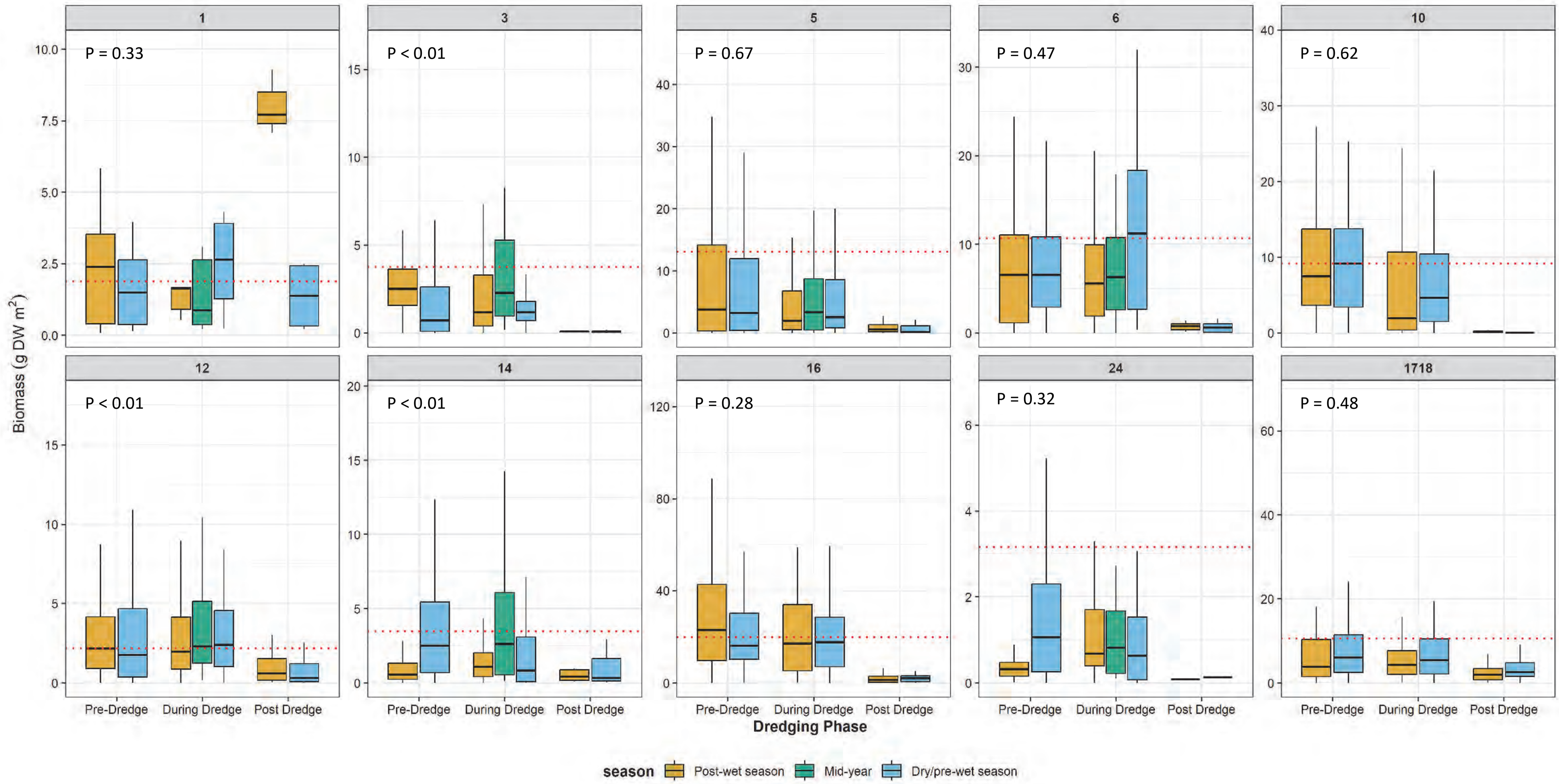


Figure 33. Seagrass above-ground biomass (gDWm^2) for each meadow across the different dredge phases (2019–2024) (P-values denote the significance of above-ground biomass (gDWm^2) across season). The red dotted line denotes the baseline above-ground biomass (gDWm^2) previously calculated for each individual meadow (see section 4.3). Boxplots display the distribution of above-ground biomass, including the interquartile range and median values, across dredge phases.

5.5.2 Effects of dredging on seagrass in the Zone Of Influence

The meadows that span the Breakwater Marina wall to Cape Pallarenda/Shelley Beach were located within the modelled Zone Of Influence for the expected case and worst case modelled scenarios (BMT 2021) (Figure 9, 34, 35).

Seagrass above-ground biomass at sites outside of the ZOI was generally higher compared to sites within the ZOI (Figure 34, 35). The substantially larger above-ground biomass at sites outside of the ZOI can be explained by the high above-ground biomass *Z. muelleri* that was present in the Cleveland Bay meadow (16): some assessment sites had > 100 $gDWm^2$ of seagrass compared to sites within the ZOI where the largest above-ground biomass at any time was 46 $gDWm^2$ (Figure 11).

Analysis of seagrass above-ground biomass across dredge phases showed that above-ground biomass was significantly different between dredge phases ($\chi^2 = 268.32$, $p < 0.01$). The GLMs examining the relationship between seagrass above-ground biomass, dredge phase, and monitoring location type (sites within the ZOI vs sites outside of the ZOI), and their interaction showed that all factors significantly influence seagrass above-ground biomass. Specifically, dredge phase ($F = 96.58$, $p < 0.01$), monitoring location type (inside/outside the ZOI) ($F = 658.8$, $p < 0.01$), and their interaction (dredge/type) ($F = 30.07$, $p < 0.\ 01$) were all statistically significant.

Seagrass inside and outside the ZOI showed similar declines in above-ground biomass across dredge phases (Figure 34a, b). There was a significant interaction between seagrass above-ground biomass inside and outside the ZOI and dredge phase (for both expected case ($F = 87.76$, $p < 0.0001$) and worst-case scenarios ($F = 90.44$, $p < 0.0001$)). Post hoc analysis shows that inside the ZOI (expected case scenario) there was no significant difference in seagrass above-ground biomass across dredge phases (Table 4; Figure 34). Outside the ZOI (expected case scenario), there was a significant decline in seagrass above-ground biomass across all dredge phases (Table 4; Figure 34).

For the worst-case modelled scenario, seagrass above-ground biomass inside and outside the ZOI showed similar declining patterns across dredge phases (Figure 35). Seagrass above-ground biomass inside the ZOI (worst case scenario) was significantly higher pre-dredge than the post-dredge phase, but during-dredge and post-dredge phases were not different (Table 4; Figure 35). Outside the ZOI (worst case scenario) seagrass above-ground biomass was significantly different between all dredging phases.

Given that seagrass above-ground biomass declines were observed at assessment sites inside and outside the ZOI, and that seagrass declines inside the ZOI (for expected case scenario) across dredge phases were not significantly different, the observed declines are considered natural occurrences indicative of system-wide influences and environmental conditions and therefore not likely attributable to dredging.

The decline in seagrass above-ground biomass has also been visualised at the meadow level of analysis to show that seagrass above-ground biomass declines occurred at meadows far away from dredging activity (e.g., meadows in the far east side of Cleveland Bay (Meadows 16 and 17/18) and Shelley Beach (Meadow 10) (Figure 36).

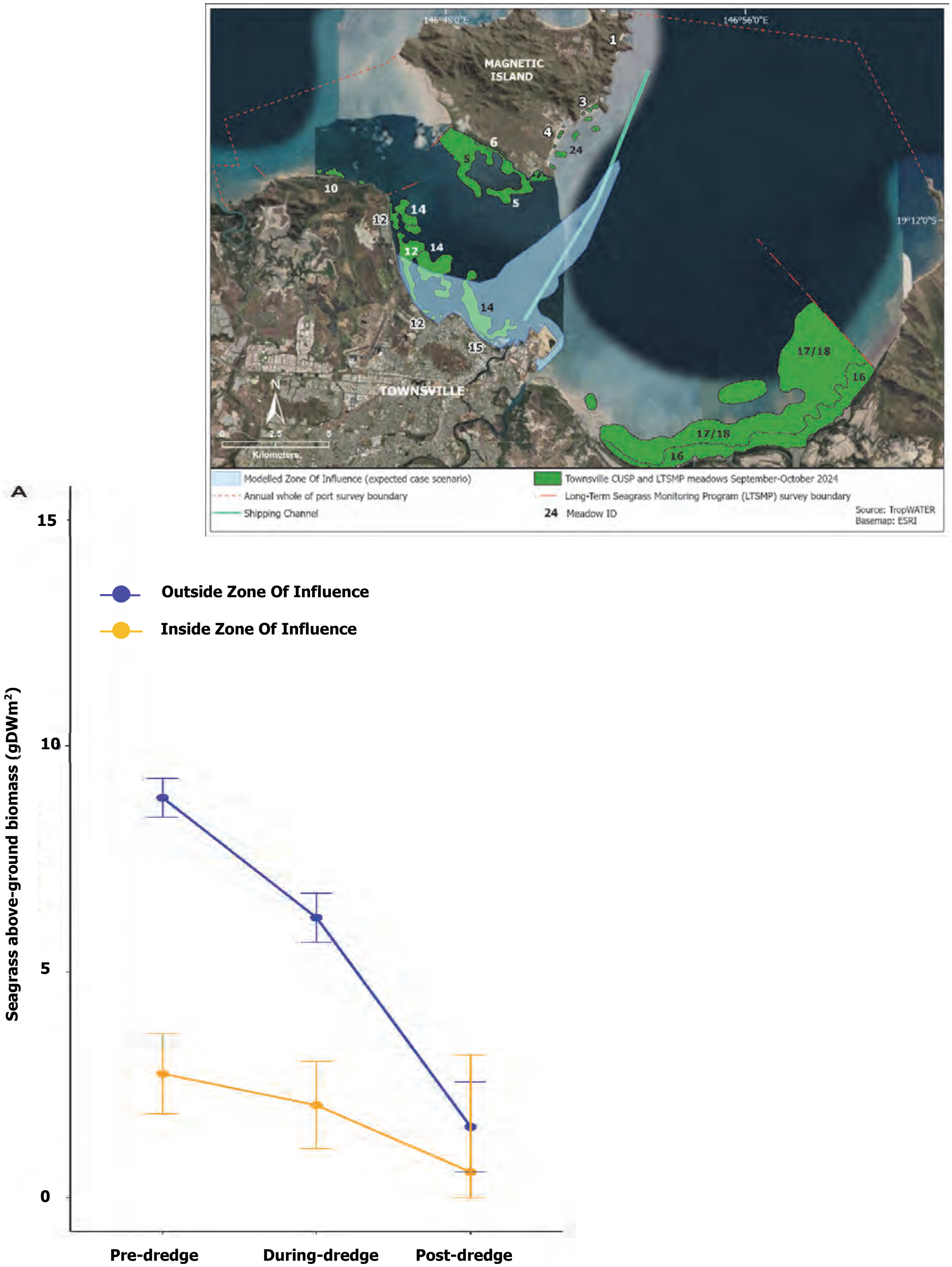
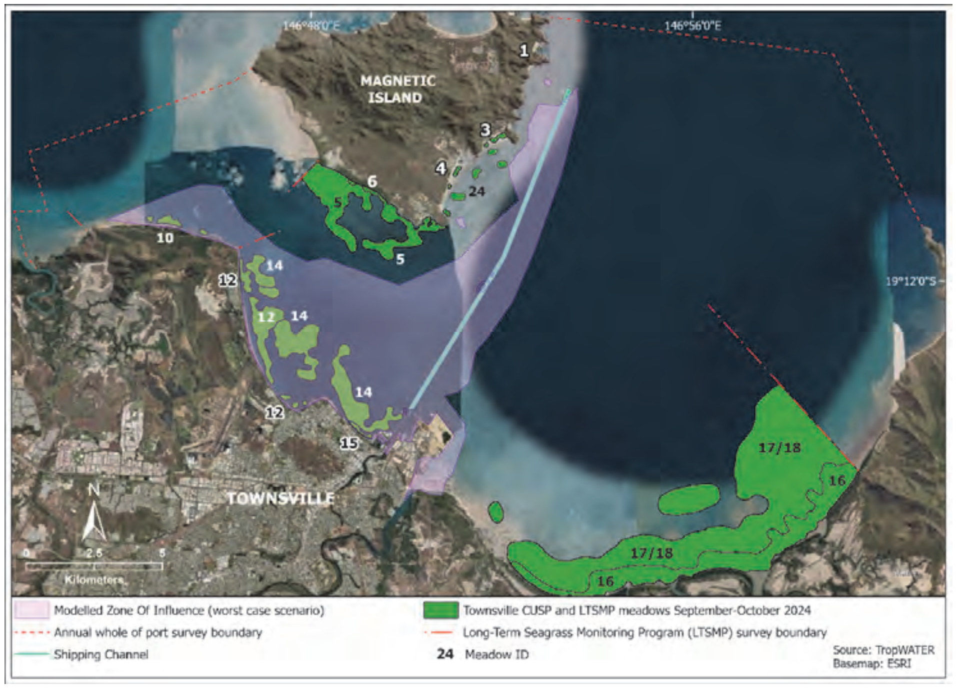


Figure 34. Predicted seagrass above-ground biomass (gDWm²) under different dredge phases based on Generalised Linear Models. Graph shows seagrass above-ground biomass for all sites across survey events and dredging phases that fall outside of the modelled Zone Of Influence (ZOI) (for the modelled expected case scenario) (blue line) vs all sites that were within the ZOI (orange line). Error bars indicate the 95% confidence intervals of the predictions based on the GLM.



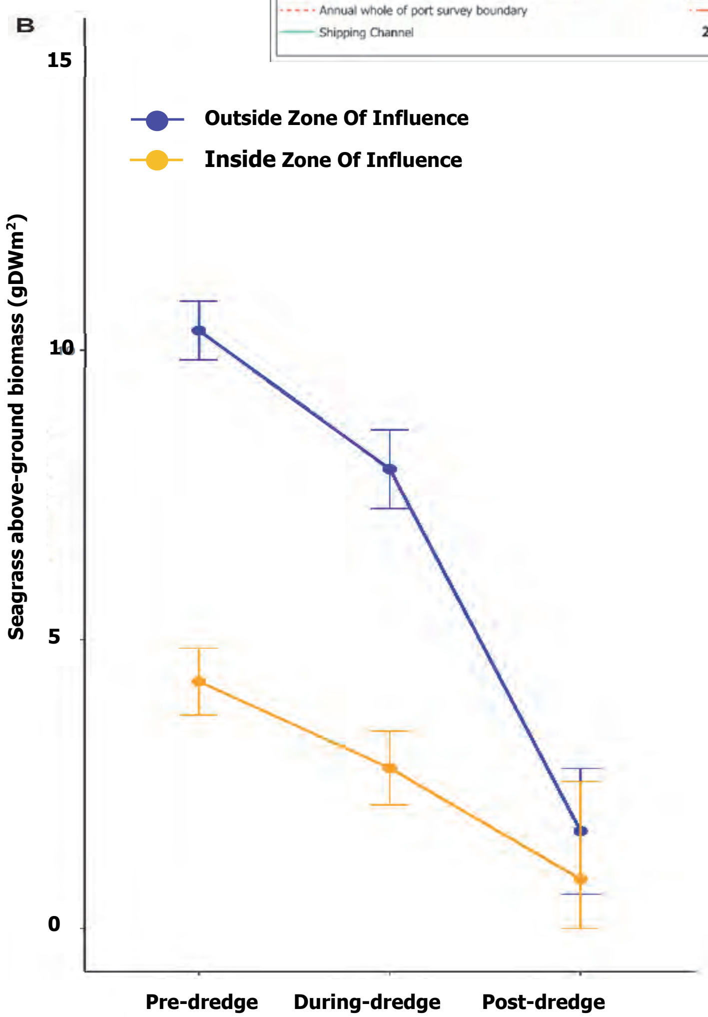


Figure 35. Predicted seagrass above-ground biomass (gDWm²) under different dredge phases based on Generalised Linear Models. Graph shows seagrass above-ground biomass for all sites across survey events and dredging phases that fall outside of the modelled Zone of Influence (ZOI) (for worst case scenario) (**blue line**) vs all sites that were within the expected case ZOI (**orange line**). Error bars indicate the 95% confidence intervals of the predictions based on the GLM.

Table 4. Post hoc summary for generalised linear models comparing sites within the expected and worst-case modelled turbidity plume scenarios across dredging phases.

<u>Expected case</u> modelled plume Zone Of Influence (ZOI) scenario			
Inside ZOI		**t ratio**	**p value**
Pre-dredge	During-dredge	-1.04	1.0
Pre-dredge	Post-dredge	-1.55	1.0
During-dredge	Post-dredge	1.05	1.0
Outside ZOI			
Pre-dredge	During-dredge	-7.51	<0.0001
Pre-dredge	Post-dredge	-13.18	<0.0001
During-dredge	Post-dredge	8.01	<0.0001
<u>Worst case</u> modelled plume Zone Of Influence (ZOI) scenario			
Inside ZOI		**t ratio**	**p value**
Pre-dredge	During-dredge	-3.40	0.009
Pre-dredge	Post-dredge	-3.75	0.002
During-dredge	Post-dredge	2.08	0.56
Outside ZOI			
Pre-dredge	During-dredge	-5.54	<0.0001
Pre-dredge	Post-dredge	-14.15	<0.0001
During-dredge	Post-dredge	9.57	<0.0001

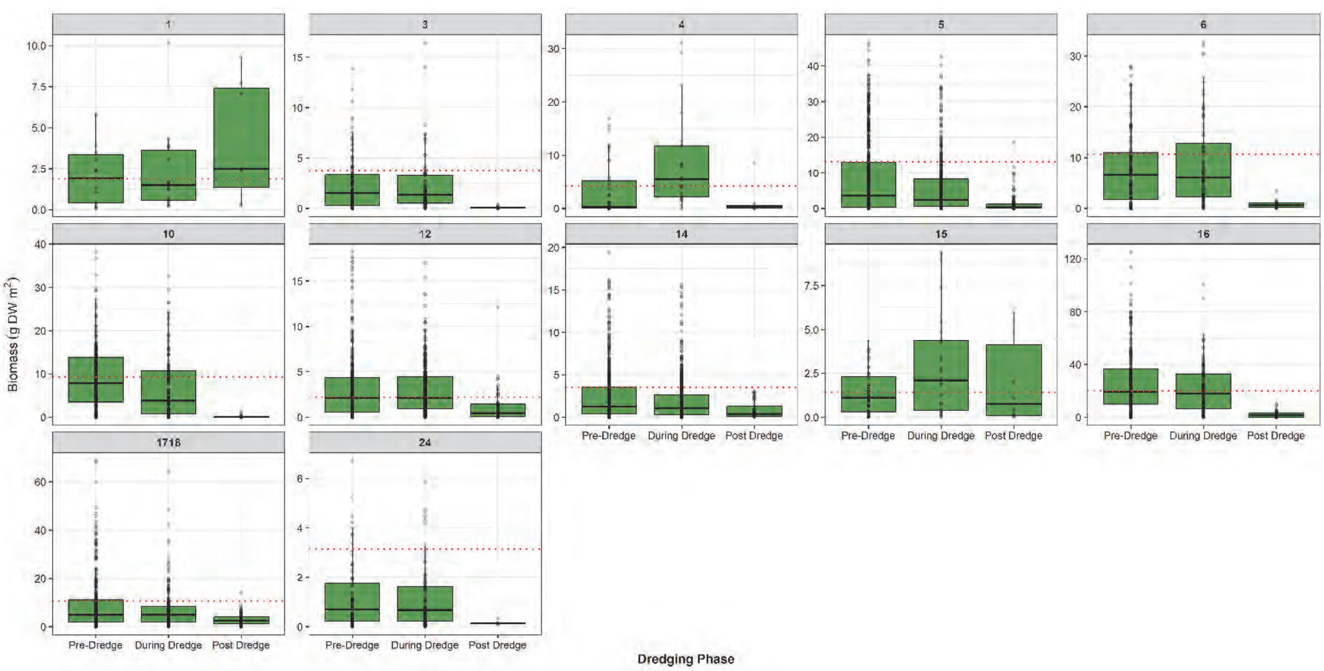


Figure 36. Seagrass above-ground biomass (gDWm²) for each monitoring meadow across different dredge phases. The red dotted line represents the mean baseline above-ground biomass for each meadow (see section 4.3 and Figures 15-28). Boxplots display the distribution of biomass, including the interquartile range and median values, as well as the spread of data across dredge phases.

For the next model, we focussed on Meadows 12 and 14 (Meadow 15 data was pooled with Meadow 14); sites that were within or outside of the expected case scenario ZOI for turbidity plume modelling.

In Meadow 12, the GLM identified significantly higher seagrass above-ground biomass between sites within and outside the ZOI ($F = 10.51$, $p < 0.01$), a significant relationship in seagrass above-ground biomass across dredge phase ($F = 15.13$, $p < 0.01$) and a significant interaction between factors ($F = 3.33$, $p < 0.01$) (i.e., there was a difference in above-ground biomass between dredge phases, but these differences were consistent inside and outside the Zone Of Influence) (Figure 37). Post hoc analysis revealed no significant difference in above-ground biomass across all sites (regardless of zone of influence) between the pre-dredge and during dredge phase ($t = -2.1$, $p = 0.08$; Figure 35a). Significant differences were found between the pre- and post-dredge ($t = -5.66$, $p < 0.01$) and during- and post-dredge phases ($t = 4.80$, $p < 0.01$). Similarly, these differences were the same for sites regardless of whether they were inside or outside the ZOI.

For Meadow 14, the model found a significant relationship in seagrass above-ground biomass across dredge phase ($F = 20.71$, $p < 0.0001$), but no significant difference was observed between sites inside and outside the expected zone of influence ($F = 1.16$, $p = 0.27$) or the interaction between the factors ($F = 1.69$, $p = 0.18$). Post hoc analysis revealed significant differences in above-ground biomass between pre-dredge and during-dredge phases ($t = -5.68$, $p < 0.0001$) and between pre-dredge and post-dredge phases ($t = -3.49$, $p = 0.001$) but not between the during-dredge and post-dredge phase ($t = 1.43$, $p = 0.32$) and these results were the same for sites regardless of whether they were inside or outside the ZOI (Figure 38).

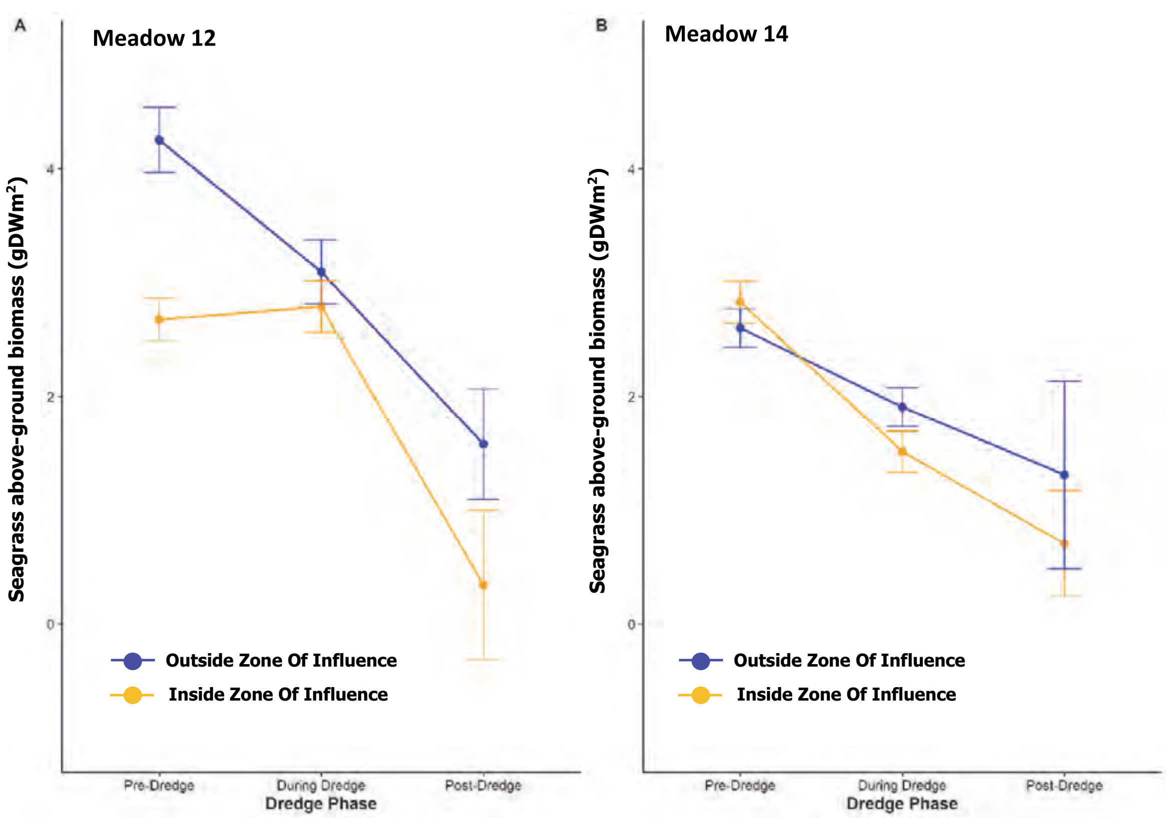


Figure 37. Predicted seagrass above-ground biomass (gDWm²) under different dredge phases based on Generalised Linear Models. A) shows seagrass above-ground biomass for Meadow 12 sites inside (orange line) and outside (blue line) the modelled Zone Of Influence (for expected case scenario). B) shows seagrass above-ground biomass for Meadow 14 sites inside and outside the expected ZOI (expected case scenario). Error bars indicate the 95% confidence intervals of the predictions based on the GLM.

Overall, the above results show that seagrass above-ground **biomass declines** between 2019 and 2024 (post-dredging) **occurred consistently at sites both inside and outside the Zone Of Influence**, including sites far beyond the modelled plume or any dredging activity (i.e., sites/meadows in the east of Cleveland Bay (Meadows 16 and 17/18). Declines in seagrass above-ground biomass occurred system-wide in the Townsville region and therefore not likely attributable to the Channel Upgrade capital dredging Project.

5.5.3 Effects of environmental parameters on seagrass

Because capital dredging was not found to be a driver of seagrass above-ground biomass decline in Townsville between 2019 and 2024, we assessed the effects of environmental variables on seagrass above-ground biomass through a series generalised additive mixed models (GAMMs).

GAMMs identified photosynthetically active radiation (PAR; mol/m²/s) and temperature (°C) as significant environmental predictors of seagrass above-ground biomass in both intertidal and subtidal seagrass systems (Table 5). In the intertidal model, seagrass above-ground biomass was significantly influenced by the 7-day running mean of PAR (Table 5; Figure 38a; $\chi^2 = 129.4$, $p < 0.001$) and 7-day running mean of temperature (Figure 38b; $\chi^2 = 248.9$, $p < 0.001$), with an adjusted R^2 of 0.222 and 18.7% deviance explained (n = 1888) (Table 5).

Similarly, the subtidal model highlighted the influence of 7-day running mean PAR (Figure 39a; $\chi^2 = 176.2$, $p < 0.001$) and 14-day running mean temperature (Figure 39b; $\chi^2 = 414.1$, $p < 0.001$), with a slightly lower adjusted R^2 of 0.162 and 20.0% deviance explained (n = 2339) (Table 5).

Analysis of PAR at CU MWMP sites shows a declining trend in PAR across the overall system over the study period (2019–2024) (note not all CU MWMP sites used in below analysis, only those that informed seagrass biomass analysis) (Figure 40). The trend in mean seabed temperature shows a peak in temperature in 2021 and 2022, with highest mean temperatures recorded in 2020 (Figure 41), while Figure 42 illustrates the mean above-ground biomass across the overall system (A), intertidal meadows (B), and subtidal meadows (C). The consistent downward trend across all three panels supports the hypothesis of a system-wide response to environmental stressors, particularly in relation to declining PAR.

We took the models further and examined what the optimal PAR and optimal temperature conditions for intertidal and subtidal seagrass systems would potentially be, based on the benthic PAR and temperature data provided from the CU MWMP. Optimal conditions for peak intertidal above-ground biomass were estimated 31.23 mol/m²/s for PAR and 33.41 °C. Subtidal above-ground biomass in Townsville peaked when PAR was maintained at 5.79 mol/m²/s and temperature at 24.26 °C. These results indicate that both light and temperature are critical drivers of seagrass survival and persistence in Townsville.

Extended periods of light reduction (see section 5.6), compounded by periods of suboptimal temperatures (see section 5.6), are consistent with the patterns observed in the GAMM results. Together, the statistical models and time series plots provide evidence that chronic declines in light and suboptimal thermal conditions were key environmental parameters driving seagrass above-ground biomass loss across the Townsville region.

Table 5. Summary of Generalised Additive Mixed Models for intertidal and subtidal above-ground biomass.

Component	Intertidal Seagrass Model	Subtidal Seagrass Model
Formula	Above-ground biomass ~ s(PAR_7) + s(temp_7)	Above-ground biomass ~ s(PAR_7) + s(temp_14)
PAR	$\chi^2 = 129.4$, $p < 0.001$	$\chi^2 = 176.2$, $p < 0.001$
Temperature	$\chi^2 = 248.9$, $p < 0.001$ (7-day average)	$\chi^2 = 414.1$, $p < 0.001$ (14-day average)
Adjusted R^2	0.222	0.162
Deviance explained	18.7%	20.0%
Sample size (n)	1888	2339

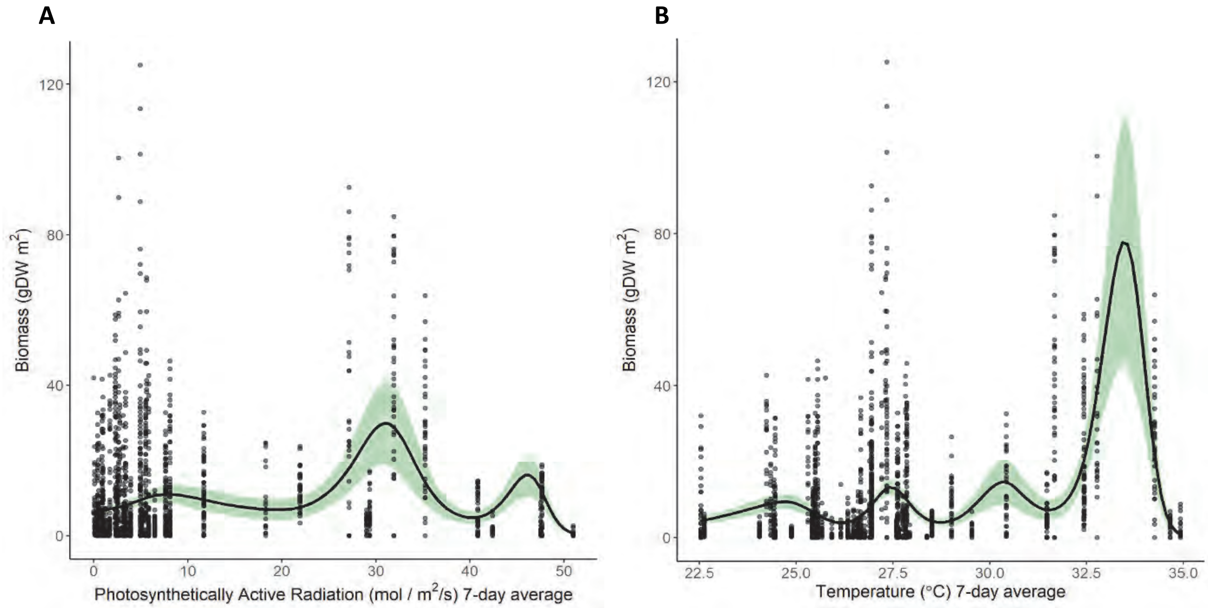


Figure 38. Relationship between modelled seagrass above-ground biomass at intertidal sites and 7-day running mean photosynthetically active radiation (PAR) (A) and seabed temperature (B). Points represent observed above-ground biomass values, the black line shows the fitted trend from the best-fit Generalized Additive Mixed Model (GAMM), and the green ribbon indicates the 95% confidence interval around the modelled estimate.

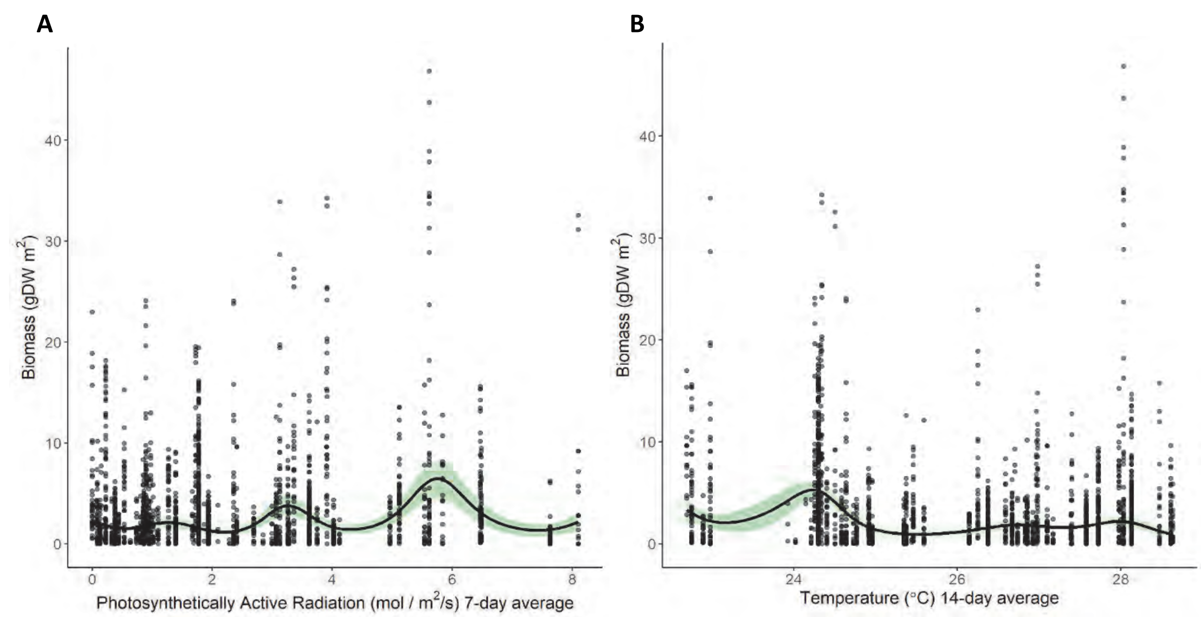


Figure 39. Relationship between modelled seagrass above-ground biomass at subtidal sites and 7-day rolling average of photosynthetically active radiation (PAR) (A) and 14-day running mean temperature (B). Points represent observed above-ground biomass values, the black line shows the fitted trend from the best-fit Generalized Additive Mixed Model (GAMM), and the green ribbon indicates the 95% confidence interval around the modelled estimate.

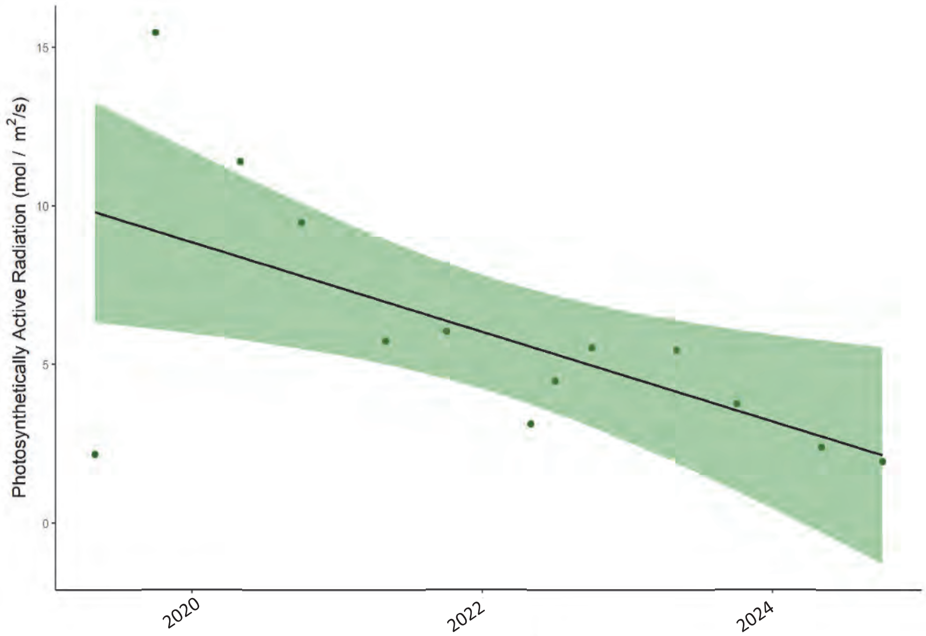


Figure 40. Mean photosynthetically active radiation (PAR) in the Townsville seagrass meadows over the study period 2019–2024. The black trendline illustrates changes in PAR over time, while the green ribbon represents the 95% confidence interval around the modelled estimates.

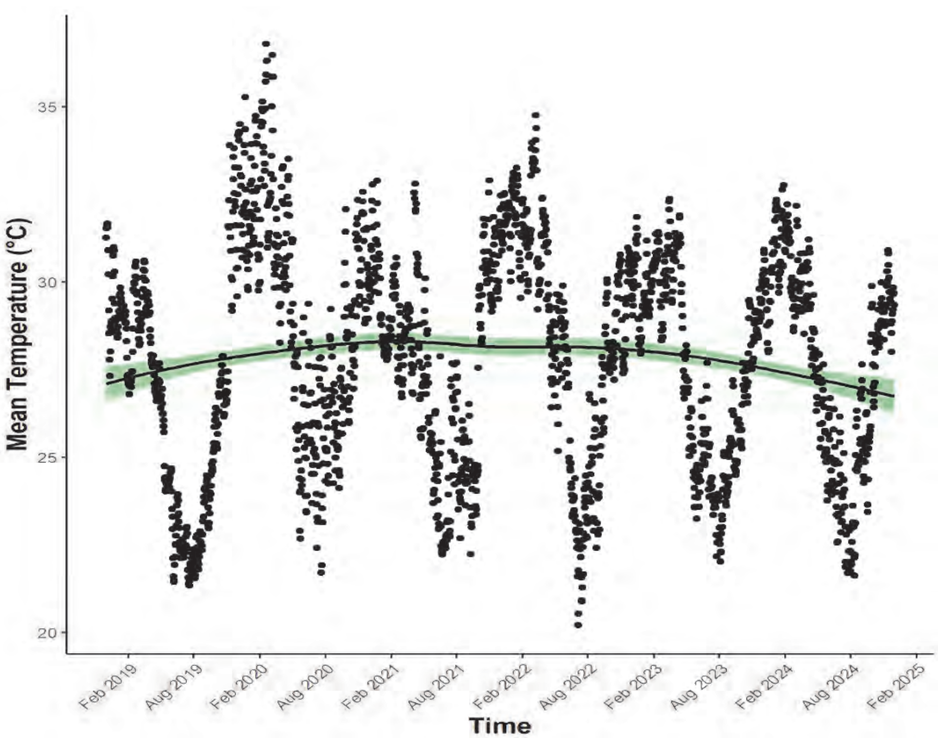


Figure 41. Mean temperature (°C) in Townsville seagrass meadows throughout the study period. Points represent the observed mean temperature for each day, the black trendline illustrates changes in temperature over time, while the green ribbon represents the 95% confidence interval around the modelled estimates.

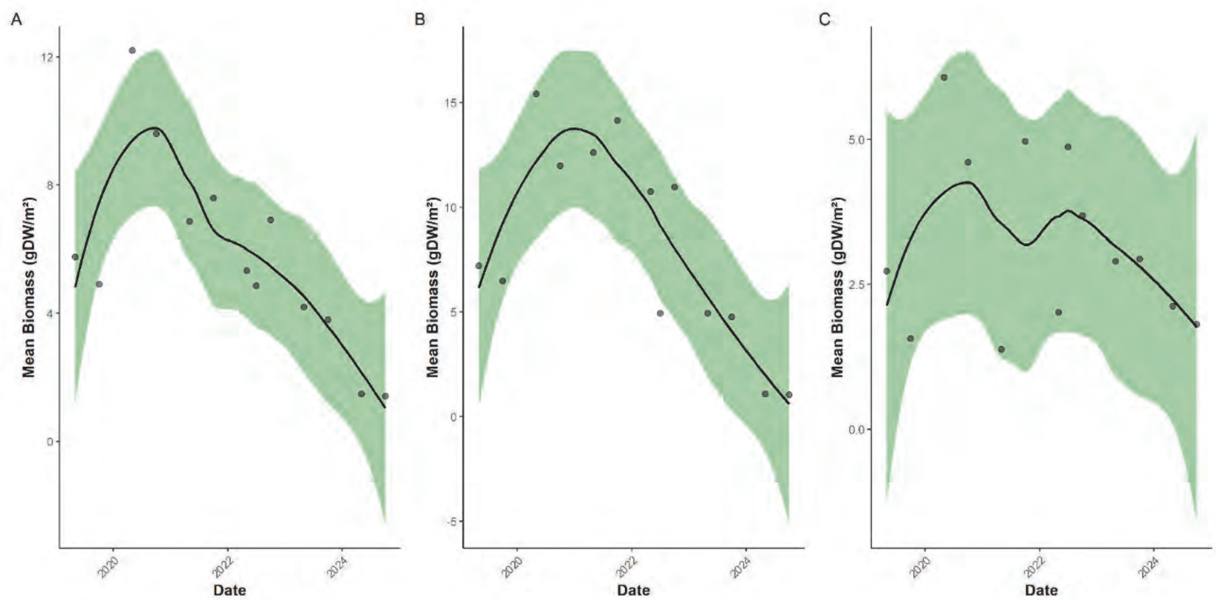


Figure 42. Temporal decline in Townsville seagrass above-ground biomass (gDWm^2) across the overall system (A), intertidal meadows (B), and subtidal meadows (C) over 2019–2024. Points indicate above-ground biomass means for the sampling time point, the black line is the modelled decline, and the green ribbon indicates 95 % confidence intervals.

5.6 Townsville Climate Patterns

5.6.1 General climate patterns and climate during the CUSP: 2019–2024 period

Townsville experiences a tropical climate characterised by distinct wet and dry seasons. The wet season, which typically occurs from November to April, contributes most of the region's annual rainfall. This period is marked by high variability in rainfall, largely influenced by tropical lows, thunderstorms, and broader climatic patterns such as the El Niño–La Niña Southern Oscillation. In contrast, the dry season extends from May to October and is dominated by southeasterly trade winds, which generally bring stable, fine weather and clear skies.

Cleveland Bay is a naturally turbid environment, where turbidity is primarily driven by wind- and wave-induced sediment resuspension (GHD 2024; Jones et al. 2020; Orpin et al. 2004, 1999). On average, the Townsville region experiences approximately 220 turbid days per year (Orpin et al. 1999), reflecting the bay's dynamic sedimentary conditions.

The Townsville region is prone to extreme weather events, particularly during the wet season, including tropical cyclones, heatwaves, and marine heatwaves. Significant events recorded during the CUSP monitoring period (2019–2024) include:

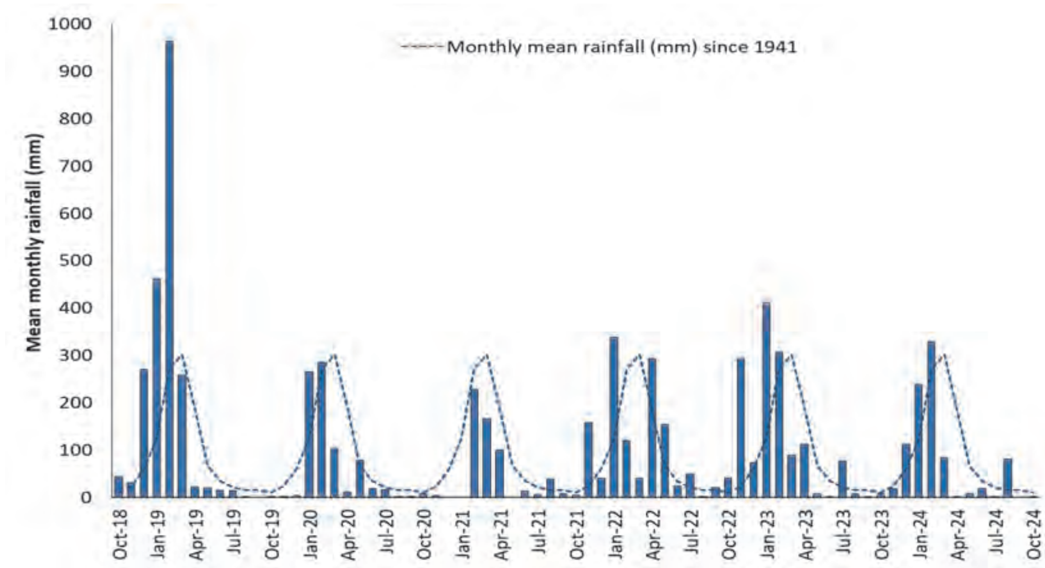
- Record flooding in January–February 2019.
- Above-average rainfall and river discharges during the 2018/19, 2021/22, and 2022/23 wet seasons.
- Extreme temperatures/marine heatwaves:
    - 2019: Australia's hottest year on record (Great Barrier Reef Marine Park Authority (GBRMPA)).
    - February 2020: Record high sea surface temperatures (GBR Outlook Report 2024)
    - Summer 2021/2022: sea temperatures above the long-term average (GBR Outlook Report 2024).
    - Summer 2023/2024: high daily means (GBR Outlook Report 2024)
- Prolonged low light conditions, as evidenced by CU MWMP threshold exceedances (GHD 2024). Exceedances and their longevity are included in the CU MWMP reports found on the PoTL website. A summary of some dates of threshold exceedances have been provided in Table 5 below.
- Tropical Cyclone Jasper (December 2023): Port of Townsville entered Condition Yellow, and CU MWMP water quality instruments were removed.
- Tropical Cyclone Kirrily (January 2024).

5.6.2 Rainfall and river flow

Rainfall in Townsville is seasonal with most of the rainfall typically occurring from December to April (Figure 43A, B). The total annual rainfall in the 12 months preceding the September–October 2024 seagrass survey was below the long-term average. For the last two years it has been above the long-term average (Figure 43B). December 2023, January, February, and August 2024 all had above average monthly rainfall measurements. January and February 2019 had record rainfalls and was the highest rainfall amount in the study period (2019–2024).

River flow for the Burdekin River (Townsville's most significant riverine system in terms of input flow), Black River and Ross Basin (Alligator Creek) were all below long-term averages in the 12 months preceding the September–October 2024 seagrass survey (Figure 44A, B). Total river flow for the Burdekin River was above the long-term annual average three out of the six years of the study period (Figure 44A).

A



B

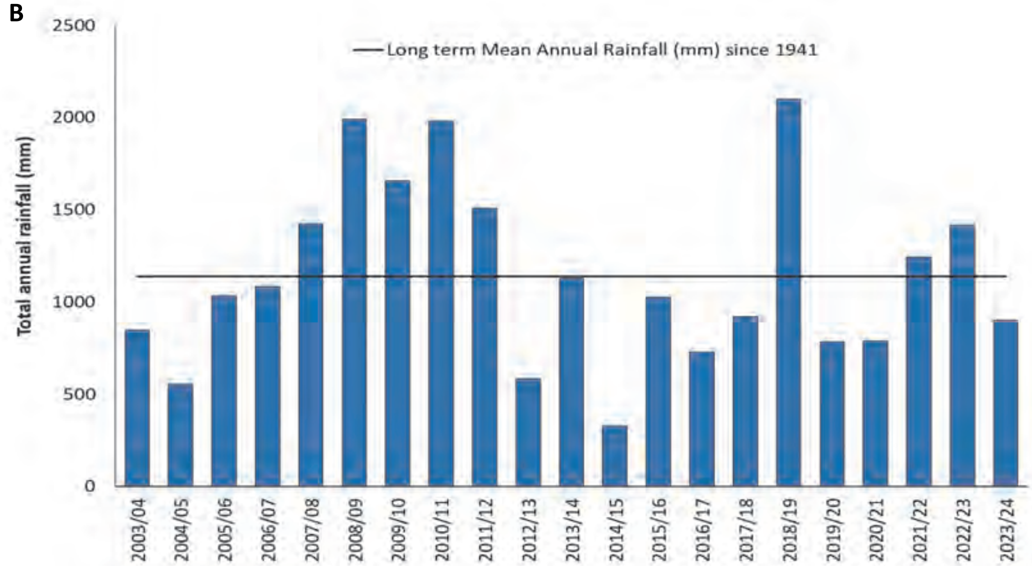


Figure 43. (A) Total monthly rainfall from October 2018–October 2024 and (B) total annual rainfall in the 12 months preceding each annual seagrass survey from 2003/2004–2023/24 recorded at Townsville airport. Data from the Bureau of Meteorology, Station 032040 http://www.bom.gov.au.

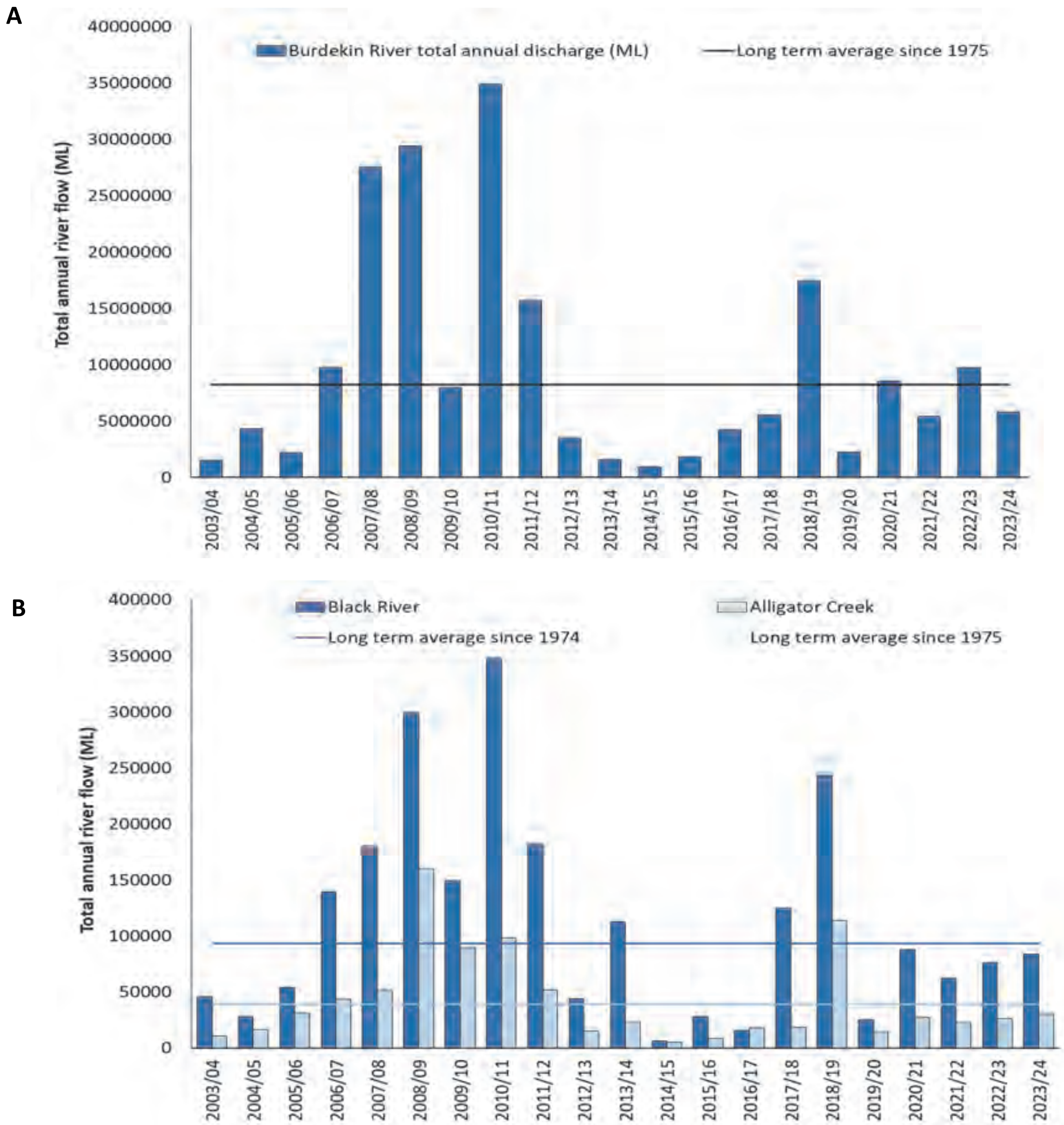


Figure 44. Total annual flow in the 12 months preceding each annual seagrass survey from 2003/04–2023/24 of the Burdekin River (A) and the Black River and Ross Basin (Alligator Creek) (B). Queensland Government Water Monitoring Information Portal: https://water-monitoring.information.qld.gov.au/.

5.6.3 Photosynthetic Active Radiation (PAR) and water temperature

The CUSP refers to benthic PAR and water temperature data from the CU MWMP to help inform seagrass habitat condition. The quantity of light reaching the seabed is a limiting factor and critical to the persistence and growth of seagrass. PAR thresholds for the CU Project and sensitive receptors (i.e., seagrass) were defined based on published scientific literature and cross checked against baseline conditions through the CU MWMP and endorsed by the Independent Technical Advisory Committee (ITAC) for the CU Project. Threshold definitions can be found in the CU MWMP annual synthesis reports on the PoTL website. Briefly, biologically relevant PAR management thresholds for Townsville seagrass were set at:

- Seagrass meadows dominated by *Halophila* or subtidal seagrass meadows – 2.5 mol/m^2/day; 7 day running mean; 28 consecutive days below threshold before impact.
- Intertidal seagrass meadows dominated by *Zostera muelleri* - 6 mol/m^2/day and *Halodule uninervis* - 5 mol/m^2/day; 14 day running mean; 28 consecutive days below threshold before impact.

Trends in daily light across the CU MWMP showed that there were many periods, across all dredge phases (pre-, during- and post-) when light fell below light thresholds for local seagrass. Examples have been included in Table 6 below. Not all sites and days have been represented in Table 6, just examples from some sites and dates, and there are data gaps in the data set.

The CU MWMP reports, through a 'multiple lines of evidence' review that water quality conditions during exceedance periods were influenced by confounding and prevailing weather conditions rather than CU dredging activities (GHD 2024). For example, high wind-wave event causing wave-driven turbidity and low light, followed by high rainfall, which resulted in periods of extended low-light conditions in the Bay (GHD 2024).

Figures for 7 day and 14 day running mean daily light (PAR) versus cloud cover, surface PAR, turbidity (NTU), daily maximum wave height, daily maximum wind speed and daily rainfall, with the 2.5 mol/m^2/day threshold displayed for the CU MWMP compliance locations (Virago Shoal, Strand Shallow and Middle Reef) can be found in the CU MWMP Annual Synthesis report Appendix A (GHD 2024) on the PoTL website.

Table 6. Examples of duration and dates across dredge phases of longest (days) exceedances of PAR thresholds for seagrass in the Townville region. Note seagrass 'days to impact' is 28 days which starts from day one of the running mean. Not all sites and days have been represented and there are data gaps in the data set.

Region	Site	Pre-dredge (2018–2021)	During dredge (2022–March 2024)	Post Dredge (from 01/04/24)
Cleveland Bay	Cleveland Bay (subtidal)	42 days: Feb – Apr 2020 48 days: Jun – Jul 2020 36 days: Sep – Oct 2021	73 days: Apr – Jul 2023 49 days: Jul – Sep 2023 40 days: Feb – Mar 2024	54 days: Apr – May 2024 51 days: Aug – Oct 2024
	Cape Cleveland (subtidal)	33 days: Sep – Oct 2021	35 days: Jul – Aug 2023 32 days: Mar – 10th April 2024	49 days: Apr – Jun 2024
	Cleveland Bay (intertidal)	Max 7 days below threshold	95 days: Feb – Jun 2022 139 days: Jun – Nov 2022 150 days: Feb – Jul 2023	0 days below threshold Site demobilised June 2024
Strand - Pallarenda	Strand Shallow (subtidal)	Max 27 days below threshold	Max 18 days below threshold	Max 19 days below threshold
	The Strand (subtidal)	64 days: Aug – Oct 2021	36 days: Apr – May 2022 63 days: Aug – Oct 2022 55 days: Dec 2022 – Feb 2023	75 days from 1st April
	Virago Shoal (subtidal)	33 days: Mar – Apr 2019 38 days: May – Jul 2020 67 days: Aug – Oct 2021	30 days: Apr – May 2022 43 days: Jul – Aug 2023	50 days: Apr – Jun 2024
Magnetic Island	Geoffrey Bay (subtidal)	43 days: Jan – Mar 2019 64 days: Aug – Oct 2021	32 days: May – Jun 2022 44 days: Jul – Aug 2023	Max 25 days below threshold
	Geoffrey Bay (intertidal)	38 days: May – Jul 2021	112 days: Mar – Jun 2022 36 days: Jun – Jul 2023	77 days: Mar – Jun 2024

5.6.4 Daily maximum wind speed

Wind and wave events have been correlated to elevated turbidity in Cleveland Bay, which in turn influence the amount of light (PAR) reaching the seabed/seagrass (CU MWMP: GHD 2020; Orpin et. 2004; 1999). Through the CU MWMP, elevated turbidity was found to occur at 38 km/hr (GHD 2022), while Orpin et al. 2004 reported that re-suspension of bottom sediment occurs at 20 km/hr. In the 12 months preceding the September–October 2024 survey, daily maximum wind speed exceeded 38 km/hr on multiple occasions and for up to 13 consecutive days (May 2024) (Figure 45). Throughout the CUSP study period (2019–2024) daily maximum wind speed has exceeded 38 km/hr for up to 30 consecutive days (January–February 2019). Maximum daily wind speeds reached 92.5 km/hr (BOM data) and 78.84 km/hr (AIMS data) on 25th January 2024, coinciding with TC Kirrily (Figure 45).

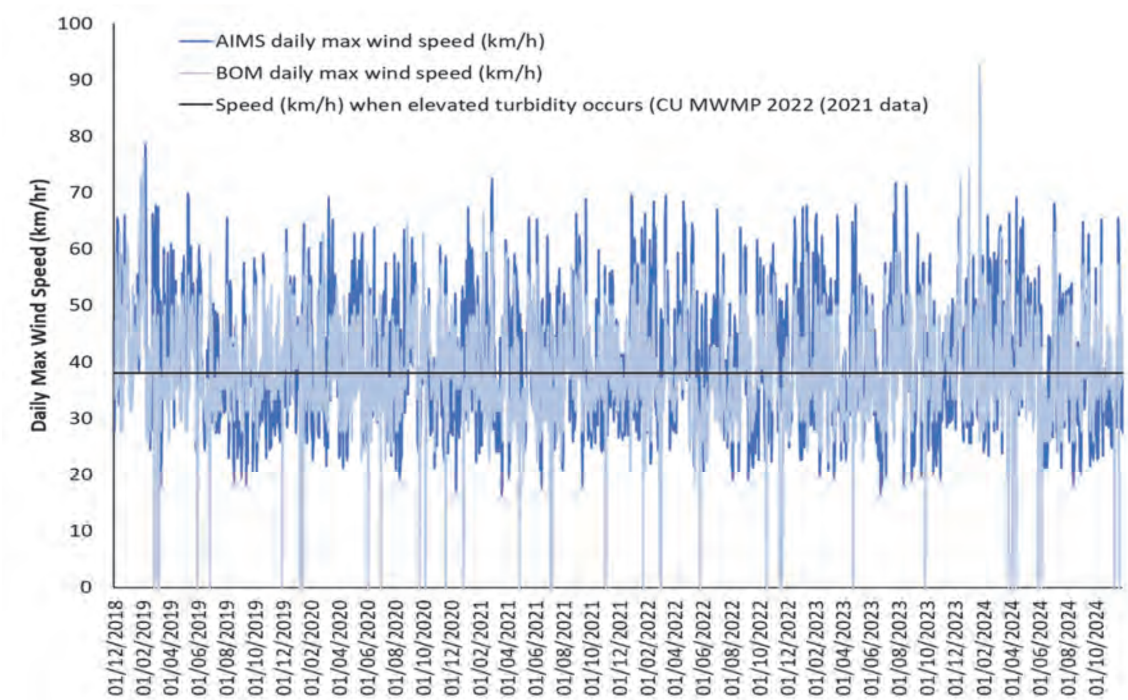


Figure 45. Daily maximum wind speeds recorded from October 2018–November 2024 at BOM station 032040 and the AIMS Cleveland Bay weather station. Black solid line is the 38 km/hr wind speed threshold at which the CU MWMP found that elevated turbidity occurred in Cleveland Bay.

5.6.5 Air and benthic sea temperature in seagrass meadows

Mean annual daily maximum air temperature for 2023/24 was 29.7°C and has been above the long-term average of 29°C for the last twelve years (Figure 46). Monthly mean maximum air temperature has also been above long-term averages for most months during the CUSP (2019–2024) (Figure 47). The CU MWMP reports that trends in benthic water temperature have been relatively consistent across monitoring locations (GHD 2024).

Models in this study found that for intertidal seagrass in Townsville (i.e., *Z. muelleri* and *H. uninervis* meadows) the optimal temperature for peak seagrass above-ground biomass, between 2019 and 2024 was a 7-day running mean of 33.41 °C. For subtidal seagrass, models identified 24.26 °C as the optimal temperature for peak seagrass above-ground biomass.

Temperature within the seagrass canopy at CU MWMP monitoring stations ranged from 17.52 °C (Shelley Beach intertidal site) to 47.09 °C (Cleveland Bay intertidal site) (Table 7). During the CUSP, extreme air temperatures and marine heatwave conditions were reported by GBRMPA on the below occasions:

- 2019: Australia's hottest year on record (GBRMPA).
- February 2020: Record high sea surface temperatures (GBR Outlook Report 2024)
- Summer 2021/2022: sea temperatures above the long-term average (GBR Outlook Report 2024).
- Summer 2023/2024: high daily means (GBR Outlook Report 2024)

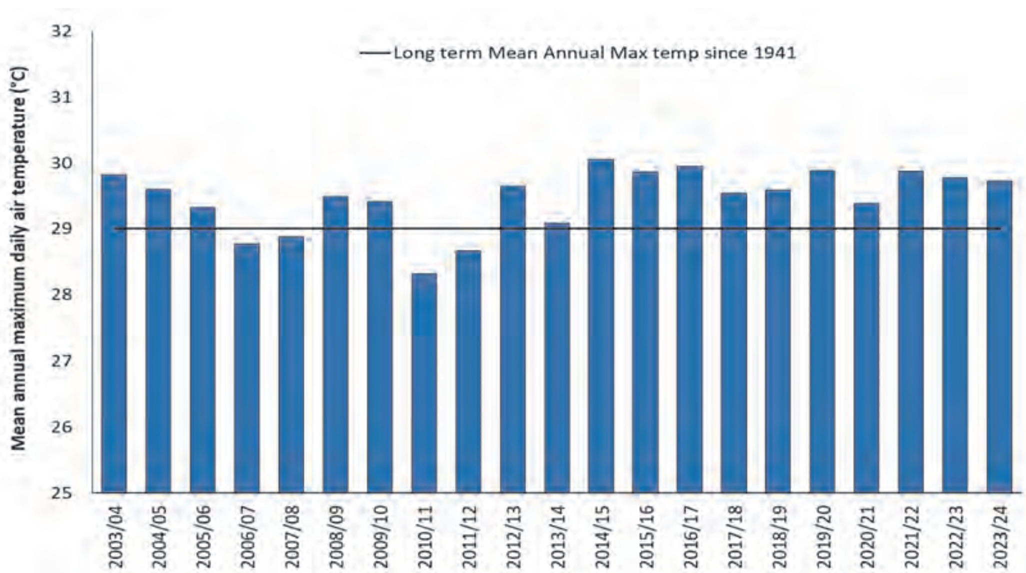


Figure 46. Mean annual maximum daily air temperature (°C) in the 12 months preceding each annual survey recorded at Townsville Airport, 2003/04–2023/24. Data from the Bureau of Meteorology, Station 032040 http://www.bom.gov.au.

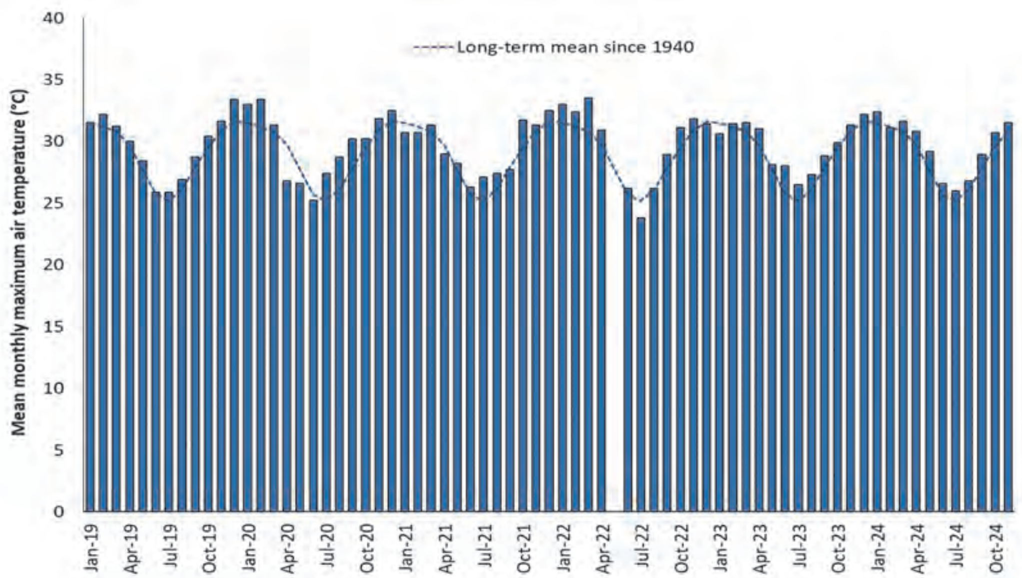


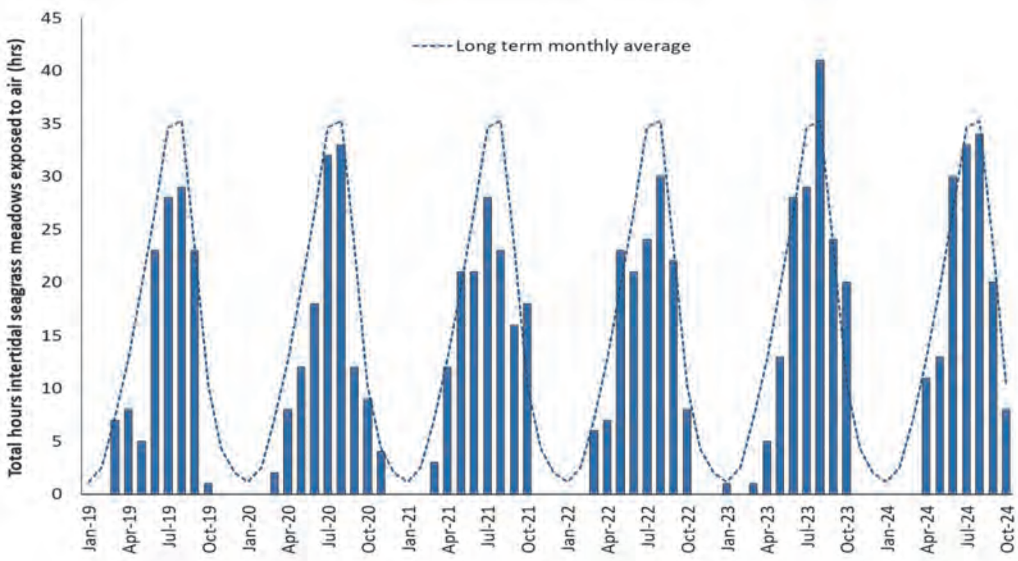
Figure 47. Mean monthly maximum daily air temperature (°C) recorded at Townsville Airport, January 2019–November 2024. Data from the Bureau of Meteorology, Station 032040 http://www.bom.gov.au.

Table 7. Temperature (°C) descriptive statistics across most monitoring locations from December 2018– November 2024.

Location	Minimum	Date	Maximum	Date
Florence Bay (subtidal)	20.71	20/07/2024	32.02	21/02/2020
Geoffrey Bay (subtidal)	20.32	16/07/2022	36.34	16/02/2020
Geoffrey Bay (intertidal)	19.89	16/08/2022	46.58	17/02/2020
Picnic Bay (subtidal)	19.49	15/07/2022	33.42	09/03/2022
Cockle Bay (subtidal)	19.99	06/07/2022	34.09	13/11/2024
Cockle Bay (intertidal)	19.17	05/07/2022	42.09	09/11/2019
Shelley Beach (intertidal)	17.52	05/07/2022	42.56	19 & 20/02/2020 07/03/2020
The Strand (subtidal)	19.82	22/07/2020	33.45	08/03/2022
Strand Shallow (subtidal)	19.94	15/07/2022	34.50	03/03/2022
Virago Shoal (subtidal)	20.10	15/07/2022	33.00	08/03/2022
Cleveland Bay (subtidal)	19.85	07/07/2022	32.54	12/02/2020
Cleveland Bay (intertidal)	17.70	10/09/2021	47.09	06/03/2020
Cape Cleveland (subtidal)	19.77	16/07/2022	31.97	16/07/2022

5.6.6 Seagrass exposure to air (intertidal seagrass meadows)

Total daytime exposure to air of intertidal seagrasses in Townsville is generally higher during the winter months and lower over summer/wet season (Figure 48A). Total hours of tidal exposure in the one-month period prior to the two 2024 seagrass surveys were 11 hours for the post-wet survey, and 34 hours for the dry season survey: both below long-term averages (Figure 48A, B). The total hours of tidal exposure in the three-month period before dry season surveys has been below the long-term average for nine years (Figure 48B).



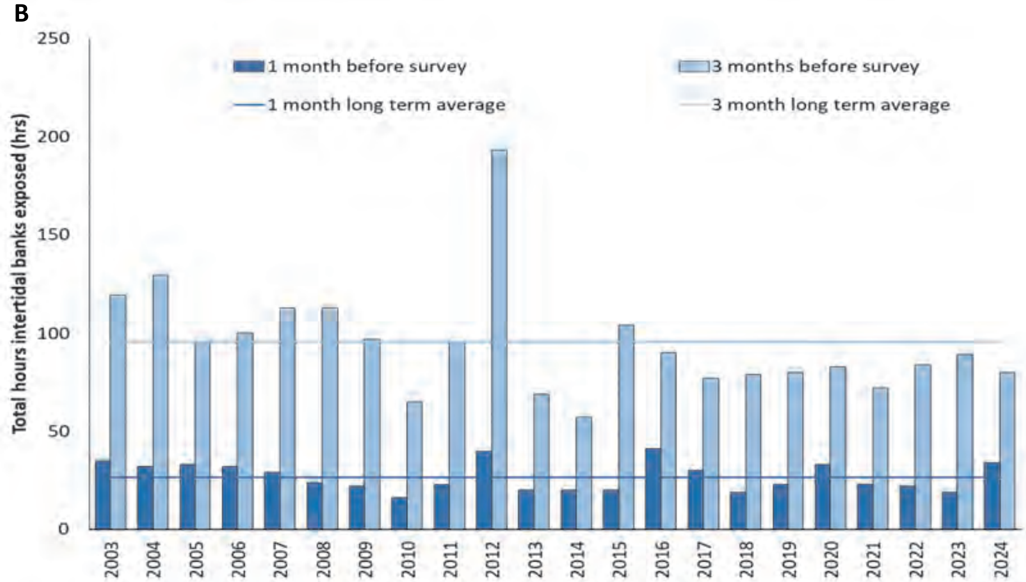


Figure 48. (A) Total monthly hours seagrass meadows exposed to daytime intertidal air Jan 2019–October 2024 and (B) total daytime exposure one month and three months (<0.8 m tidal height) prior to the annual monitoring surveys in Townsville (Maritime Safety Queensland, www.msq.qld.gov.au).

6 DISCUSSION

6.1 Overview of seagrass condition in Townsville

Seagrass meadows in Townsville were in an overall poor condition at the end of 2024. Demonstrating a trending decline in above-ground biomass for most meadows over the last several years. Despite this, an extensive footprint of seagrass remains within the Townsville region, with persistent higher light requiring species still present in the region providing a foundation for recovery. The presence of turtles and dugongs, and dugong feeding trails in meadows indicated herbivorous marine megafauna continue to make extensive use of the available seagrass habitat.

Declines in seagrass cover in Townsville were also recorded in the GBRMPA Marine Monitoring Program (MMP). Seagrass monitoring at Shelley Beach recorded 0% cover at the end of 2024 (www.seagrasswatch.org/burdekin/). On Magnetic Island, the intertidal site MI1 recorded its lowest seagrass cover since 2016, while MI2 had 17.8% cover, and the subtidal site (MI3s) recorded 4.7% cover of seagrass. The intertidal sites on Magnetic Island were dominated by the colonising species *Halophila ovalis* (McKenzie et al. 2024). At Bushland Beach, seagrass cover at the end of 2024 was the lowest recorded since 2011. Beyond Townsville, annual monitoring at Abbot Point also recorded declines in seagrass above-ground biomass and/or area between 2022 and 2024 (McKenna et al. 2024; TropWATER in prep). Further south, at Mackay/Hay Point, seagrass trends were more variable, with some meadows showing declines and others increases in above-ground biomass and/or area between 2023 and 2024 (TropWATER, in prep).

6.2 Townsville seagrass and the Channel Upgrade Project

The process of dredging has the potential to impact seagrass habitat directly (e.g., removal, burial/smothering) or indirectly (e.g., increased turbidity = altering the light spectra and/or reducing availability of underwater light for photosynthesis) and can result in high levels of stress and mortality to benthic primary producers such as seagrasses (see McCook et al. 2015 for a full synthesis on the biophysical impacts of dredging in the GBR).

One of the overarching goals of the CUSP was to assess seagrass condition at sites in relation to the pre-, during- and post-dredging phases of the CU Project in parallel with recorded *in situ* environmental data. The program provided seagrass condition at assessment sites within the modelled Zone Of Influence (ZOI) and outside the ZOI with varying proximity to dredge activity and covering the range of species and meadow types typical throughout the Townsville region.

CUSP monitoring results revealed a declining trend in Townsville's seagrass condition between 2019 and 2024. However, statistical analyses comparing seagrass above-ground biomass, the most sensitive condition indicator, in pre-, during-, and post-dredge phases showed no significant differences in seagrass above-ground biomass trends that could be attributed to dredging activities. This conclusion is supported by the below findings from the CUSP and the CU MWMP:

- Seagrass above-ground biomass declines occurred beyond the modelled ZOI (for expected and worst-case modelled scenarios).
    - Seagrass above-ground biomass declines occurred at a Townsville region/Bay wide scale, not just within the ZOI.
    - Analysis showed that seagrass declines inside the ZOI were not statistically different across dredge phases while seagrass declines outside the ZOI, across dredge phases were significantly different.
- Statistical models identified photosynthetically active radiation (PAR), and temperature (°C) as significant environmental predictors of seagrass above-ground biomass decline rather than dredging.
    - Models identified that the 7-day running mean PAR and temperature significantly influenced seagrass above-ground biomass in intertidal seagrass meadows.
    - Models identified that 7-day and 14-day running mean PAR and temperature, respectively, significantly influenced seagrass above-ground biomass in subtidal seagrass meadows.
    - There was an overall decreasing trend in PAR across the study period (2019–2024).

- The CU MWMP report that declines in PAR were:
  - Recorded at sentinel as well as reference locations (including Paluma Shoal) across the study period (2018–2024).
  - Declines in PAR through the study period were attributed to meteorological influences on the system (high cloud cover, and high winds, elevated wave heights and rain, which increase turbidity and in turn reduce PAR) rather than mechanical dredging.
  - Declines in PAR were recorded in post-dredge data (2024; Table 6) across sites, including sites beyond the ZOI (i.e., Cleveland Bay and Cape Cleveland (Table 6)).

Given that seagrass above-ground biomass and PAR declines occurred Townville region/Bay wide, that PAR and temperature were found to influence seagrass above-ground biomass and that declines in PAR were associated with meteorological influences on the system, the observed declines in seagrass above-ground biomass are most likely because of system -wide influences and therefore not attributable to dredging.

6.3 System-wide influences and drivers of seagrass

Annual seagrass monitoring in Townsville has shown patterns of loss and recovery over the duration of the LTSMP (est. 2007). By 2017/2018, most meadows had recovered from losses associated with Tropical Cyclone Yasi and associated La Niña conditions (consecutive years of above-average rainfall and river discharge). Between 2019 and 2024, the focus of this report, Townsville seagrass meadows were exposed to:

- Catastrophic floods in January/February 2019 which triggered another significant decline in seagrass in the region.
- Above-average rainfall and river discharges during the 2018/19, 2021/22, and 2022/23 wet seasons.
- Extreme temperatures/marine heatwaves:
  - 2019: Australia's hottest year on record (GBRMPA).
  - February 2020: Record high sea surface temperatures (GBR Outlook Report 2024)
  - Summer 2021/2022: sea temperatures above the long-term average (GBR Outlook Report 2024).
  - Summer 2023/2024: high daily means (GBR Outlook Report 2024)
- Tropical Cyclones (TC Jasper December 2023; TC Kirrily January 2024).
- High wind, elevated wave and low light (PAR) conditions (as evidenced and reported through the CU MWMP data and reports for the CU Project).

Seagrass distribution, abundance, and species composition are shaped by a complex interplay of natural and climate-related drivers. River flow, water temperature, tidal exposure, sediment and light availability (including factors such as turbidity and water clarity) all strongly influence seagrass growth, survival and resilience (Bass, 2024; Chartrand et al. 2016; Collier et al. 2012; Ralph et al. 2007; Rasheed and Unsworth 2011; Unsworth et al. 2012). In Townsville, seagrass above-ground biomass and distribution in coastal areas have been found to be significantly influenced by benthic light (PAR) and temperature (this study; Collier et al., 2017; Collier et al., 2018; Petus et al. 2014; Collier et al. 2012; Lambrechts et al. 2010).

Benthic light available to seagrass in the Townsville region is significantly influenced by periods of high cloud cover, high winds, elevated wave heights, river flow and rainfall (GHD 2024; Jones et al. 2020; Petus et al. 2014; Bainbridge et al. 2012; Lambrechts et al. 2010). Wind driven wave activity and riverine inputs become particularly important during strong trade winds when resuspension of fine sediments can increase turbidity and reduce the light available to seagrass meadows (Jones et al. 2020; Bainbridge et al. 2012; Lambrechts et al. 2010). In Cleveland Bay wave resuspension of bottom sediment occurs about 220 days per year and is the predominant process that drives turbidity in Townsville (Orpin et al. 1999). Orpin (2004) found that wind speeds consistently above 20 km/hr in Cleveland Bay correlated with elevated turbidity. The CU MWMP found that elevated turbidity occurs when daily maximum wind speeds are above a 38km/hr average (GHD Annual Report 2022); all impacting the total available light to seagrass habitats. When the light environment begins to deteriorate, an imbalance in the plant's carbon budget is created where a greater amount of carbon is used for respiration than is being fixed through photosynthesis. If sustained this can eventually lead to the loss of seagrass above-ground biomass and cover (York and Smith 2013; Ralph et al. 2007; Erftemeijer and Lewis 2006; Fourqurean et al. 2003).

Trends in daily light across the CU MWMP showed that there were many periods, across all dredge phases (pre-, during- and post-dredging) when light fell below critical biological thresholds for local seagrass (Table 6). For instance, before dredging began, Cleveland Bay seagrass (a reference location for the seagrass program) was exposed to up to 48 days of low light (light below threshold) between June and July 2020. During dredging (2023), Cleveland Bay subtidal seagrass experienced up to 73 consecutive days of low light between April and July 2023, while intertidal habitats in Cleveland Bay were subjected to 150 days of low light in the same period. In contrast, seagrass meadows between the Breakwater Marina wall and Cape Pallarenda (seagrass within the Zone Of Influence) were only exposed to up to 19 days below threshold during dredging (Strand Shallow water quality site). After dredging, Cleveland Bay subtidal seagrass experienced 54 days of low light between April and May 2024; The Strand (shallow) 19 days; and Geoffrey Bay intertidal seagrass 77 days of low light in the same period. The CU MWMP reported that low light exceedances were closely linked to periods of high cloud cover, high winds, elevated wave heights and rainfall. For example, there were Townsville region wide losses of light between July and October 2023 which coincided with >100 days of maximum wind speeds over the 20km/hr threshold (Orpin et al. 2004) and 73 days over the 38 km/hr at which elevated turbidity occurs (CU MWMP). The MMP have also reported that PAR in the Burdekin region has been getting progressively lower over their long-term dataset (McKenzie et al. 2024).

The 'shoulder periods' around daytime tidal exposure are likely to provide some of the highest useful periods of light for intertidal seagrasses. However, the period of air exposure, while high in light may not provide a net gain to the plants from photosynthesis due to exposure related stresses to the plant (Petrou et al. 2013). Excessive daytime tidal exposure can be damaging to seagrass as intertidal seagrasses may exhibit photo-inhibition and desiccation at high solar irradiances and air temperatures leading to declines in net photosynthesis (Petrou et al. 2013). In August 2023 for example, intertidal seagrass meadows were exposed to air for a total of 41 hours. This was well above the long-term average for August. The cumulative impacts of long periods of low light (as recorded between July and October 2023), above average exposure to air (August and October 2023, and above-average air temperatures (August 2023) are likely to have created significant stress to seagrass over this period. Light limitation can increase the susceptibility and exacerbate the effects of thermal stress in seagrass (Jung et al. 2023; Collier et al. 2011).

The interaction between light and in water and air temperatures can play a key role in the survival of seagrasses in inshore turbid environments. Exposure to extreme temperatures for prolonged periods of time can cause photoinhibition: metabolic demands increase pushing seagrasses to the point where respiration outstrips photosynthesis, regardless of adequate light conditions (Bass et al. 2024; Collier et al. 2018; Collier et al. 2017; Chartrand et al. 2016; Collier et al. 2011; Lee et al. 2007; Matheson 2022). *Zostera muelleri* for example, can sustain growth at higher temperatures if light is sufficiently abundant, but declines sharply once temperatures exceed ~30–33 °C (Collier et al. 2011; Chartrand et al. 2016; York et al. 2013). *Zostera muelleri* carbon fixation and above-ground biomass have been shown to decline significantly under saturating light levels in conjunction with temperatures of >33°C (Collier et al. 2011). Collier et al. (2017) found that the thermal optimum for gross photosynthesis for *Z. muelleri* was 31°C while for *H. uninervis* and *C. serrulata* it was 35°C. Models in this study found that for intertidal seagrass in Townsville (i.e., *Z. muelleri* and *H. uninervis* meadows) the optimal temperature for peak seagrass above-ground biomass, between 2019 and 2024 was a 7-day running mean of 33.41 °C. For subtidal seagrass, models identified 24.26 °C as the optimal temperature for peak seagrass above-ground biomass.

Seabed temperatures recorded by the CU MWMP at several of our seagrass monitoring sites, particularly intertidal meadows, frequently reached or exceeded 33 °C — and even approached 40 °C — over the past few years. For example, intertidal meadows dominated by *Z. muelleri* exceeded 33.41 °C for ten or more consecutive days on three occasions in 2019, four occasions in 2020, two in 2021, two in 2022 (the longest period occurring in the March 2022 marine heatwave; 22 days), 2023 was mostly data deficient over the summer period, while there were only a max of six days above 33.41 °C in 2024 (to November 2024). The shallow subtidal seagrass meadow along the Strand was exposed to fourteen consecutive days of above 33 °C temperatures in March 2022. The MMP reported that 2021–2022 was the warmest period (within seagrass canopy temperatures) in the Burdekin region since the MMP commenced. Within-canopy temperatures decreased through 2023 but remained above long-term averages (McKenzie et al. 2024).

When environmental conditions are not favourable for seagrass growth and persistence, as individual one-off events these unfavourable conditions are not likely to have a significant residual impact on seagrass (except for extreme events such as cyclones and floods). However, successive, and concurrent events during and over multiple years are likely to lead to cumulative pressures on seagrass habitat. These cumulative pressures in Townsville were likely to have caused the seagrass condition loss recorded in the Townsville region. Additionally, while extreme events like cyclones and floods have clear observable and recorded impacts on seagrass habitat, identifying the primary drivers of seagrass decline when multiple pressures occur simultaneously or in quick succession becomes more complex to untangle.

Additional factors such as sediment dynamics, grazing pressure from dugongs and turtles, nutrients, and propagule supply, which were not monitored in the program, are all potential drivers of declines / key influences of seagrass change as well. In the July 2022 seagrass report, we reported some declines in the condition of the *H. uninervis* meadow along the Strand between the May 2022 survey and the July 2022 survey. We attributed those declines to be most likely due to herbivory. Substantial numbers of dugong feeding trails and significant cropping was observed in this meadow, which can temporarily reduce measured above-ground biomass despite stable or continuous meadow coverage (Scott et al. 2018).

Cleveland Bay is a naturally turbid environment and experiences natural fluctuations in light and turbidity. The fact that seagrass habitat persists in this kind of environment and has gone through cycles of natural loss and recovery, indicates a degree of adaptation and resilience to these conditions.

6.4 Seagrass resilience, implications for management and future monitoring

The LTSMP and CUSP, combined with the CU MWMP provide an insight into the resilience of Townsville seagrasses to environmental perturbations. Seagrasses in Townsville have demonstrated multiple times that they have the capacity to recover following major environmental events and withstand long periods of low light. But as has been seen in other Queensland locations (e.g., Mourilyan Harbour (Shepherd et al. 2024)) repeated disturbances over multiple years may lead to long-term loss, with recovery trajectories far less certain.

Resilience is the capacity of an ecosystem to withstand disturbance and to adapt to change without shifting to an alternative state, often incorporating a resistance and recovery element (Connolly et al. 2018; McKenzie et al. 2024; Unsworth et al. 2015). Resilience can be assessed through a set of measurable biological characteristics (e.g., species composition (diversity, proportion of colonising species vs persistent species) and reproductive effort (seeds/sediment seed bank, reproductive structures).

While reproductive effort is not monitored through the LTSMP or CUSP, the MMP does measure reproductive effort at two locations (3 sites) in Townsville: Shelley Beach and Magnetic Island. The MMP has reported (data from the 2022-2023 period) that reproductive effort was low in coastal intertidal habitats (i.e., Shelley Beach), absent at reef subtidal habitats (i.e., Picnic Bay) and slightly higher at reef intertidal habitats (i.e., Cockle Bay) than in the previous seven years. Seed banks persist, but densities were reduced in coastal, and reef intertidal habitats compared to previous years. Reduced reproductive effort may limit seed bank replenishment. The LTSMP and CUSP have recorded a gradual loss of *Z. muelleri* as the dominant species in some meadows and this may affect local seed bank replenishment, making recovery increasingly dependent on propagule transport from other areas.

While Townsville's seagrass meadows were in an overall poor condition at the end of 2024, positive indicators include good spatial coverage, maintained species composition and the continued presence of persistent and higher light requiring species in subtidal meadows. The presence of dugong feeding trails in some meadows, also indicates ongoing ecological function, despite reduced seagrass above-ground biomass.

Legacy effects of meteorological system-wide pressures have likely caused the current condition of Townsville's seagrass. Considering the poor condition of Townsville seagrass at the end of 2024, Port of Townsville (PoTL) have commissioned a post-wet season 2025 assessment of seagrass, to update seagrass meadow condition in the region.

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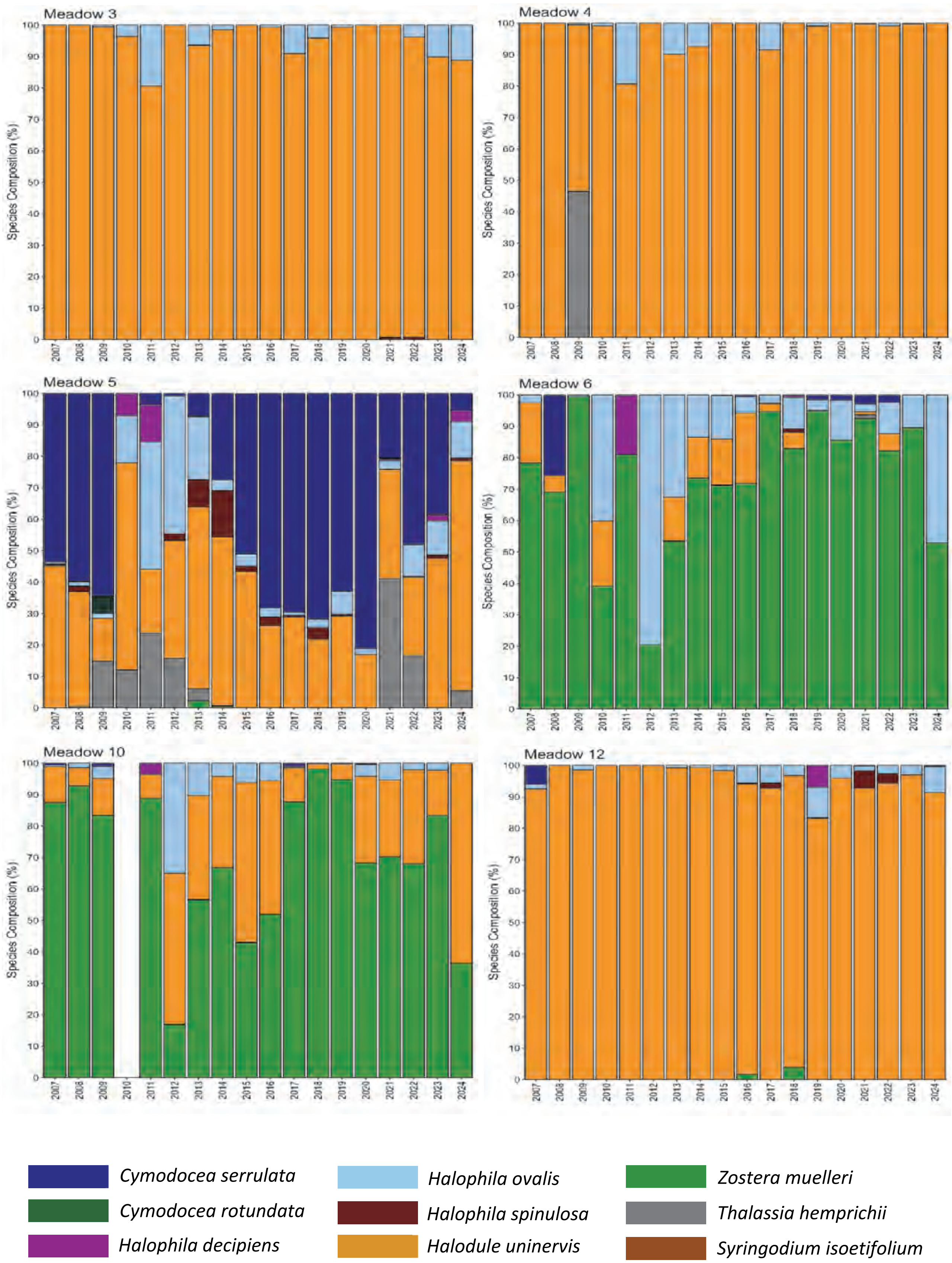
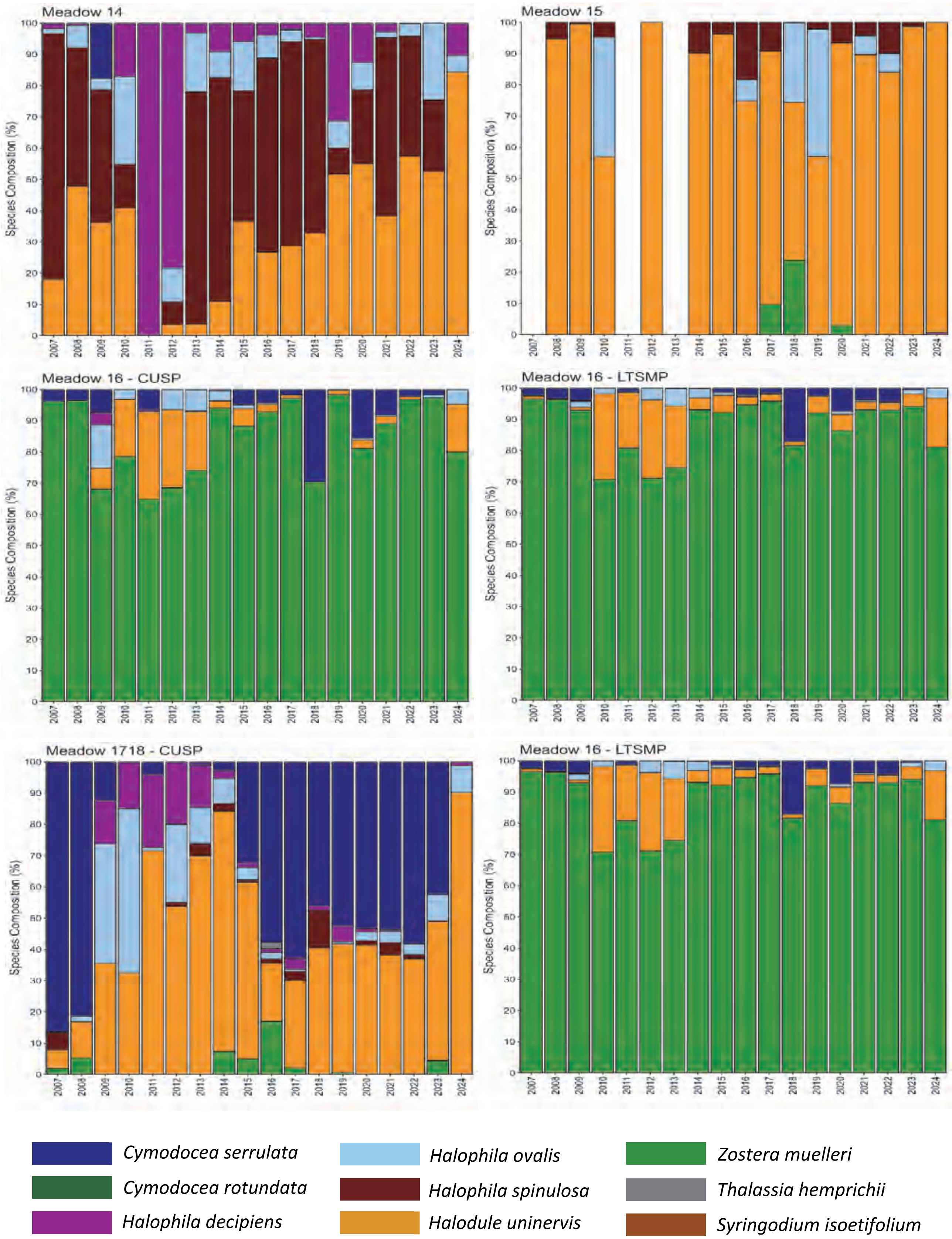
8 APPENDICES

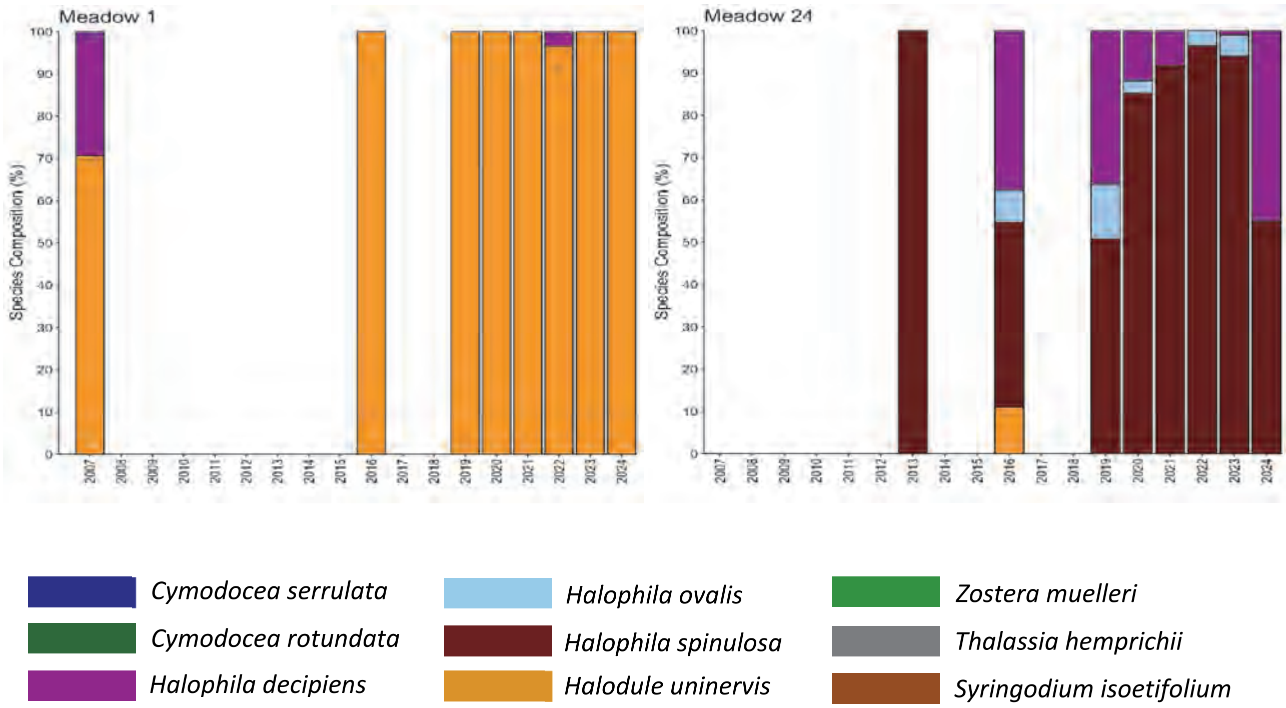
8.1 Appendix 1. Detailed meadow species composition; 2007-2024





Meadow 14
Meadow 15
Meadow 16 - CUSP
Meadow 16 - LTSMP
Meadow 1718 - CUSP
Meadow 16 - LTSMP
Species Composition (%)
Cymodocea serrulata
Cymodocea rotundata
Halophila decipiens
Halophila ovalis
Halophila spinulosa
Halodule uninervis
Zostera muelleri
Thalassia hemprichii
Syringodium isoetifolium

Meadows 1, 24 and deep-water meadow 19 were surveyed as part of broadscale surveys; 2007, 2013, 2016. From 2019 they have been surveyed annually: 2019-2024.



8.2 Appendix 2. Analysis results of original EIS and AEIS nominated impact/reference meadows and dredge phase

8.2.1 Effects of dredging on EIS and AEIS nominated impact/reference meadows

Seagrass above-ground biomass at sites within impact meadows across dredge phases was found to be significantly lower during and after dredging compared to pre-dredge values ($t = -4.46$, $p < 0.0001$; $t = -6.41$, $p < 0.0001$, respectively) (Table A2; Figure A2.1). Significant reductions in above-ground biomass also occurred across all dredging phases at sites within reference meadows, with marked declines observed from pre-dredge to during dredge ($t = -5.06$, $p < 0.0001$) and from pre-dredge to post-dredge ($t = -13.68$, $p < 0.0001$) (Table A2; Figure A2.1). These declines have been discussed in more detail in section 5.2.

Overall, these analyses show that seagrass above-ground biomass declines across dredging phases occurred within impact meadows as well as reference meadows.

When comparing between impact meadows and reference meadows between dredge phases, seagrass above-ground biomass was found to be significantly lower overall in impact meadows compared to reference meadows before dredging, and during dredging ($t = -22.55$, $p <0.0001$; $t = -14.45$, $p < 0.0001$ respectively; Figure A2.1). The significantly larger above-ground biomass in reference meadows can be explained by the high above-ground biomass *Z. muelleri* that was present in the Cleveland Bay meadow (16): some assessment sites had > 100 gDWm^2 of seagrass compared to impact sites where the largest above-ground biomass at any time was 46 gDW m^2 (Figure 11).

After dredging analysis showed that there was no significant difference in seagrass above-ground biomass between impact and reference sites during post-dredge sampling ($t = -1.08$, $p = 1.0$) (Table A2; Figure A2.1). These results underscore that seagrass declines in Townsville occurred across both reference and impact meadows. These results have also been visualised at the meadow level of analysis (Figure A2.2). The declining trend in Townsville seagrass have been reported on in further detail in section 5.2.

Table A2. Post hoc summary for generalized linear models comparing sites within impact meadows, sites within reference meadows and impact vs references meadows. Values are from text above.

Impact sites vs Impact sites			
Impact	**Impact**	t ratio	p value
Pre-dredge	During-dredge	-4.46	< 0.0001
Pre-dredge	Post-dredge	-6.41	< 0.0001
Reference vs Reference			
Reference	**Reference**		
Pre-dredge	During-dredge	-5.06	< 0.0001
Pre-dredge	Post-dredge	-13.68	< 0.0001
Impact vs Reference			
Impact	**Reference**		
Pre-dredge	Pre-dredge	-22.55	< 0.0001
During dredge	During dredge	-14.45	< 0.0001
Post-dredge	Post-dredge	-1.08	1.0

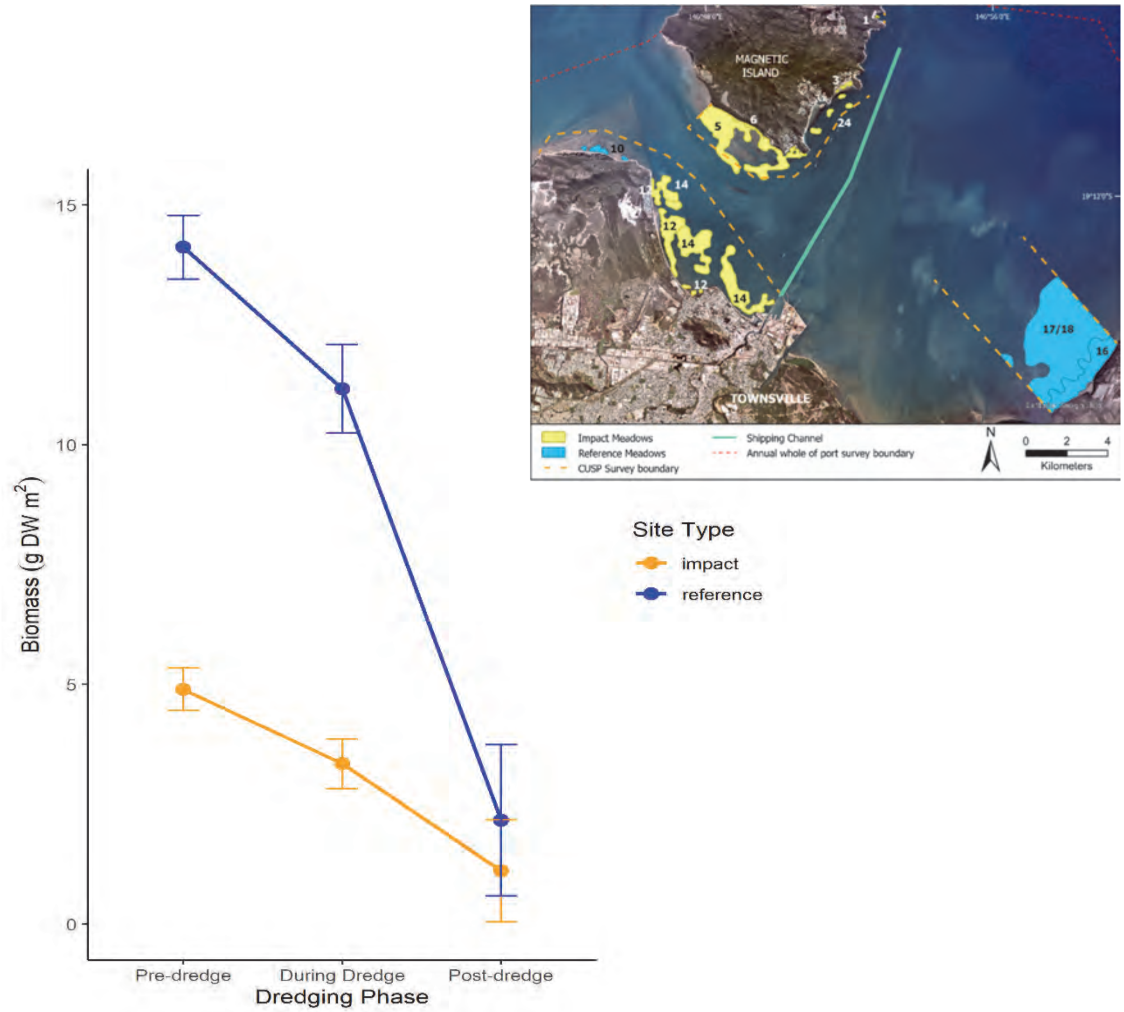


Figure A2.1. Mean seagrass above-ground biomass (gDWm²) across different dredge phases at sites within impact meadows (n = 3563) and at sites within reference meadows (n=1389) based on Generalised Linear Models (GLMs). Error bars indicate the 95% confidence intervals of the predictions based on the GLM.

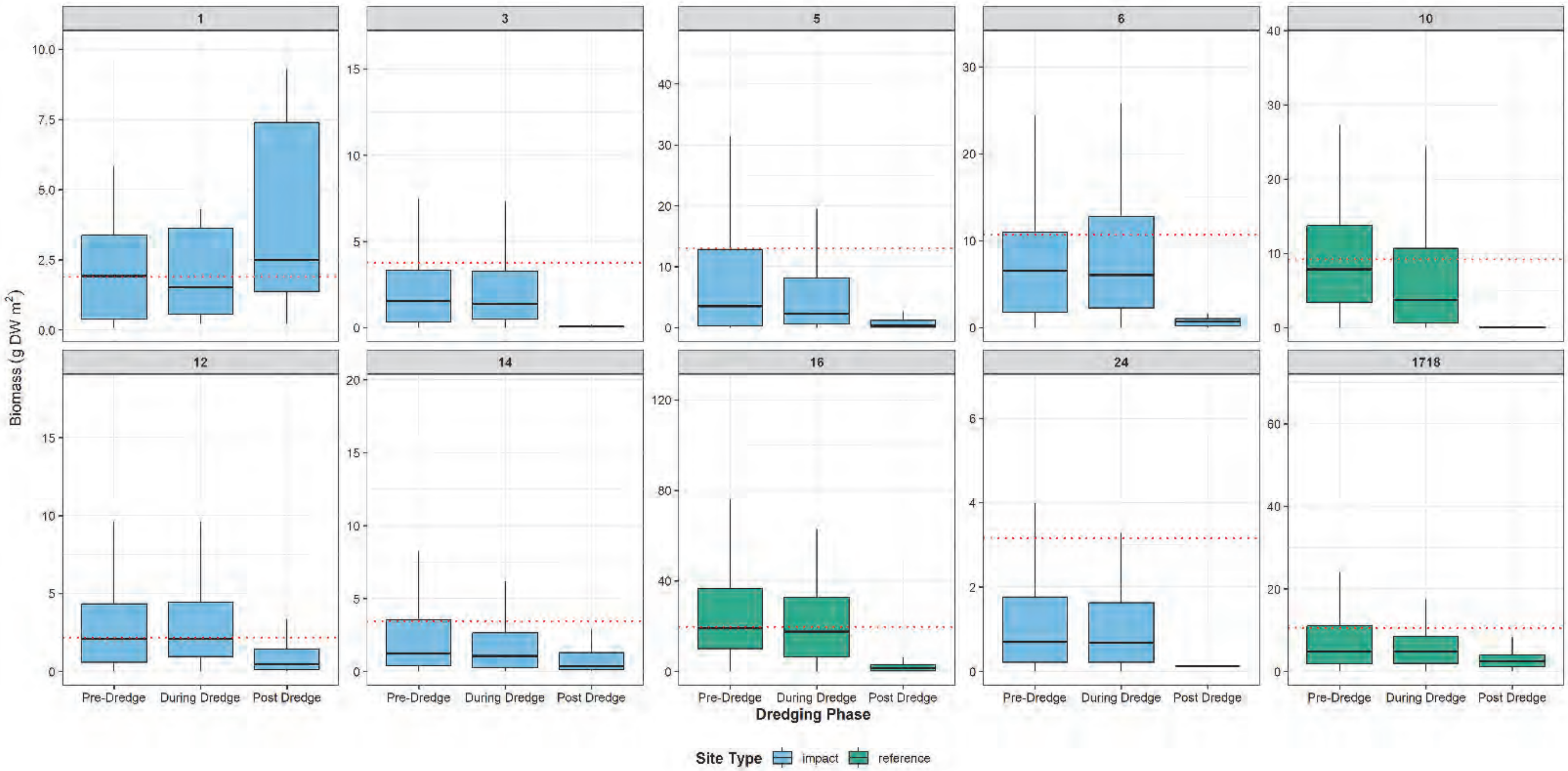


Figure A2.2. Seagrass above-ground biomass (gDWm²) for each CUSP monitoring meadow across different dredge phases. Green box plots are reference meadows, blue box plots are impact meadows. The red dotted line represents the mean baseline above-ground biomass for each meadow (see section 4.3). Boxplots display the distribution of above-ground biomass, including the interquartile range and median values, across dredge phases.