PORT OF WEIPA LONG-TERM SEAGRASS MONITORING PROGRAM: 2000 - 2022

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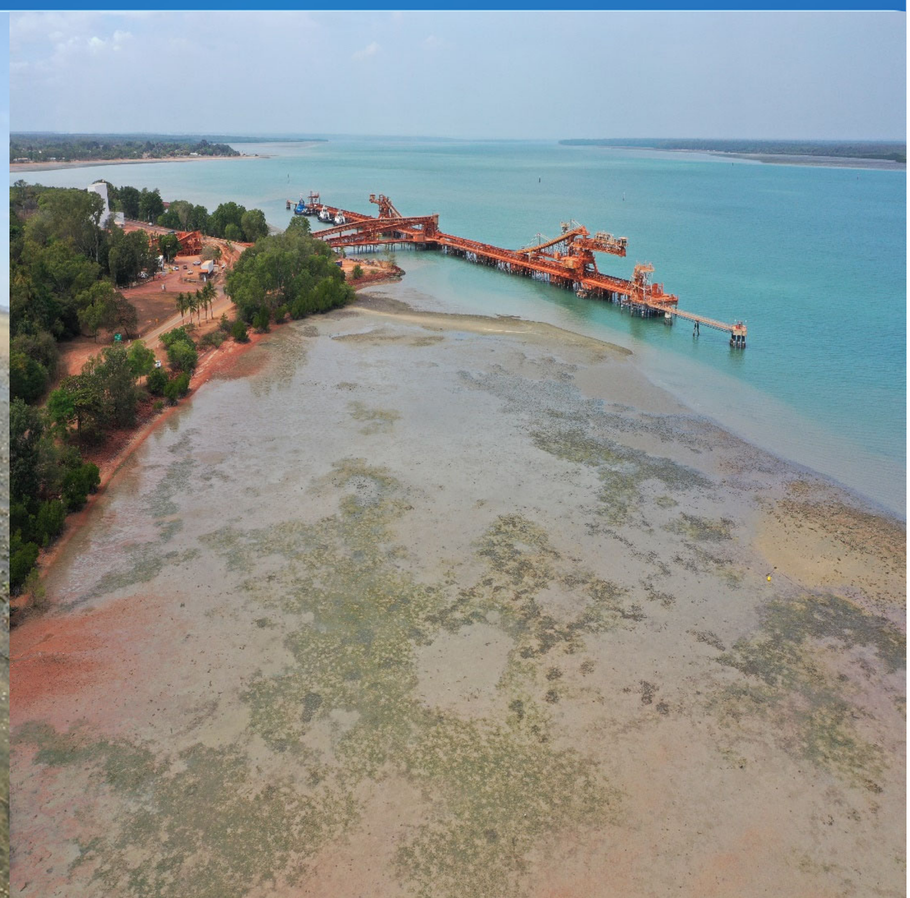

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2000 - 2022

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KEY FINDINGS

Seagrass Condition

Good

Likely causes of seagrass condition:

↑ *Favourable seagrass resilience leading into the 2021/22 wet season*

↓↑ *Unfavourable light conditions during wet season followed by good light for the rest of the year*

↑ *Favourable growing conditions despite variable climate conditions following the wet season events*

- Overall seagrasses in the Port of Weipa were in good condition in 2022.

- Individual monitoring meadows were in very good, good or satisfactory condition for all three indicators measured (species composition, area and biomass).

- The area of seagrass meadows in the Intensive Monitoring Area (IMA), the region closest to the port, remains above the long term average for the 7th year in a row.

- The intertidal *Halodule uninervis* meadows (A3, A5) for the second consecutive year, continue to have their highest recorded seagrass biomass since monitoring began in 2000.

- Seagrass across the broader port area (including Pine River Bay, Embley, Hey and Mission Rivers) was in similar condition to previous years with no notable changes.

- During a longer than usual wet season, light conditions were below the ideal threshold for seagrass growth but did not appear to affect seagrass condition in the longer-term.

- Climate conditions over the past few years has been variable however the overall good condition of seagrass has likely improved seagrass resilience across the port of Weipa in 2022.

Contents

ACKNOWLEDGEMENTS

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ACRONYMS

Benthic macro-invertebrate (BMI)

Geographic Information System (GIS)

Grams dry weight per square metre (g DW m-2)

Inverse distance weighted (IDW)

James Cook University (JCU)

Northern Great Barrier Reef (nGBR)

Reliability estimate (R)

Standard error (SE)

The Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER)

IN BRIEF

Seagrasses have been monitored annually in the port of Weipa since 2000. Each year all seagrasses within the Intensive Monitoring Area (IMA) around the major areas of port activity are mapped. Five core seagrass meadows within the IMA representing the range of different seagrass community types found in Weipa are assessed for changes in biomass, area and species composition (condition indicators). Changes to these metrics are then used to develop a seagrass condition index (see section 2.3).

Seagrasses in the Port of Weipa were in an overall good condition in 2022. The area and biomass of four of the five core monitoring meadows were rated as good or very good compared with their long-term average (Figure 1). Seagrass biomass in the intertidal *H. uninervis* meadows (A3, A5) was the highest recorded since monitoring began in 2000 continuing recent trends. Meadow A7 condition declined to satisfactory due to a reduction in area. Five seagrass species were recorded in the survey which is consistent with historical surveys. Seagrasses had an extensive footprint within the IMA and total area was above the long-term average for the seventh consecutive year (Figure 2).

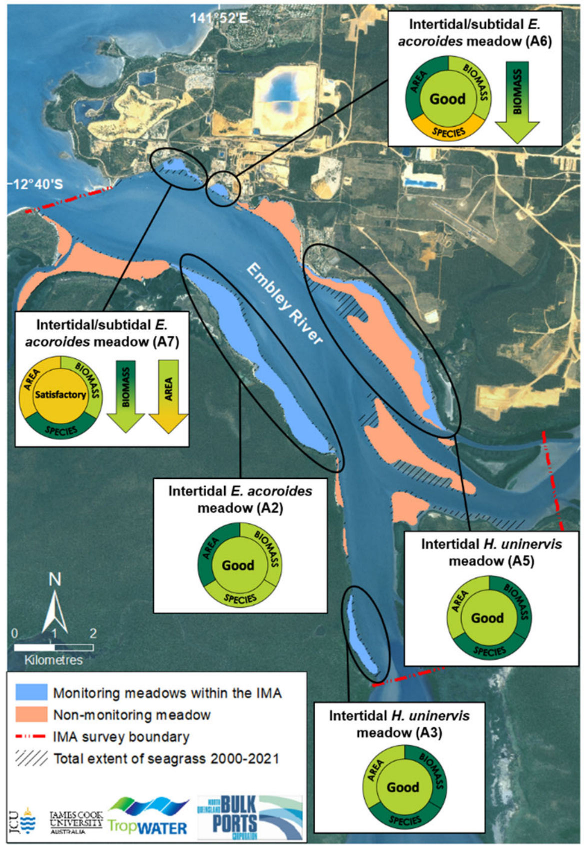


Figure 1. Seagrass meadow condition in the Port of Weipa 2022.

Seagrasses in Weipa continue to be in an overall healthy condition in 2022 and have been in a good condition since 2017. The maintenance of healthy seagrass coincides with a period of stable climate conditions over the past few years that has likely facilitated seagrass growth and increased plant reserves. The prolonged period of good seagrass health provides Weipa seagrass with a high level of resilience to low light conditions experienced during the wet season and other stresses. During the 2021/22 wet season light levels in meadow A7 were below seagrass thresholds for long periods of time (~four months). Entering the wet season with high levels of resilience likely provided seagrass with the ability to resist wet season pressures by utilising stored energy reserves. Critically there was no further reductions of light below the plant's likely light requirements for the remainder of the year and they could therefore

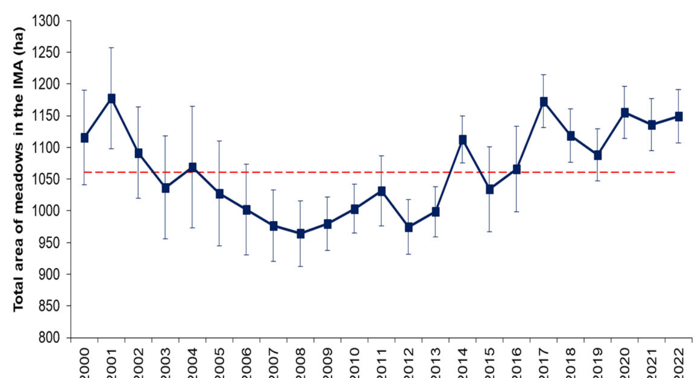


Figure 2. Total area of seagrass within the Weipa Intensive Monitoring Area from 2000 to 2022. (error bars = "R" reliability estimate). Red dashed line indicates 20-year mean of total meadow area.

replenish used energy stores. High levels of resilience would also have put seagrass in a good position to withstand above average rainfall in 2021/22 in line with the onset of La Niña.

The Weipa seagrass monitoring program forms part of a program that examines seagrasses in the majority of Queensland commercial ports and other areas where seagrasses face the highest levels of cumulative risk. It also forms a component of James Cook University's broader seagrass assessment and research program (see www.tropwater.com).

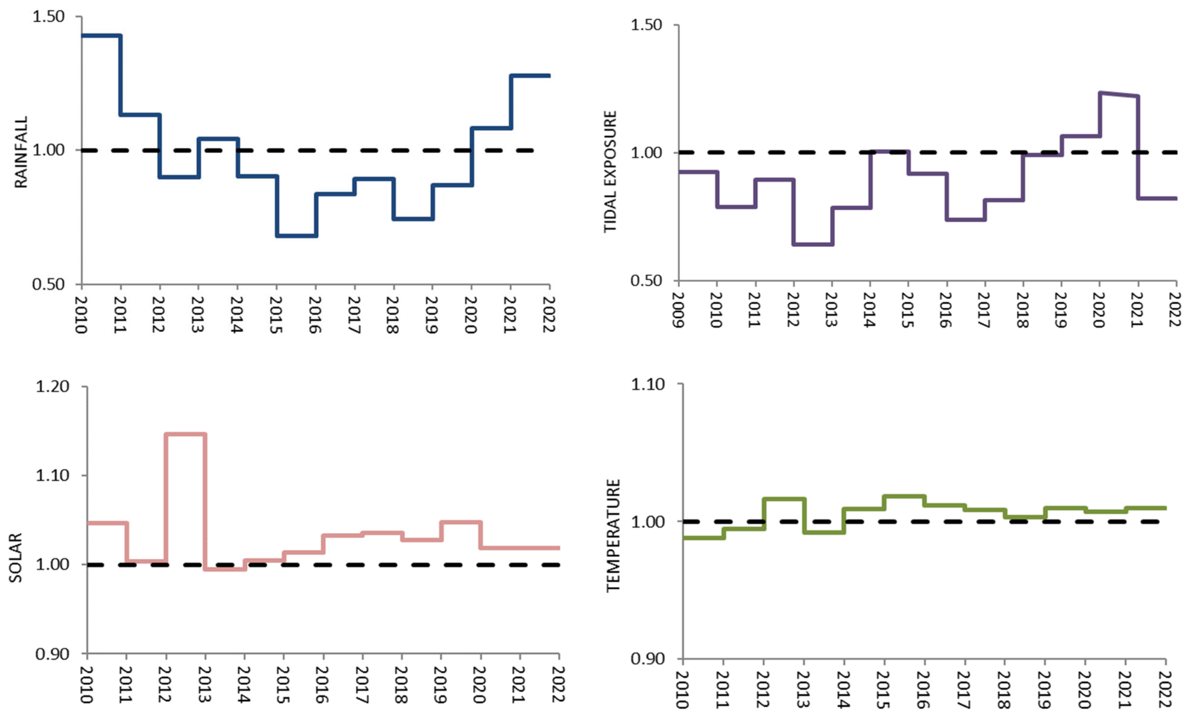


Figure 3. Recent climate trends in Weipa: Change in climate variables as a proportion of the long-term average. (See section 3.2 for detailed climate data).

INTRODUCTION

Seagrasses are one of the most productive marine habitats on earth and provide a variety of important ecosystem services worth substantial economic value (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 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 (Waycott et al. 2009; Dunic et al. 2021). Explanations for seagrass decline include natural disturbances such as storms, disease and overgrazing by herbivores, as well as 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; Scott et al. 2021a). 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. 2012). These hot-spots arise because 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).

1.1 Queensland Ports Seagrass Monitoring Program

A long-term seagrass monitoring and assessment program is established in the majority of 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).

Location of Queensland Port seagrass assessment sites.

This strategic long-term assessment and monitoring program for seagrass provides port managers and regulators with key information to ensure effective management of 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 the drivers of seagrass change.

For more information on the program and reports from the other monitoring locations see www.tropwater.com

1.2 Weipa Seagrass Monitoring Program

Diverse and productive seagrass meadows and benthic macro- and mega-fauna occur in the Port of Weipa. North Queensland Bulk Ports (NQBP) commissioned TropWATER to establish a long term seagrass monitoring program for Weipa's port in 2000 (Roelofs et al. 2001; 2003; 2005). The first three years (2000 to 2002) of the seagrass monitoring program provided important information on the distribution, abundance and seasonality of seagrasses within the greater port limits. Due to the large area of the port, the approach for long term monitoring has been to focus monitoring efforts on seagrass meadows located near the port and shipping infrastructure and activities. This area is known as the Intensive Monitoring Area (IMA; Figure 5). Meadows within the IMA represent the range of seagrass meadow communities identified in the greater Weipa region. Every three years (i.e., 2000, 2002, 2005, 2008, 2011, 2014, 2017, 2020) seagrass monitoring surveys are expanded to include a greater area of the Weipa port limits (i.e. Pine River Bay, Mission River, Embley River and Hey River), with a focus on mapping seagrass meadow distribution, meadow cover type and species composition in these areas (Figure 5).

Results from seagrass monitoring surveys are used by NQBP to assess the health of the port marine environment and help identify any possible detrimental effects of port operations (e.g. dredging) and other activity on seagrass meadows. Seagrass monitoring surveys satisfy environmental monitoring requirements as part of the port's Long-Term Dredge Management Plan and are used by management agencies to assess the status and condition of seagrass resources in the region.

As part of the seagrass monitoring program in Weipa, light (Photosynthetically Active Radiation (PAR)) and temperature conditions within the seagrass meadows have been assessed since September 2010 (Figure 11).

This report presents the results of the long-term seagrass monitoring assessments conducted in August 2022. The objectives were to:

1. Map seagrass distribution and determine meadow biomass, area and species composition in core monitoring meadows;
2. Briefly assess seagrass meadows outside the IMA to record any significant changes in seagrass condition;
3. Assess changes in seagrass meadows compared with previous monitoring surveys;
4. Assess light and temperature conditions in seagrass meadows;
5. Incorporate the results into the Geographic Information System (GIS) database for the Port of Weipa.

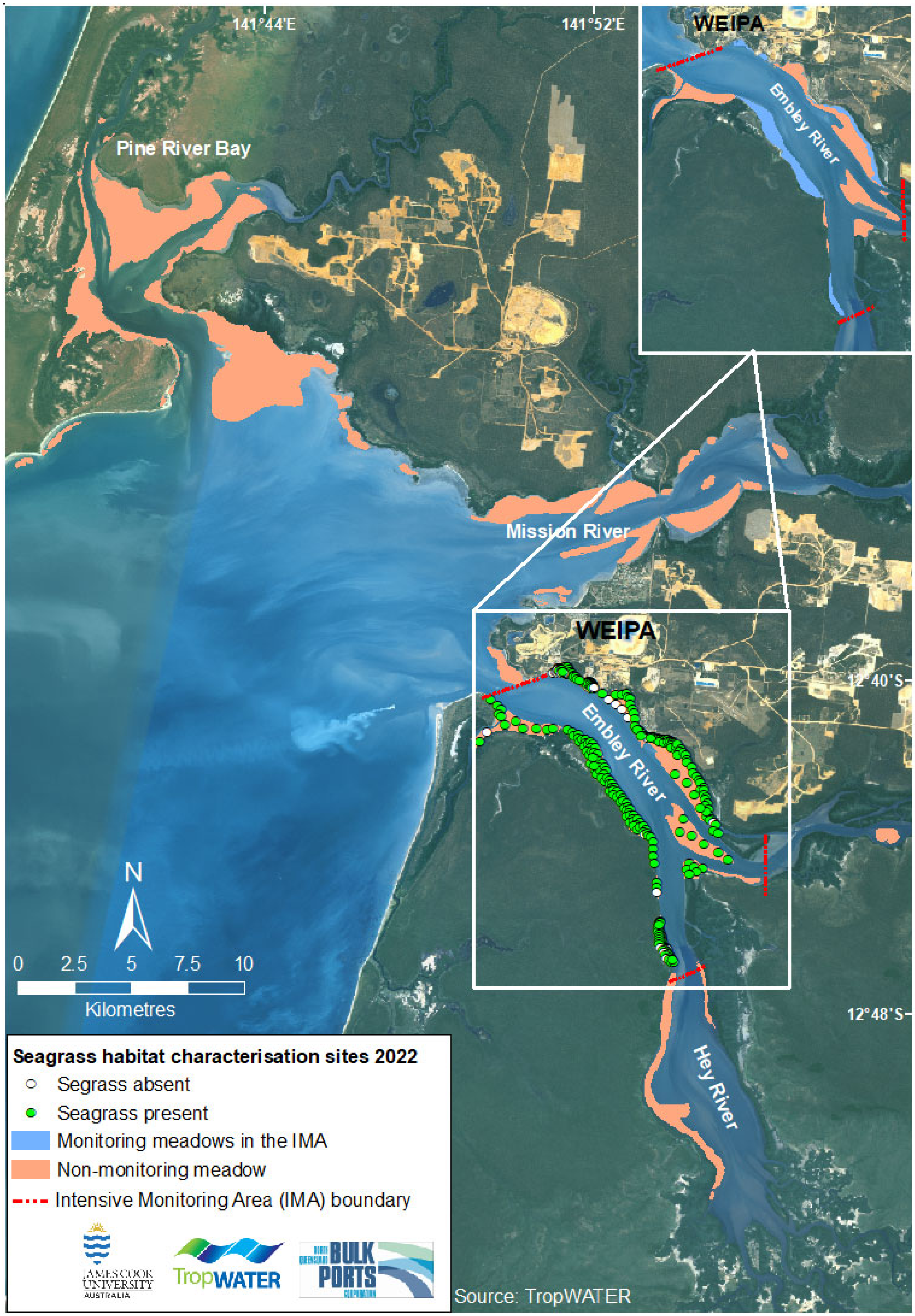


Figure 5. Location of 2022 seagrass survey sites and seagrass meadows in the Port of Weipa IMA. Meadows outside the IMA were mapped in 2020.

METHODS

Field Surveys

Annual monitoring of seagrass within the port of Weipa was conducted between August 25th – 2nd September 2022. Annual monitoring focuses on five core monitoring meadows within the Intensive Monitoring Area (IMA) (Figure 5 & 14) (Roelofs et al. 2001). These meadows were selected for detailed assessment because they were representative of the range of seagrass meadow communities identified in the baseline surveys, and because they were located in areas likely to be vulnerable to impacts from port operations and developments.

Two levels of sampling were used in the 2022 survey:

- Assess and map seagrass distribution, species composition and biomass in the five core monitoring meadows (A2, A3, A5, A6, and A7; Figure 11);
- Map seagrass distribution and species composition in non-core monitoring meadows across the IMA. (Figure 5 & 14).

Seagrass meadows were surveyed using a combination of helicopter aerial assessments and boat-based camera surveys (Figure 6). At each site surveyed seagrass meadow characteristics including seagrass species composition, above-ground biomass, seagrass and algal percent cover, sediment type, position fixes (GPS; ±5m) and depth below mean sea level for subtidal meadows were recorded. A detailed outline of these methods can be found in Roelofs et al. (2001).

Figure 6. Seagrass methods using (A) helicopter aerial surveillance, and (B, C) boat-based camera surveillance.

Results from baseline surveys required the analysis of biomass for meadows where the large growing species *E. acoroides* was present but not dominant to use a different method compared to meadows where *E. acoroides* was dominant (Roelofs et al. 2003). The dry weight biomass for *E. acoroides* is many orders of magnitude higher than other tropical seagrass species and dominates the average biomass of a meadow where it is present. Isolated *E. acoroides* plants occurring within the *Halodule* dominated meadows A3 and A5 are excluded from all biomass and species composition analyses in order to track the dynamics of the morphologically smaller *Halodule* species in these two meadows.

Seagrass biomass (above-ground) was determined using a "visual estimates of biomass" technique (as described by Mellors 1991; Kirkman 1978). This technique involves an observer ranking seagrass biomass in the field in three random placements of a 0.25m^2 quadrat at each site. Ranks are made in reference to a series of quadrat photographs of similar seagrass habitats for which the above-ground biomass has previously been measured. The relative proportion of the above-ground biomass (percentage) of each seagrass species within each survey quadrat was also recorded. Field biomass ranks are then converted into above-ground biomass in grams dry weight per square metre (g DW m^{-2}). At the completion of sampling, each observer ranks a series of calibration quadrats that represent the range of seagrass biomass in the survey. After ranking, seagrass in these quadrats is harvested and the actual biomass determined in the laboratory. A separate regression of ranks and biomass from these calibration quadrats is then generated for each observer and applied to the field survey data to determine above-ground biomass.

2.2 Habitat mapping and Geographic Information System

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

- *Site Layer:* The site (point) layer contains data collected at each site, including:
  - 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 biomass standard error (SE); percent cover of seagrass, algae, and open substrate; presence/absence of DFTs.
  - Sampling method and any relevant comments.

- *Meadow layer:* 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 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 (Figure 7).
  - Meadow identification number – a unique number assigned to each monitoring meadow to allow comparisons among surveys.
  - Sampling method and any relevant comments.

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

Seagrass meadows were described using a standard nomenclature system. Seagrass community type is defined using the dominant species' percent contribution to mean meadow biomass (for all sites within a meadow) (Table 1). Community density is based on mean biomass and the dominant species within the meadow (Table 2).

Table 1. Seagrass meadow community types.

Community type	Species composition
Species A	Species A is 90-100% of composition
Species A with Species B	Species A is 60-90% of composition
Species A with Species B/Species C	Species A is 50% of composition
Species A/Species B	Species A is 40-60% of composition

Table 2. Seagrass meadow density categories.

Density	Mean above ground-biomass (grams dry weight per metre square (g DW m^{-2}))				
	***H. uninervis* (narrow)**	***H. ovalis* *H. decipiens***	***S. isoetifolium***	***T. hemprichii***	***E. acoroides***
Light	< 1	< 1	< 5	< 15	< 40
Moderate	1 - 4	1 - 5	5 - 25	15 - 35	40 - 100
Dense	> 4	> 5	> 25	> 35	> 100

Isolated seagrass patches

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

Aggregated seagrass patches

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

Continuous seagrass cover

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

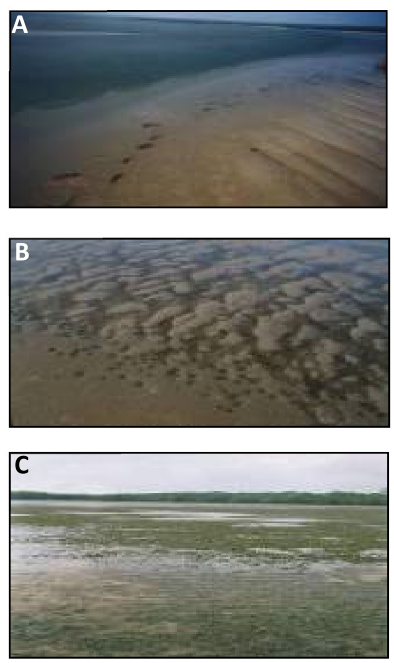


Figure 7. Seagrass meadow landscape categories: (A) isolated seagrass patches, (B) aggregated seagrass patches, (C) continuous seagrass cover.

Seagrass meadow boundaries were constructed using seagrass presence/absence site data, field notes, GPS marked meadow boundaries, colour satellite imagery of the survey region (Source: ESRI; Google Earth), and aerial photographs taken during helicopter surveys.

Meadow area was determined using the calculate geometry function in ArcGIS®. Meadows were also assigned a mapping precision estimate (in metres) based on mapping methods used for that meadow (Table 3). 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 3. Mapping precision and methods for seagrass meadows in the Port of Weipa.

Mapping precision	Mapping method
≤5m	Meadow boundaries determined from helicopter and camera/grab surveys; Inshore boundaries mapped from helicopter; Offshore boundaries interpreted from survey sites and recent satellite imagery; Relatively high density of mapping and survey sites; Recent satellite imagery aided in mapping.

2.3 Seagrass meadow condition index

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

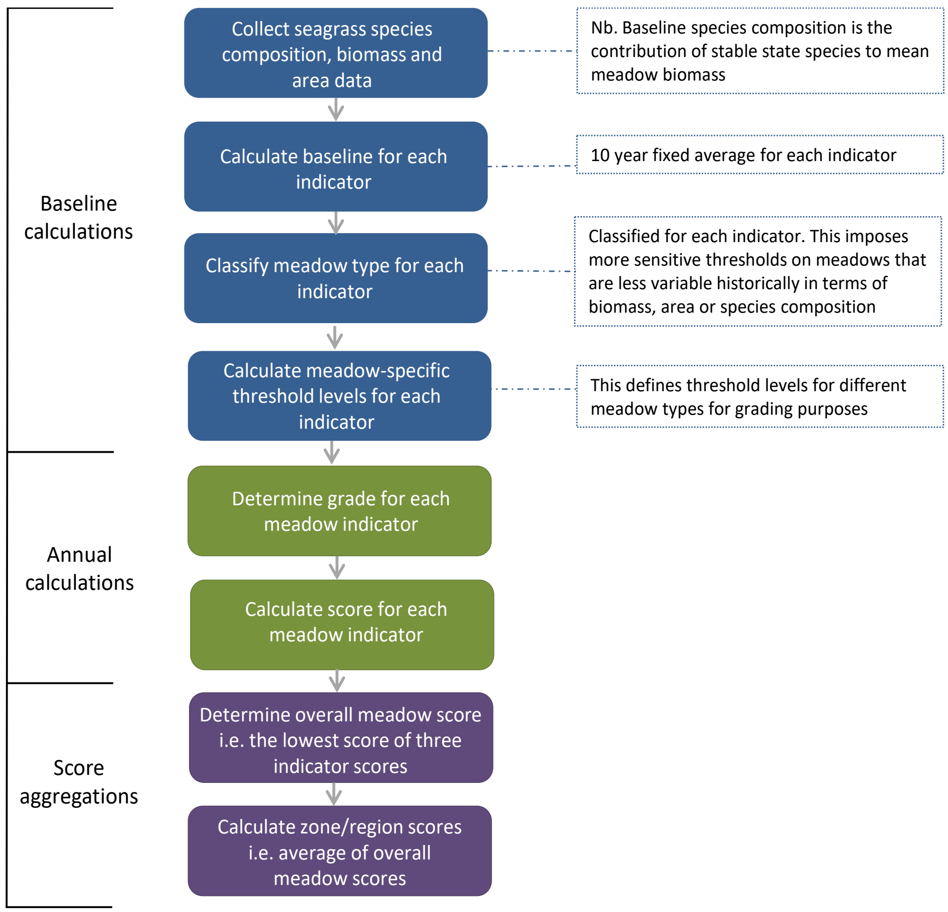


Figure 8. Flow chart to develop Weipa seagrass grades and scores.

2.4 Environmental data

Environmental data was collated for the twelve months preceding the survey. Tidal data was provided by Maritime Safety Queensland (MSQ) for Weipa (MSQ station # 100281). Total daily rainfall (mm) and global solar exposure was obtained for the nearest weather station from the Australian Bureau of Meteorology (Weipa Airport station #027045; http://www.bom.gov.au/climate/data/).

Irradiance (Photosynthetically Active Radiation (PAR) mol photons m^{-2} day^{-1}) conditions and temperature within the seagrass meadows at Weipa are assessed in the intertidal A2 meadow, and in the subtidal/intertidal A7 and A6 meadows (Figure 11), using custom built benthic data logging stations (Figure 9). A PAR logger has also been placed on land at the NQBP work shed that acts as a control logger. Each independent logging station within the meadows consists of 2π cosine-corrected irradiance loggers (Submersible Odyssey Photosynthetic Irradiance Recording Systems) with supporting electronic wiper units. Irradiance loggers were calibrated using a cosine corrected Li-Cor underwater quantum sensor (LI-190SA; Li-Cor Inc., Lincoln, Nebraska USA) and corrected for immersion effect using a factor of 1.33 (Kirk 1994). Readings were made at 15 minute intervals and used to estimate total daily irradiance (PAR) reaching seagrasses. The electronic wiper unit fitted to each irradiance logger automatically cleaned the optical surface of the sensor every 15 minutes to prevent marine organism fouling. Autonomous Thermodata® iBTag submersible temperature loggers were deployed with each of these units, recording seabed temperature every 30 minutes.

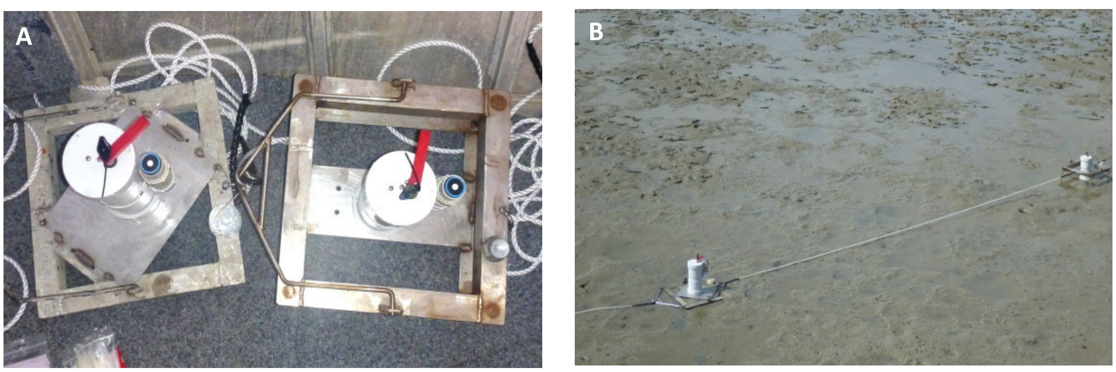


Figure 9. (A) Logging station consisting of a stainless steel frame with PAR loggers and temperature loggers attached, and wiper units (B) deployment of logging stations on the A2 meadow.

RESULTS

Seagrass

In 2022 seagrass was present at 85% of sites surveyed with the IMA, comprising of four species (Figure 10). A total of 338 sites across 14 meadows were surveyed (Figure 5). *Syringodium isoetifolium,* a fifth species*,* was present again in meadows outside the IMA at the entrance to Pine River Bay in a similar footprint to observations during the 2020 broad-scale survey.

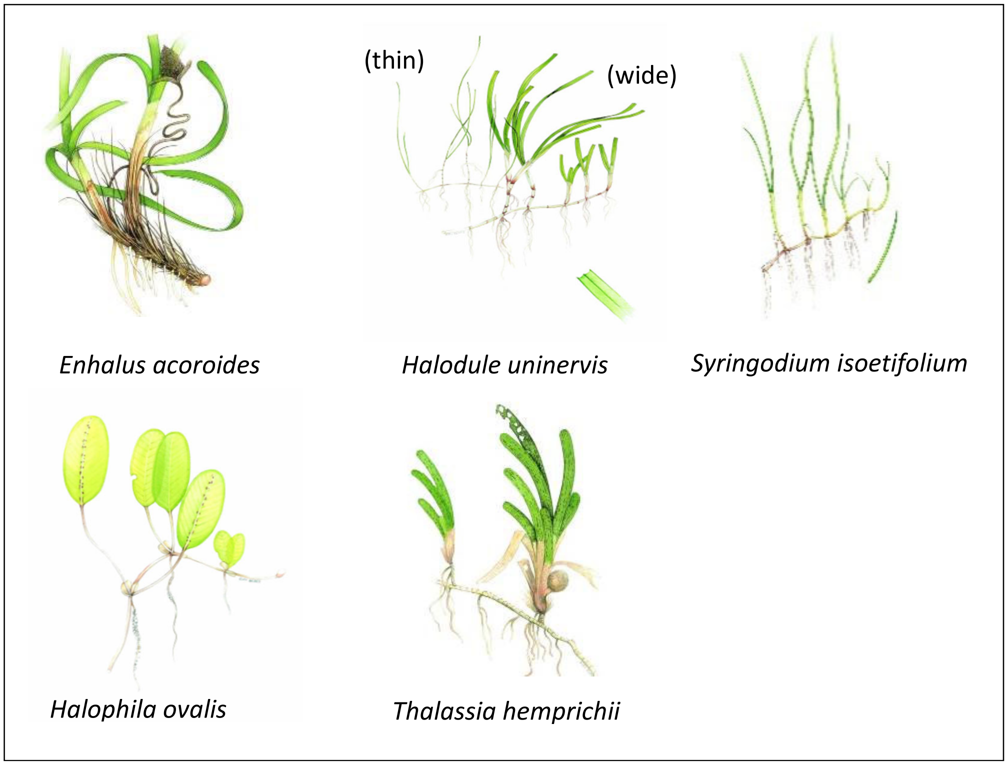


Figure 10. Seagrass species present in the Port of Weipa 2022.

3.1.1 Seagrass in the Intensive Monitoring Area

Fourteen seagrass meadows were mapped within the IMA in 2022 (Figure 11). The total seagrass meadow area was 1149 ± 41 ha, which is higher than the previous year and also above the 20-year average of seagrass monitoring in Weipa (Figure 12). For the past seven years seagrass meadow area in the IMA has been above the long-term average (Figure 12).

Of the 14 meadows in the IMA, 10 were dominated by low density cover of large and persistent seagrass *E. acoroides* (Figure 11). The other four meadows were dominated by low to moderate cover of *H. uninervis* and *Thalassia hemprichii* (Figure 11).

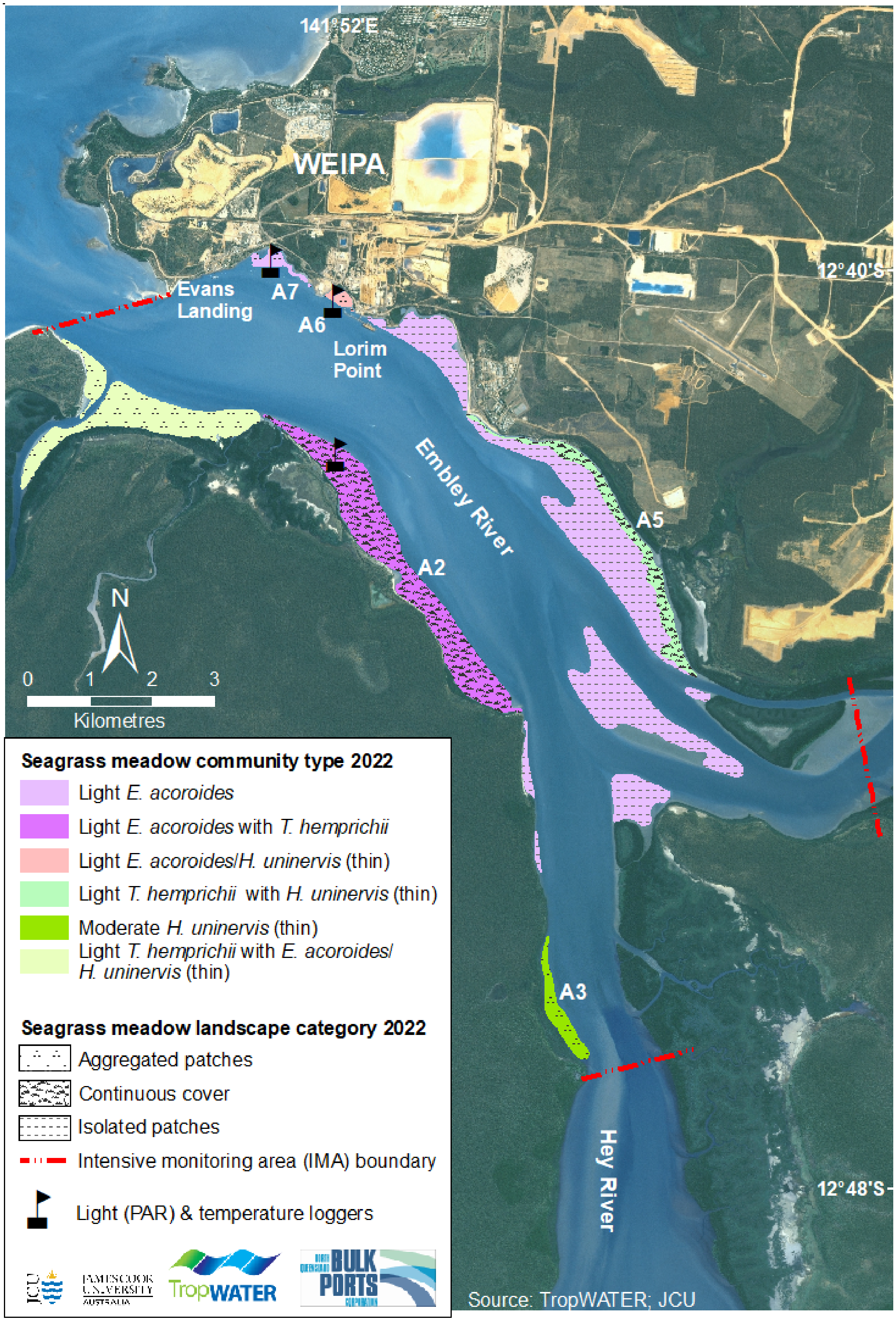


Figure 11. Meadow type and landscape category for seagrass within the Intensive Monitoring Area 2022.

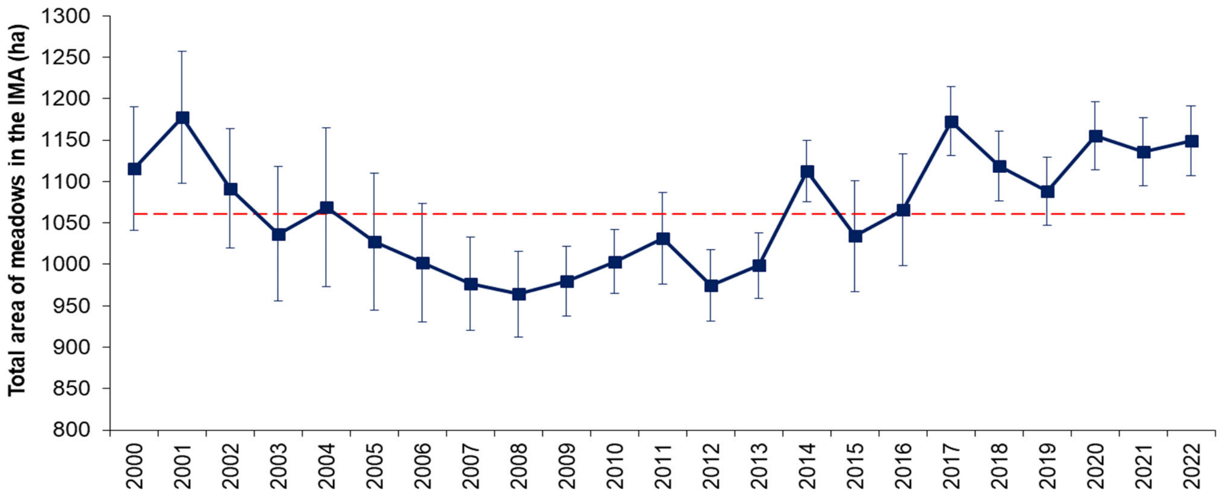


Figure 12. Total area of seagrass within the Weipa Intensive Monitoring Area from 2000 to 2022 (error bars = "R" reliability estimate). Red dashed line indicates 21-year mean of total meadow area.

The browning of *E. acoroides* blades is known as burning which indicates stress and may lead to the death of seagrass blades (Unsworth et al. 2012). Burning was observed at 13% of survey sites within the IMA in 2022, which is low compared to recorded occurrences of burning across all years (since 2010) (Figure 13). Tidal exposure was below average in 2022 which would have also reduced the amount of burning of seagrass.

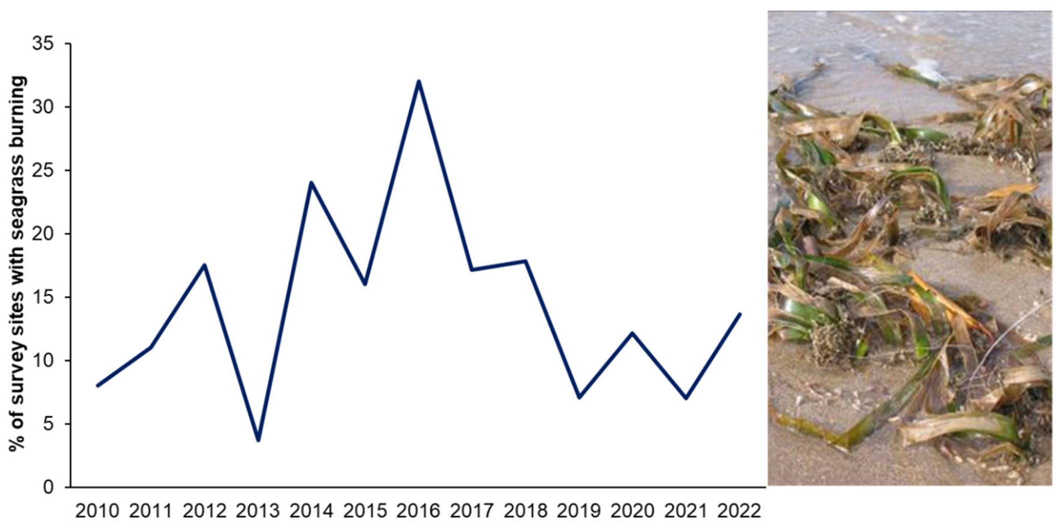


Figure 13. Percentage of sites within the IMA that have evidence of *Enhalus acoroides* burning in the Weipa IMA meadows.

In 2022 dugong feeding trails (Figure 14) were common throughout the IMA meadows and the broader survey area. Dugong feeding trails were recorded in *H. ovalis* and *H. uninervis* patches in the non-monitoring A1 meadow and also in the monitoring meadows of A3 and A5. Dugong feeding trails were common in the *H. uninervis* and *H. ovalis* meadows in Pine River Bay, and upstream in the Hey River.

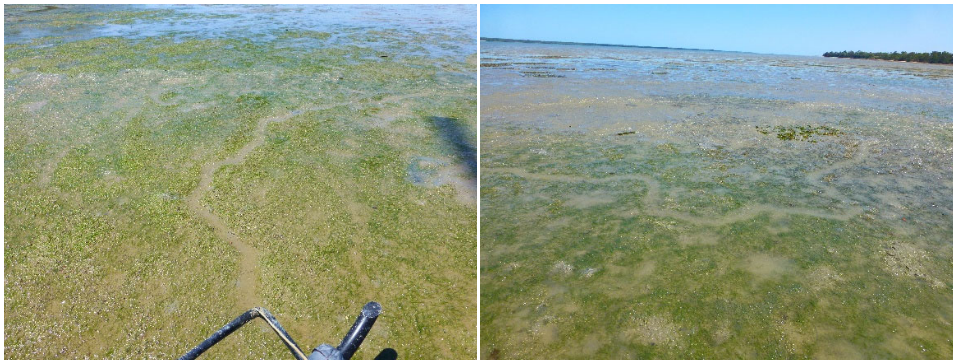


Figure 14. Examples of Dugong feeding trails in the A5 Weipa monitoring meadow (photos are from 2019).

3.1.2 Seagrass condition in the core annual monitoring meadows

The Weipa meadows were in a good condition overall in 2022 (Table 4). The condition of seagrass in the core annual monitoring meadows has generally been stable over the last five years. All three seagrass condition indicators (seagrass biomass, area and species composition) were graded as satisfactory, good or very good across all the monitoring meadows (Table 4).

Table 4. Grades and scores for seagrass indicators for 2022 in the port of Weipa.

Meadow	Biomass	Area	Species Composition	Overall Meadow Score
A2	0.76	0.88	0.69	0.73
A3	0.93	0.82	1.00	0.82
A5	1.00	0.78	0.99	0.78
A6	0.83	0.96	0.55	0.69
A7	0.79	0.63	1.00	0.63
Overall Score for the Port of Weipa				**0.73**

3.1.2.1 Enhalus acoroides dominated meadows (Meadows A2, A6, A7)

Enhalus acoroides was dominant in all three meadows but the meadows also included *H. uninervis*, *H. ovalis* and *T. hemprichii* (Appendix 3). Seagrass biomass density was light in all *E. acoroides* dominated meadows. Meadows close to Lorim Point A6 and A7 had aggregated patches of seagrass (Figure 11), while Meadow A2, on the western side of the Embley River had a continuous cover of seagrass (Figure 11).

Meadow A2: The overall seagrass condition was good in 2022 with no change in overall condition from last year (Table 4, Figure 15). Meadow area has been at or above the long-term average for the last ten years (Figure 15). Meadow biomass has stabilised around the long term average for the past 4 years and remains in a good condition. This meadow had signs of widespread burning tips of *E. acoroides*, however this did not reduce the biomass condition overall.

Meadow A6: In 2022 *s*eagrass overall condition was classified as good with area in a very good condition, biomass in a good condition and species composition was satisfactory (Figure 18). For the sixth consecutive year seagrass area in meadow A6 is above the baseline mean. Biomass of the meadow was categorised as good in 2022, a slight decline below the threshold from very good in 2021 (Figure 18). Over the last three years there has been a reduction in the species composition of the large, persistent seagrass *E. acoroides* and an increase in the smaller colonizing *H. uninervis* and *H. ovalis* (Table 4, Figure 18, Appendix 3). The increase in small colonizing species has resulted in species composition being classed as satisfactory for the last three years and in 2022 these colonizing species made up 41% of the overall meadow biomass (Figure 18).

Meadow A7: Due to a decline in biomass and area in 2022 the overall condition of this meadow was classed as satisfactory (Table 4, Figure 19). The meadow is exclusively comprised of *E. acoroides* which is reflected in the relatively high biomass of the meadow (Figure 19). Similar to last year, seagrass density 'hot spots' (areas of higher biomass) occurred in the middle and subtidal areas of the meadow (Figure 19). The western and eastern ends of the meadow had a low biomass of seagrass and were very patchy (Figure 19).

3.1.2.2 Halodule uninervis dominated meadows (A3, A5)

Both A3 and A5 meadows remained in a good condition in 2022. Seagrass biomass density in the two *H. uninervis* dominated monitoring meadows consisted of aggregated patches to continuous cover of seagrass (Figure 11). The meadows had a moderate to high biomass for the species and also had other species of seagrass present including *Thalassia hemprichii* and *Halophila ovalis* (Figure 10, 11).

Meadow A3: Seagrass in the A3 meadow located in the Hey River was in good condition in 2022. Seagrass biomass was above the 10 year long term average for the 5th year in a row and biomass remains high for this species (Figure 16). Species composition was almost exclusively *H. uninervis* and for the first time since monitoring began, a small quantity (3%) of *T. hemprichii* was present (Figure 16). The footprint of the meadow remains above the long term average and is in a good condition (Figure 16).

Meadow A5: Seagrass biomass in the A5 meadow was above the long term average and one of the highest recorded in the program for the second consecutive year (Figure 17). There has been a species dominance shift to almost 50:50 split between *T. hemprichii* and *H. uninervis* in this meadow in 2022. This meadow has been in a good condition for the last four years as biomass and species composition improve (Table 4, Figure 17). Meadow area was in good condition for the third consecutive year and was above the 10-year baseline (Figure 17).

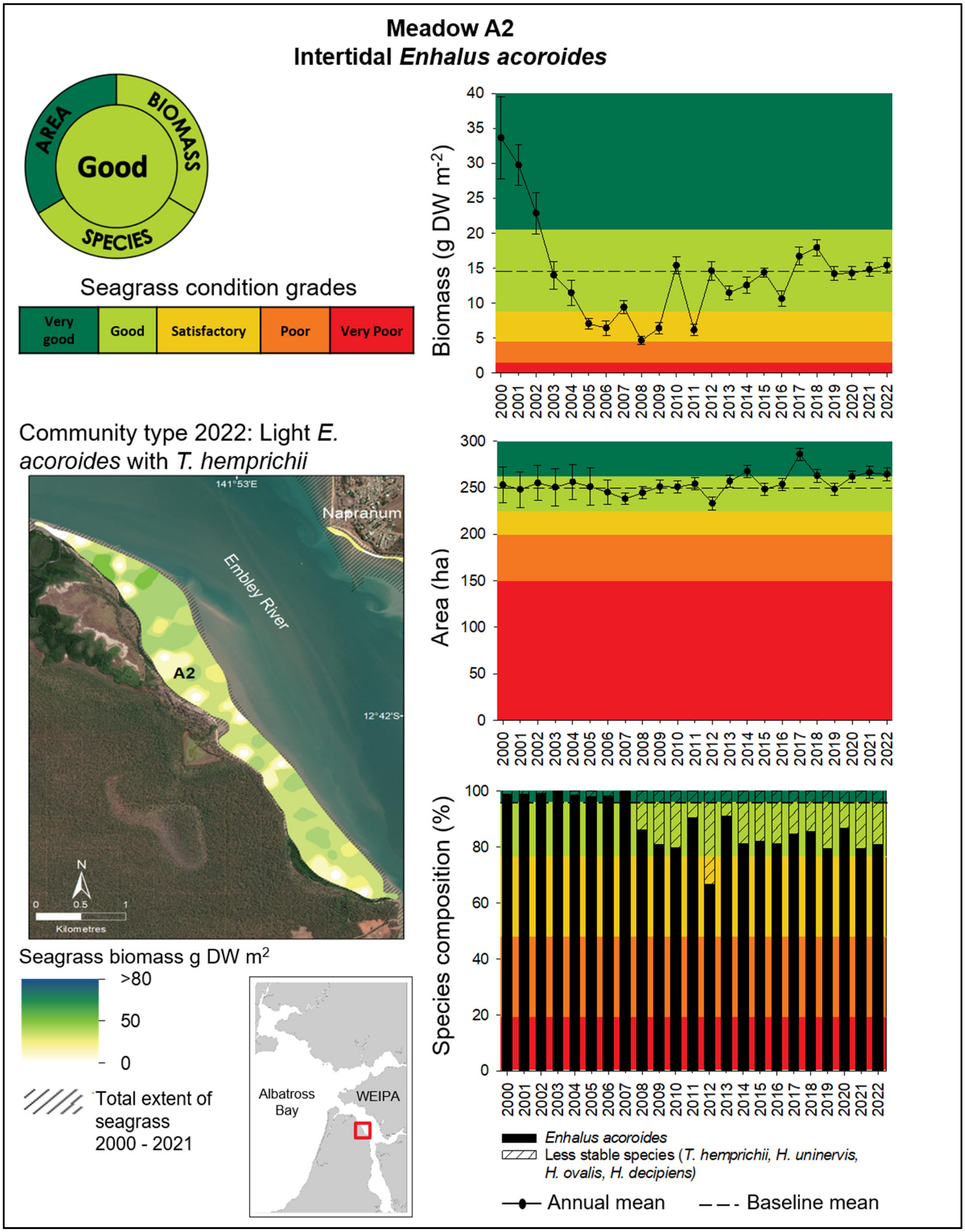


Figure 15. Changes in biomass, area and species composition for the *E. acoroides* dominated core monitoring meadow A2 in Weipa; 2000 to 2022 (biomass error bars = SE; area error bars "R").

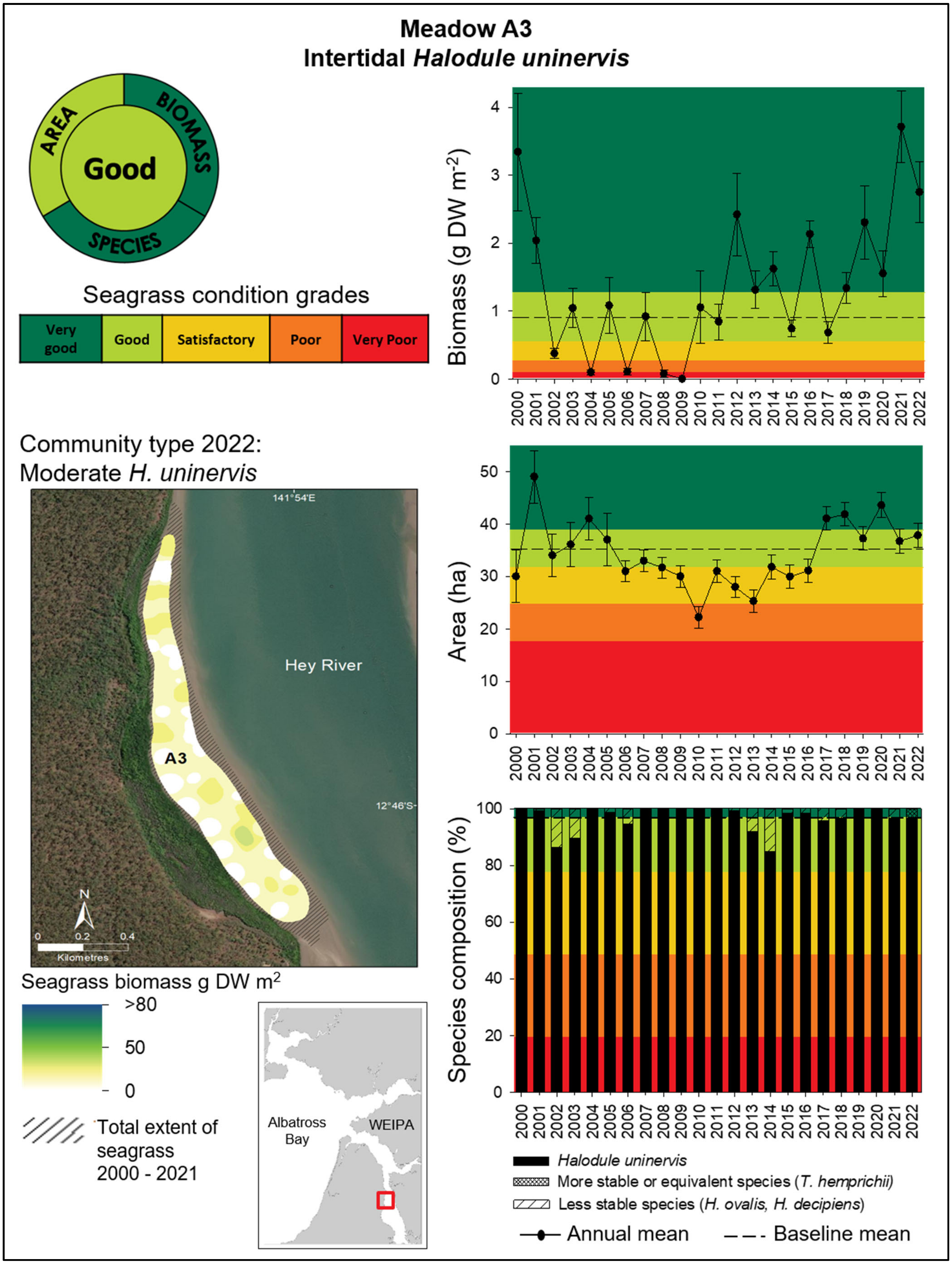


Figure 16. Changes in biomass, area and species composition for the *H. uninervis* dominated core monitoring meadow A3 in Weipa; 2000 to 2022 (biomass error bars = SE; area error bars "R").

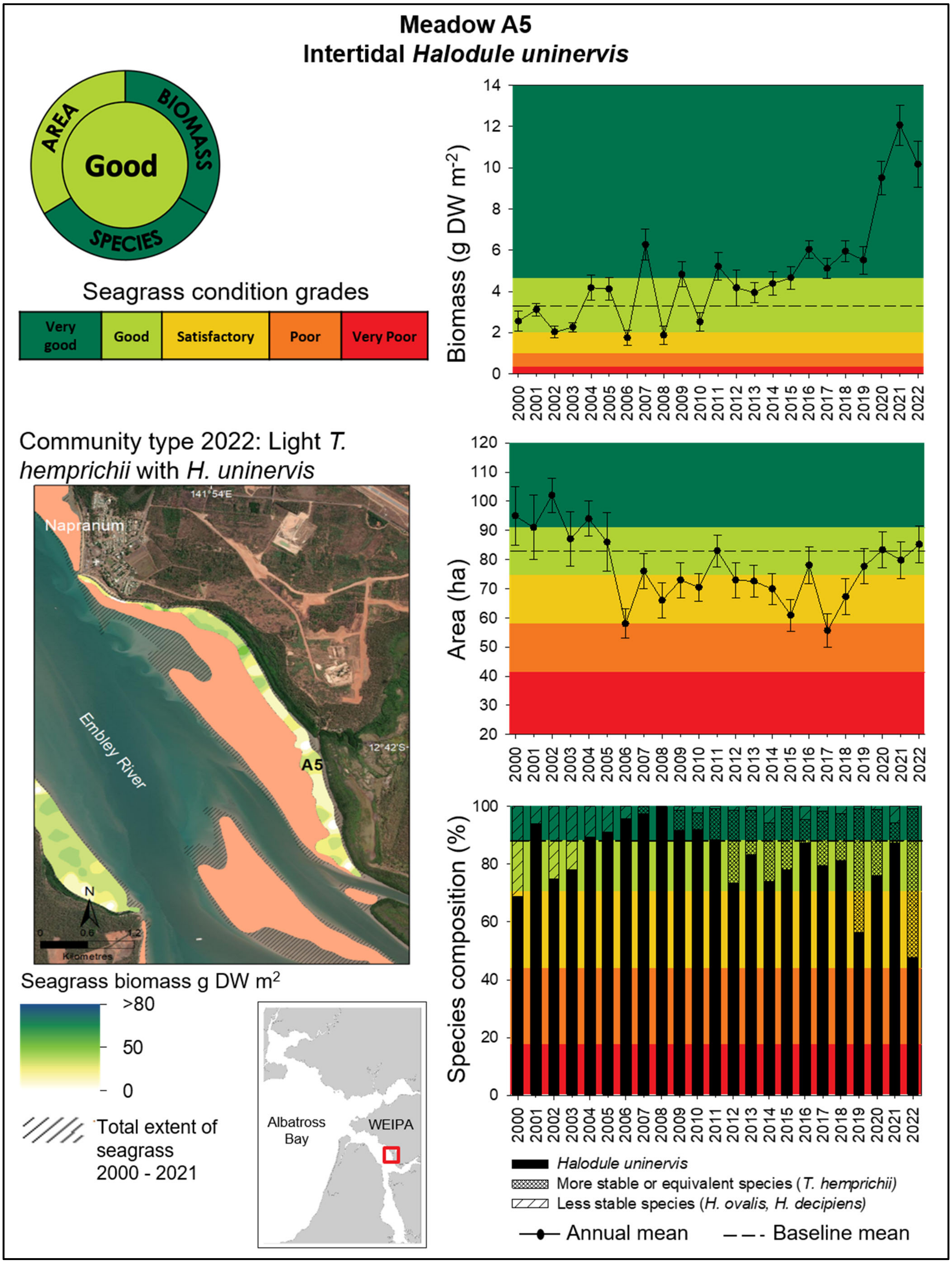


Figure 17. Changes in biomass, area and species composition for the *H. uninervis* dominated core monitoring meadow A5 in Weipa; 2000 to 2022 (biomass error bars = SE; area error bars "R").

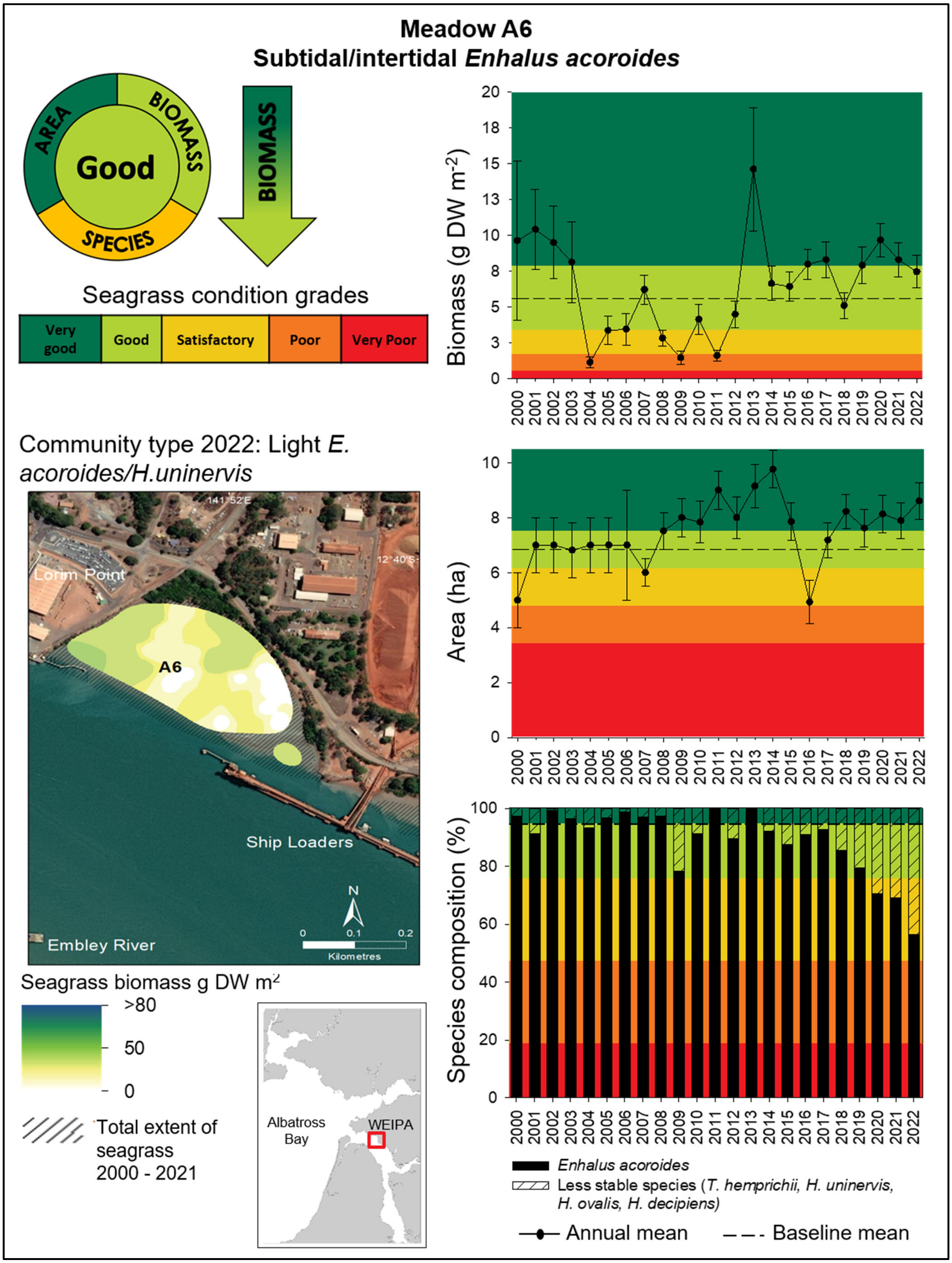


Figure 18. Changes in biomass, area and species composition for the *E. acoroides* dominated core monitoring meadow A6 in Weipa; 2000 to 2022 (biomass error bars = SE; area error bars “R”).

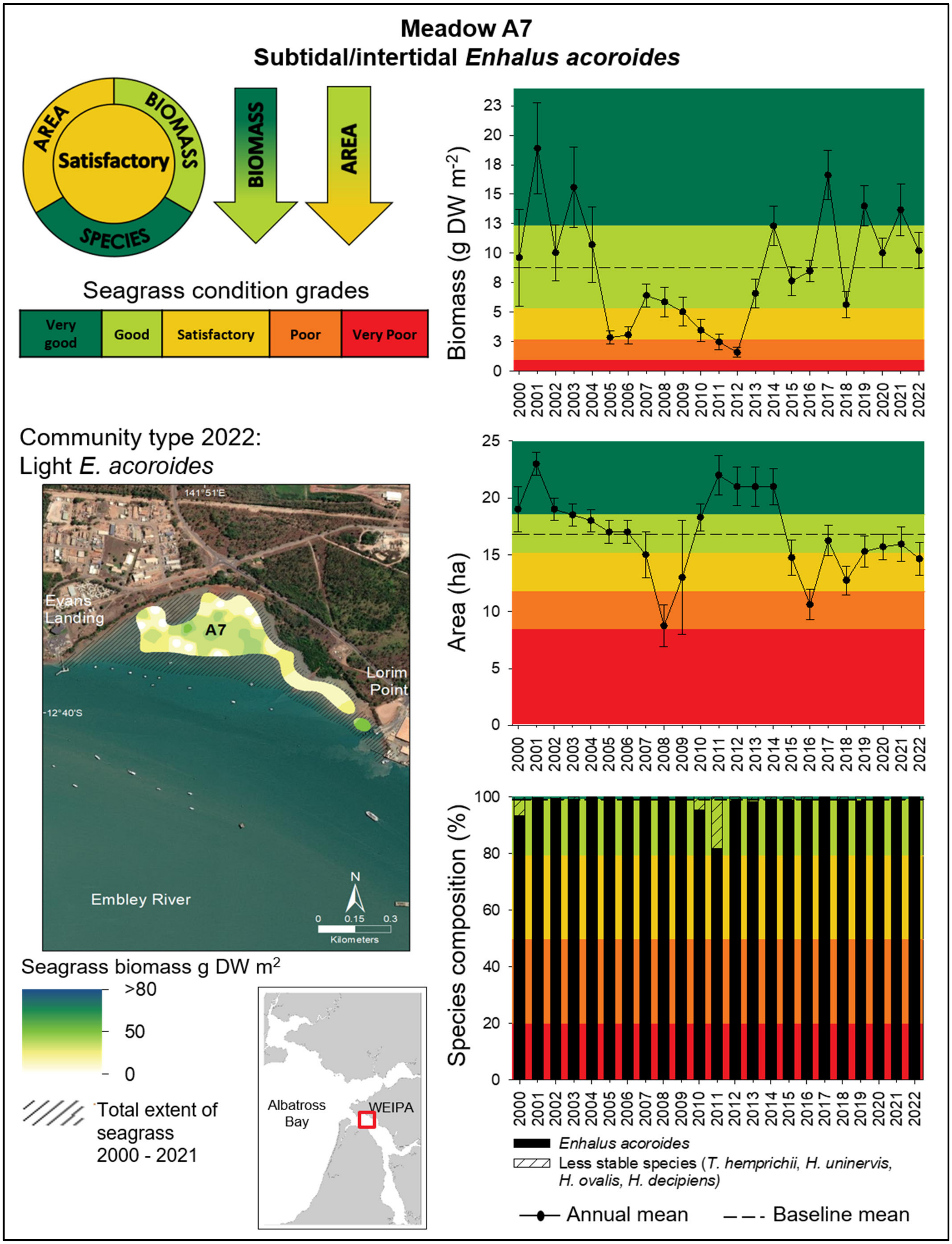


Figure 19. Changes in biomass, area and species composition for the *E. acoroides* dominated core monitoring meadow A7 in Weipa; 2000 to 2022 (biomass error bars = SE; area error bars "R").

3.1.3 Seagrass condition in the broader Port of Weipa

Since the last broadscale survey in 2020, seagrass meadows in 2022 had similar area and species composition throughout the broader port area including Hey River, Embley River, Mission River and Pine River Bay. The Hey and Embley River meadows generally consisted of isolated patches of *E. acoroides* and *H. uninervis* and had dugong feeding trails present. The Mission River meadows mainly consisted of isolated patches of *H. uninervis* and *E. acoroides*. The larger meadow towards the river mouth had high biomass and consisted of *H. uninervis*, *S. isoetifolium* and *T. hemprichii* along with many dugong feeding trails (Figure 20). Pine River Bay meadows are some of the largest and have the densest seagrass within the survey area. Meadows with isolated patches of *E. acoroides* and *H. ovalis* were found on the banks further upstream in Pine River consistent with previous years. At the mouth of the Pine River estuary seagrass meadows consisted of large continuous cover meadows of *T. hemprichii*, *S. isoetifolium* and *E. acoroides* with some *H. uninervis* and *H. ovalis* (Figure 20).

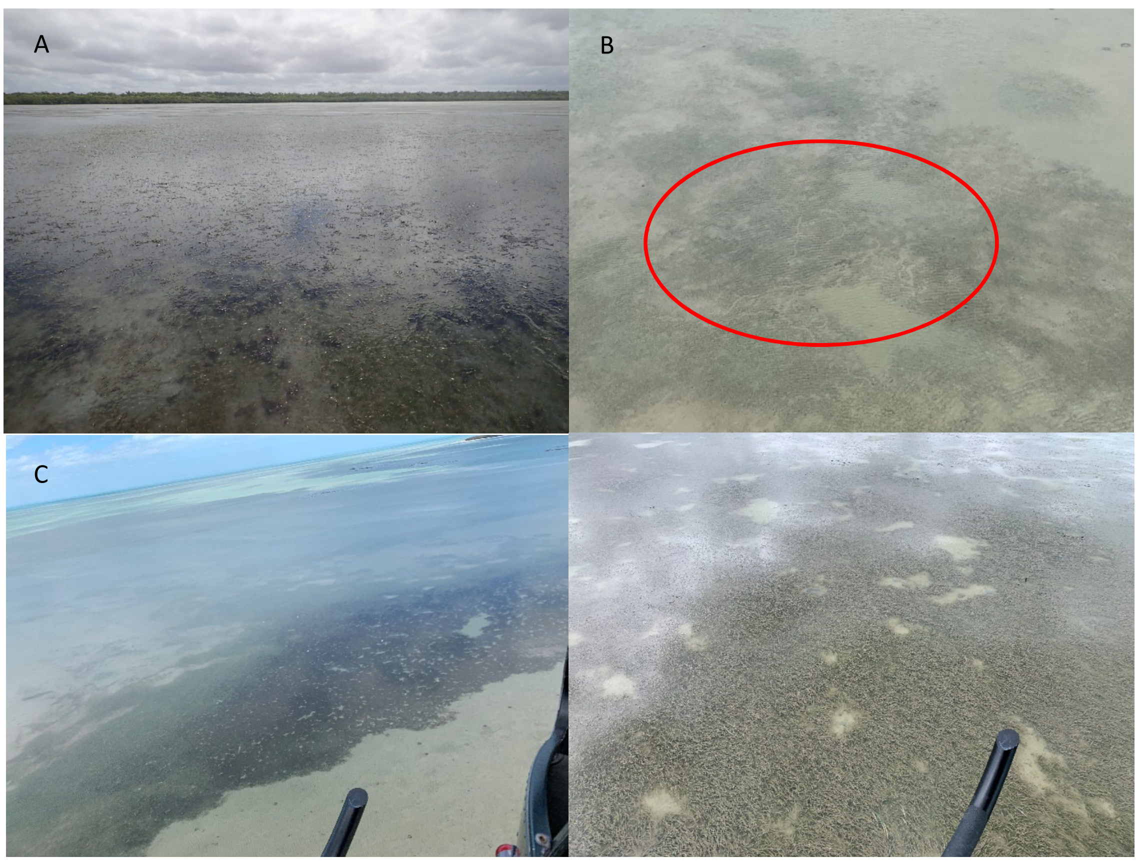


Figure 20. *Syringodium isoetifolium* (A) and dugong feeding trails in a *Halodule uninervis* meadow (B) in Pine River. Large continuous meadows at the mouth of Pine River (C) and high biomass *S. isoetifolium* within these meadows (D).

3.2 Weipa environmental data

3.2.1 Rainfall

Total annual rainfall in Weipa (2451mm) was above the long-term average for the second year in a row (Figure 21a). Monthly rainfall was above average from December 2021 to July 2022 and followed typical wet season trends leading up to the annual survey (Figure 21b).

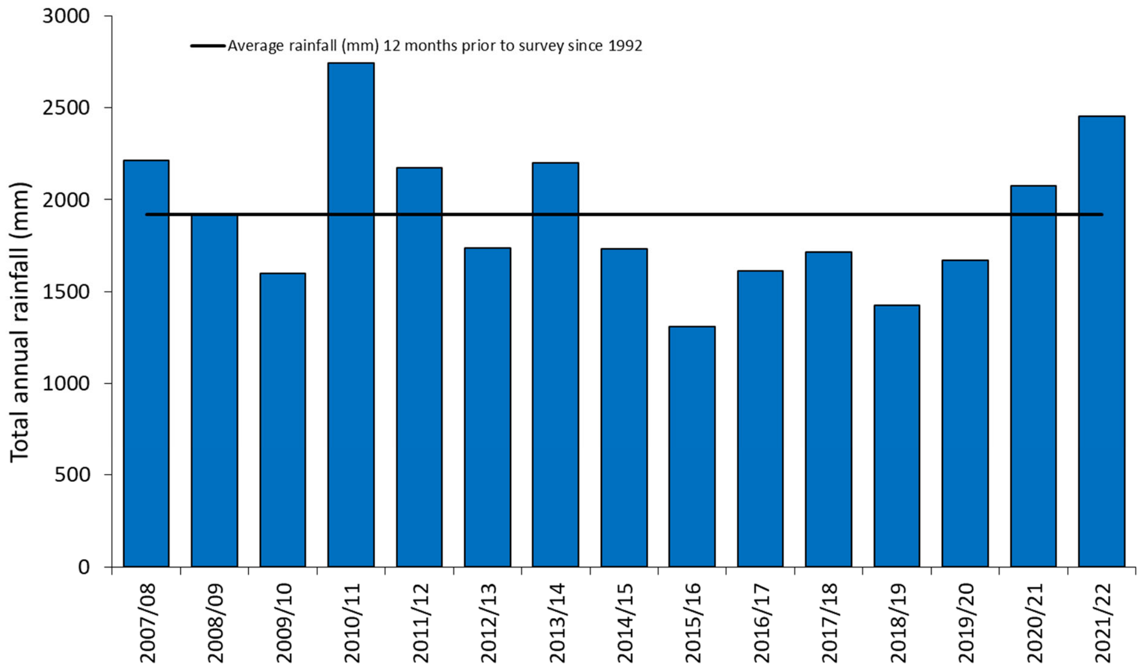


Figure 21a. Total annual rainfall recorded at Weipa Airport; 2006-2022. Data is twelve months prior to survey.

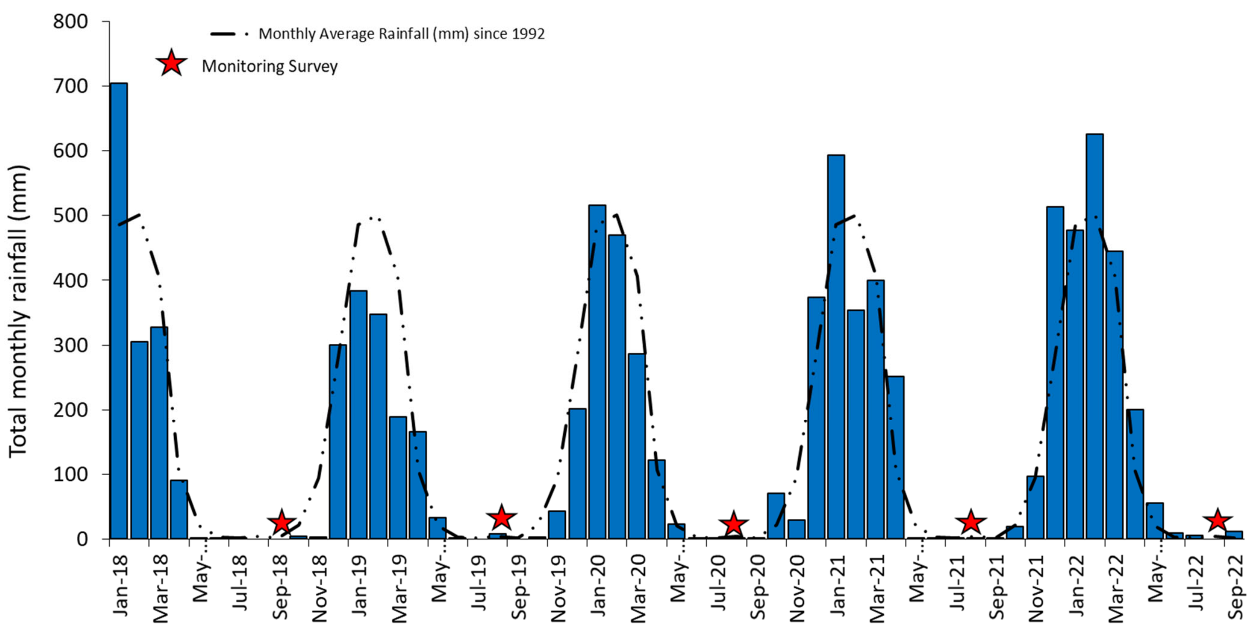


Figure 21b. Total monthly rainfall (mm); January 2018 – September 2022.

3.2.2 Daytime Tidal Exposure

The amount of tidal exposure to daytime air for intertidal meadows (322 hours) was below the long-term average (392 hours) for the first time since 2018/19 (Figure 22a). In the three months prior to the survey daytime tidal exposure was below the monthly average (Figure 22b). Intertidal seagrass meadows have a greater amount of daytime exposure during the winter/dry season months and minimal to no exposure during the summer/wet season months (Figure 22b).

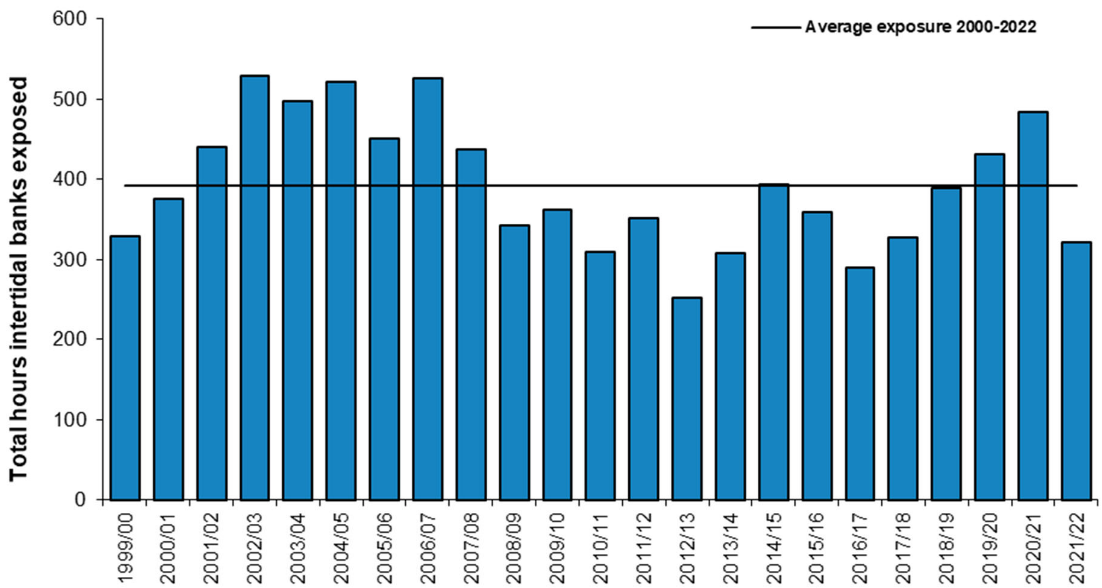


Figure 22a. Total daily tidal exposure to air 1999/00 -2021/22. Data is twelve months prior to survey.

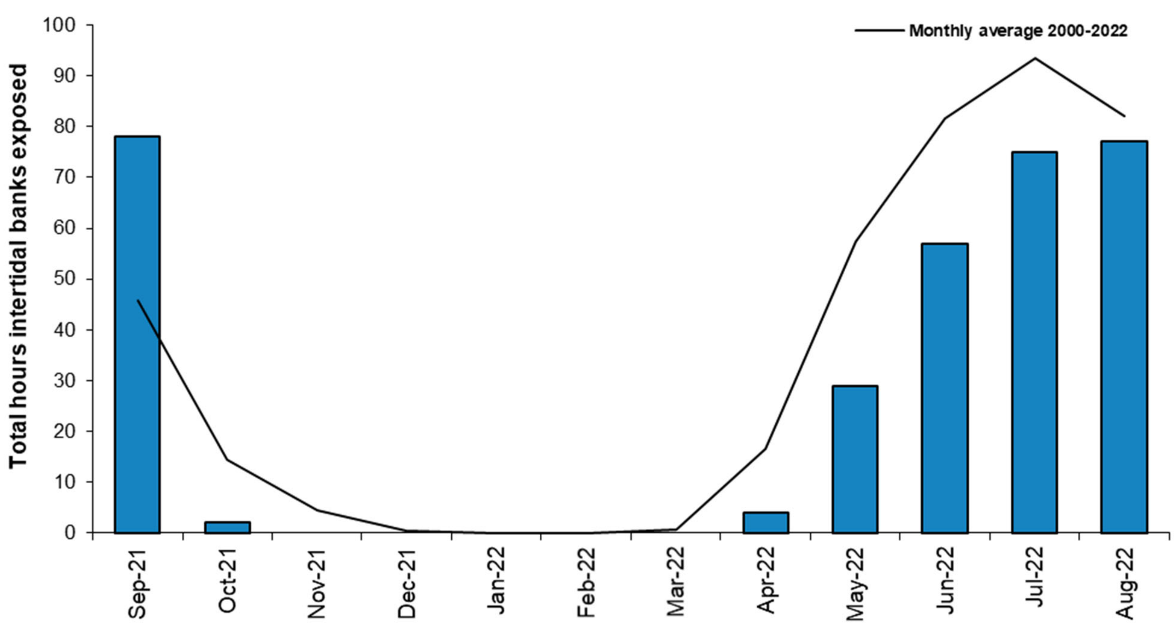


Figure 22b. Monthly total daytime tidal exposure to air (hours; ≤0.9m tidal height); August 2021 – July 2022.

3.2.4 Benthic Daily Photosynthetically Active Radiation (PAR (light))

Total daily PAR is measured in the shallow intertidal meadow on the western bank of the Embley River (A2), and in the deeper meadows between Evans Landing and Lorim Point (meadows A6 and A7) (Figure 11). Outside of the wet/high rainfall season meadows A2 and A7 experienced better light conditions compared to previous year, while meadow A6 experienced light at similar levels to last year (Figure 23). Meadow A2 and A7 also experienced a longer period of light below ideal light requirements for healthy seagrass growth during the wet season (Figure 23b). The period between December and March coincides with the wet/high rainfall season in the region which was above the long-term average in 2021/22.

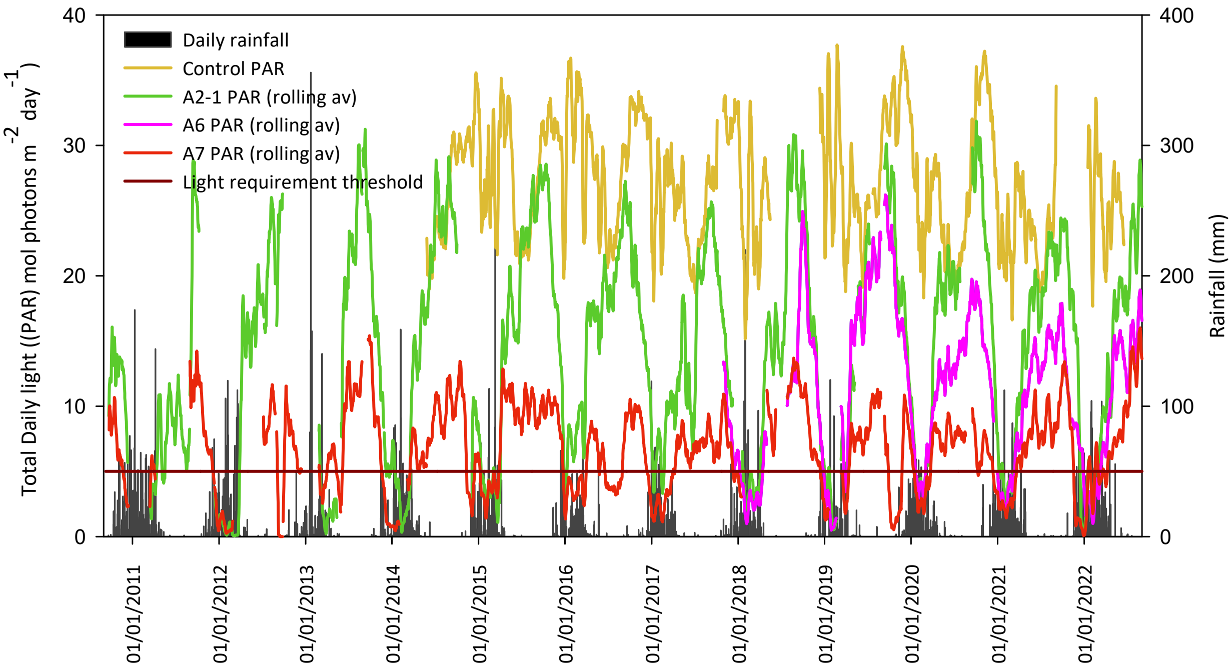
PAR was less in the deeper meadows (A6 and A7) than the shallower A2 meadow as would be expected due to greater light attenuation with depth of water and shorter periods of low tide exposure to air. In the twelve months prior to the seagrass survey PAR ranged from (see Figure 23);

- Control logger (above water): 7.47 – 56.29 mol m^{-2} day^{-1};
- A2 intertidal meadow: 0.02 – 36.40 mol m^{-2} day^{-1};
- A6 & A7 intertidal/subtidal meadows: 0.007 – 26.35 mol m^{-2} day^{-1}.

The longest ongoing integration period (14-day rolling average) that PAR fell below the acute threshold (5 mol m-2 day-1) during 2021/2022 at each site was (Figure 23b):

- A2 meadow: 54 days below threshold December 2021 – March 2022
- A6: 74 days below threshold December 2021 – March 2022
- A7: 114 days below threshold November 2021 – April 2022

a)



*A6 PAR site established late 2017

b)

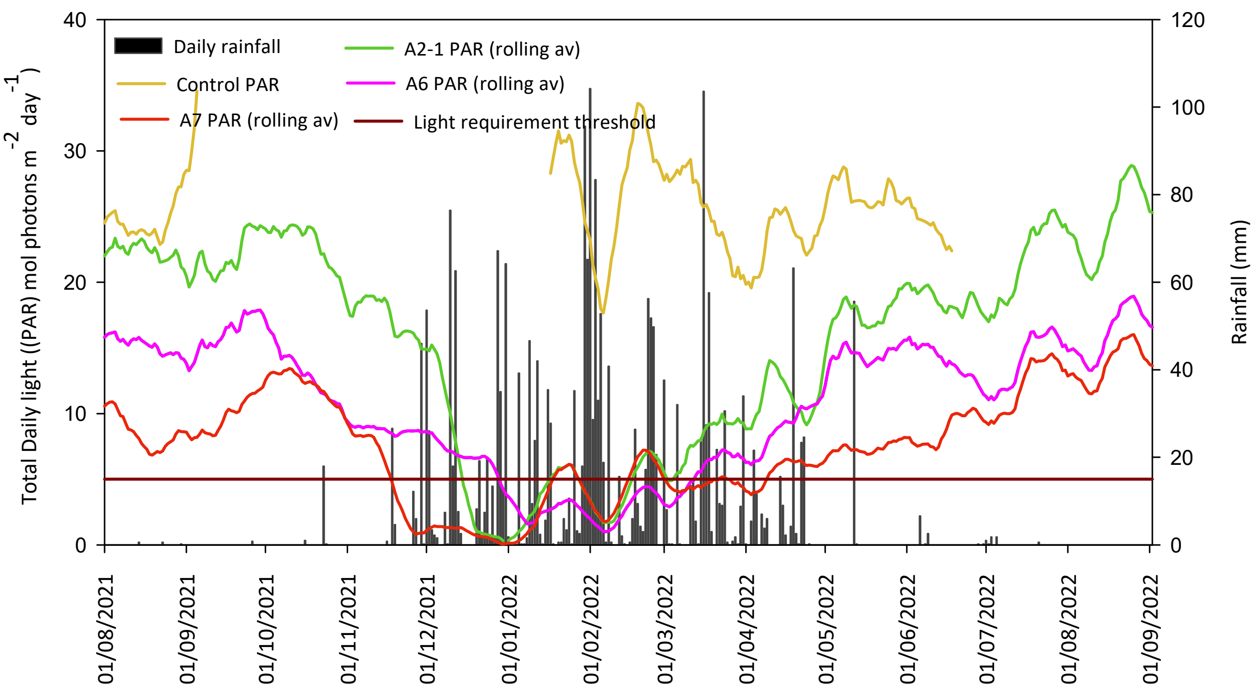


Figure 23 (a) Daily photosynthetically active radiation (PAR; mol photons m^{-2} day^{-1}) and total daily rainfall (mm) at Weipa; January 2011 – August 2022. (b) Period of low light over the 2021-2022 wet season.

DISCUSSION

In 2022 the Port of Weipa seagrasses were in an overall good condition. The footprint and biomass of seagrass within the IMA port region was similar to last year. Total seagrass meadow area within the IMA was one of the highest recorded since monitoring began in 2000 (fourth highest). Seagrass outside the IMA in the broader region of Hey River, Mission River and Pine River Bay maintained similar species composition and meadow area compared to the broadscale survey that was undertaken in 2020. There was an abundance of dugong feeding trails both within the IMA and in the broader survey region, signs of a healthy population of dugong and a productive seagrass ecosystem.

The condition of seagrasses within the monitoring meadows in the IMA region have remained in a good condition in four of the five meadows since 2017. Within three of the stable meadows (A2, A3, A5) all three seagrass condition indicators biomass, area and species composition have remained consistent or shown improvement. Notably the species composition of the monitoring meadow (A6) closest to the ship loading facility continued to shift toward the less stable species at the expense of the more stable larger growing *E. acoroides,* with *T. hemiprichii*, *H. uninvervis*, and *Halophila spp.*, making up a larger proportion of the species composition in 2022 than previous years. There has been a gradual decline in *E. acorodies* over the past 6 years and in 2022 biomass was also slightly less as a result of this species shift. The addition of these opportunistic and colonising species still provide important ecosystem services but are less resilient to disturbance and any further decline should be closely monitored and potential causes of changes in species composition investigated.

Changes in species composition have occurred in both *H. uninervis* dominated meadows (A3 and A5) where the larger growth form *T. hemprichii* has either increased its proportion of the meadow biomass or been recorded for the first time. The shift in species composition could indicate favourable conditions as both species can undergo rapid horizontal rhizome elongation enabling rapid meadow growth and colonisation of new habitats (Marba & Duarte 1998). The increase in biomass of the larger more persistent *T. hemprichii* within these meadows may be a sign of seagrass successional change and potentially could lead to a longer term shift in the make up of these meadows.

Meadow A7 was the only meadow to decline in condition in 2022 although it was still rated as satisfactory compared with its baseline condition. Biomass and species composition were in good and very good condition, however area declined from the previous year. The decline in area was the first after three years of good condition grades and the actual change in area was small at only 1.3 ha.

Rainfall in Weipa has been above average for the past two years and in 2022 the wet condition continued outside of the regular wet-season with higher than average rainfall occurring in months April to July than in previous years. However, the above average rainfall does not seem to have led to any chronic longer-term impacts to seagrass in 2022 as biomass remained in a good or very good condition across all meadows. Sustained rainfall and associated river flow and turbidity can be a key factor in determining seagrass condition as it affects benthic light levels and the ability of seagrass to photosynthesise (Collier et al. 2016). The resilience of seagrasses to the recent wetter conditions is likely through a combination of the previous few years good growing conditions allowing the large *E. acoroides* to build up sufficient stores of carbohydrates to maintain it through low light periods as well as the opportunistic growth characteristics of *H. uninervis* allowing it to rapidly expand and spread during the higher light levels that were recorded in the dry season of 2022.

Enhalus acoroides is a persistent species that has a large storage of carbohydrate energy reserves in below-ground structures that can sustain the plant (Kilminster et al. 2015). *Enhalus acoroides* biomass and meadow area have remained constant over the last five years despite experiencing long periods (> 2 months) of light levels below the likely threshold for net gain from seagrass photosynthesis during the wet season. Under low light conditions carbohydrates (sucrose) in *E. acoroides* rhizomes decline indicating that they utilise these energy stores during times of stress (Lockett 2022). The utilisation of rhizome carbohydrates under low light conditions has recently been assessed in Weipa with variations in carbohydrates detected throughout the year, reaching lowest concentrations at the conclusion of the wet season but with no change in above ground biomass (Lockett 2022). Longer term research to determine the role of below ground energy stores on *E. acoroides* resilience is needed to better understand the processes involved and the generality of the patterns observed in recent studies conducted in Weipa (Lockett 2022). The ability of *E. acoroides* to utilise long term energy stores to maintain biomass and health indicates traditional light threshold values to manage this species may not be particularly effective on their own without considering the state of stored energy reserves.

Lower levels of air exposure during low tide of intertidal meadows in 2022 was also likely to benefit *E. acoroides* meadows, protecting them from the effects of desiccation and “burning”. In 2022 observations of burnt tips in *E. acoroides* were in the low range and were concentrated in the A2 meadow which was able to maintain above ground biomass in good condition.

Seagrass monitoring similar to the Port of Weipa is conducted in other parts of Queensland and includes Karumba in the south of the Gulf of Carpentaria and Thursday Island in Torres Strait to the north of the Port of Weipa. Over the past two monitoring years there has been improvements in the seagrass biomass and area of the Karumba seagrass monitoring meadows (Scott et al. 2022). Seagrass meadows at Karumba consist of small opportunistic *H. uninervis* and the increase in *H. uninervis* biomass over the past two years in Karumba mirrors increases in *H. uninervis* biomass in Weipa over the same period. Although seagrasses in Karumba have been recovering from localised flood impacts in the area in 2019. Seagrass condition (biomass, area, species composition) in Thursday Island was in an overall good condition in 2022 and has been in similar condition to Weipa in the past few years (Scott et al. 2022). Thursday Island has similar species compositions to Weipa including *E. acoroides*, *H. uninervis, T. hemprichii* and *H. ovalis* (Scott et al. 2022). Increased *H. uninervis* biomass across both monitoring ports in the Gulf of Carpentaria reflect improved growing conditions for *H. uninervis* over the past two years. The continued good condition of seagrasses in Weipa in 2022 indicates they should have good levels of resilience to natural or anthropogenic disturbances into 2023.

APPENDICES

Appendix 1. Seagrass meadow condition index

Baseline Calculations

Baseline conditions for seagrass biomass, meadow area and species composition were established from annual means calculated over the first 10 years of monitoring (2000-2009). This baseline was set based on results of the Gladstone Harbour 2014 pilot report card (Bryant et al. 2014). The 2002-2009 period incorporates a range of conditions present in the Port of Weipa, including El Niño and La Niña periods, and multiple extreme rainfall and river flow events. The 10-year long-term baseline will be reassessed each decade.

Baseline conditions for species composition were determined based on the annual percent contribution of each species to mean meadow biomass of the baseline years. The meadow was classified as either single species dominated (one species comprising ≥ 80% of baseline species), or mixed species (all species comprise <80% of baseline species composition). Where a meadow baseline contained an approximately equal split in two dominant species (i.e. both species accounted for 40–60% of the baseline), the baseline was set according to the percent composition of the more persistent/stable species of the two (see Grade and Score Calculations section and Figure A1).

Meadow Classification

A meadow classification system was developed for the three condition indicators (biomass, area, species composition) in recognition that for some seagrass meadows these measures are historically stable, while in other meadows they are relatively variable. The coefficient of variation (CV) for each baseline for each meadow was used to determine historical variability. Meadow biomass and species composition were classified as either stable or variable (Table A1). Meadow area was classified as either highly stable, stable, variable, or highly variable (Table A1). The CV was calculated by dividing the standard deviation of the baseline years by the baseline for each condition indicator.

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

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

Threshold Definition

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

Table A2. Threshold levels for grading seagrass indicators for various meadow classes relative to the baseline. Upwards/downwards arrows are included where a change in condition has occurred in any of the three condition indicators (biomass, area, species composition) from the previous year.

Seagrass condition indicators/ Meadow class		Seagrass grade				
		A Very good	B Good	C Satisfactory	D Poor	E Very Poor
Biomass	Stable	>20% above	20% above - 20% below	20-50% below	50-80% below	>80% below
	Variable	>40% above	40% above - 40% below	40-70% below	70-90% below	>90% below
Area	Highly stable	>5% above	5% above - 10% below	10-20% below	20-40% below	>40% below
	Stable	>10% above	10% above - 10% below	10-30% below	30-50% below	>50% below
	Variable	>20% above	20% above - 20% below	20-50% below	50-80% below	>80% below
	Highly variable	> 40% above	40% above - 40% below	40-70% below	70-90% below	>90% below
Species composition	Stable and variable; Single species dominated	>0% above	0-20% below	20-50% below	50-80% below	>80% below
	Stable; Mixed species	>20% above	20% above - 20% below	20-50% below	50-80% below	>80% below
	Variable; Mixed species	>20% above	20% above- 40% below	40-70% below	70-90% below	>90% below
	Increase above threshold from previous year		 BIOMASS	Decrease below threshold from previous year		 BIOMASS

Grade and Score Calculations

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

Score calculations for each meadow's condition required calculating the biomass, area and species composition for that year (see Baseline Calculations section), allocating a grade for each indicator by comparing values against meadow-specific thresholds for each grade, then scaling biomass, area and species composition values against the prescribed score range for that grade.

Scaling was required because the score range in each grade was not equal (Table A3). Within each meadow, the upper limit for the very good grade (score = 1) for species composition was set as 100% (as a species could never account for >100% of species composition). For biomass and area, the upper limit was set as the maximum mean plus standard error (SE; i.e. the top of the error bar) value for a given year, compared among years during the baseline period.

An example of calculating a meadow score for biomass in satisfactory condition is provided in Appendix 2.

Table A3. Score range and grading colours used in the Port of Weipa.

Grade	Description	Score Range	
		Lower bound	Upper bound
A	Very good	≥0.85	1.00
B	Good	≥0.65	<0.85
C	Satisfactory	≥0.50	<0.65
D	Poor	≥0.25	<0.50
E	Very poor	0.00	<0.25

Where species composition was determined to be anything less than in "perfect" condition (i.e. a score <1), a decision tree was used to determine whether equivalent and/or more persistent species were driving this grade/score (Figure A1). If this was the case then the species composition score and grade for that year was recalculated including those species. Concern regarding any decline in the stable state species should be reserved for those meadows where the directional change from the stable state species is of concern (Figure A1). This would occur when the stable state species is replaced by species considered to be earlier colonisers. Such a shift indicates a decline in meadow stability (e.g a shift from *H. uninervis* to *H. ovalis*). An alternate scenario can occur where the stable state species is replaced by what is considered an equivalent species (e.g. shifts between *C. rotundata* and *C. serrulata*), or replaced by a species indicative of an improvement in meadow stability (e.g. a shift from *H. decipiens* to *H. uninervis* or any other species). The directional change assessment was based largely on dominant traits of colonising, opportunistic and persistent seagrass genera described by Kilminster et al. (2015). Adjustments to the Kilminster model included: (1) positioning *S. isoetifolium* further towards the colonising species end of the list, as successional studies following disturbance demonstrate this is an early coloniser in Queensland seagrass meadows (Rasheed 2004); and (2) separating and ordering the *Halophila* genera by species. Shifts between *Halophila* species are ecologically relevant; for example, a shift from *H. ovalis* to *H. decipiens*, the most marginal species found in the Port of

Weipa, may indicate declines in water quality and available light for seagrass growth as *H. decipiens* has a lower light requirement (Collier et al. 2016) (Figure A1).

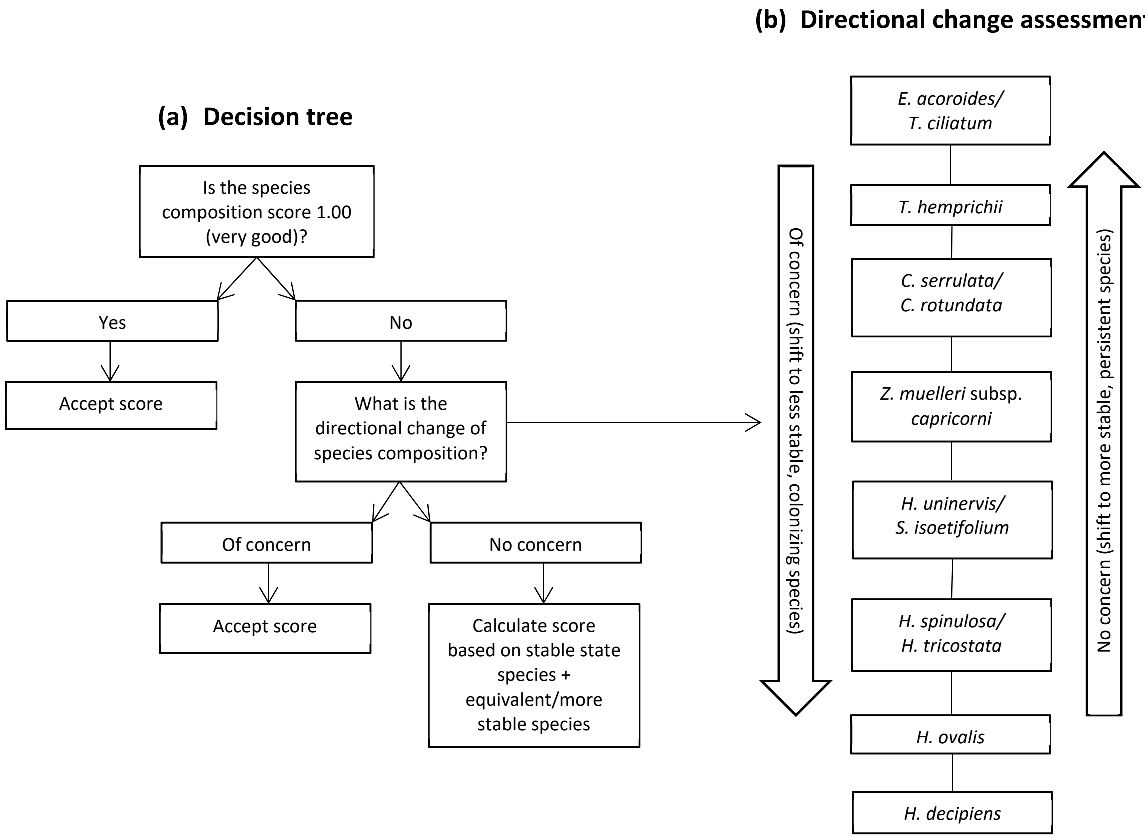


Figure A1. (a) Decision tree and (b) directional change assessment for grading and scoring species composition in the Port of Weipa.

Score Aggregation

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

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

Seagrass species composition is an important modifier of seagrass meadow state. A change in species to more colonising forms can be a key indicator of disturbance and a meadow in recovery from pressures. As not all seagrass species provide the same services a change in species composition can lead to a change in the function and services a meadow provides. Originally, the species composition indicator was considered in the same way as biomass and area, if it was the lowest score, it would inform the overall meadow score. However, while seagrass species is an important modifier it is not as fundamental as the actual presence of seagrass (regardless of species). While the composition may have changed there is still seagrass present to perform at least some of the roles expected of the meadow such a food for dugong and turtle for example. The old approach led to some unintended consequences with some meadows receiving a "0" score despite having good area and biomass simply because the climax species for that meadows base condition had not returned after losses had occurred. So while it is an important modifier, species composition should not be the sole determinant of the overall meadow score (even when it is the lowest score). As such the method for rolling up the 3 indicator scores was modified so that in the circumstances where species composition is the lowest of the 3 indicators, it contributes 50% of the score, with the other 50% coming from the lower of the 2 fundamental indicators (biomass and area). This maintains the original design philosophy but provides a 50% reduction in weighting that species composition could effectively contribute.

The change in weighting approach for species composition was tested across all previous years and meadows in the Port of Weipa as well the other seagrass monitoring locations where we use this scoring methodology (Cairns, Townsville, Abbot Point, Mackay, Hay Point, Mourilyan Harbour, Torres Strait, Gladstone and Karumba). A range of different weightings were examined, but the 50% weighting consistently provided the best outcomes. The change resulted in sensible outcomes for meadows where species composition was poor and resulted in overall meadow condition scores that remained credible with minimal impact to the majority of meadow scores across Weipa (and the other locations), where generally meadow condition has been appropriately described. Changes only impacted the relatively uncommon circumstance where species composition was the lowest of the 3 indicators. The reduction in weighting should not allow a meadow with very poor species composition to achieve a rating of good, due to the reasons outlined above, and the 50% weighting provided enough power to species composition to ensure this was the achieved compared with other weightings that were tested.

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

Appendix 2. Calculating meadow scores

An example of calculating a meadow score for biomass in satisfactory condition in 2016.

1. Determine the grade for the 2016 (current) biomass value (i.e. satisfactory).

2. Calculate the difference in biomass (B_{diff}) between the 2016 biomass value (B_{2016}) and the area value of the lower threshold boundary for the satisfactory grade ($B_{satisfactory}$):

$$B_{diff} = B_{2016} - B_{satisfactory}$$

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

3. Calculate the range for biomass values (B_{range}) in that grade:

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

Where $B_{satisfactory}$ is the upper threshold boundary for the satisfactory grade.

Note: For species composition, the upper limit for the very good grade is set as 100%. For area and biomass, the upper limit for the very good grade is set as the maximum value of the mean plus the standard error (i.e. the top of the error bar) for a given year during the baseline period for that indicator and meadow.

4. Calculate the proportion of the satisfactory grade (B_{prop}) that B_{2016} takes up:

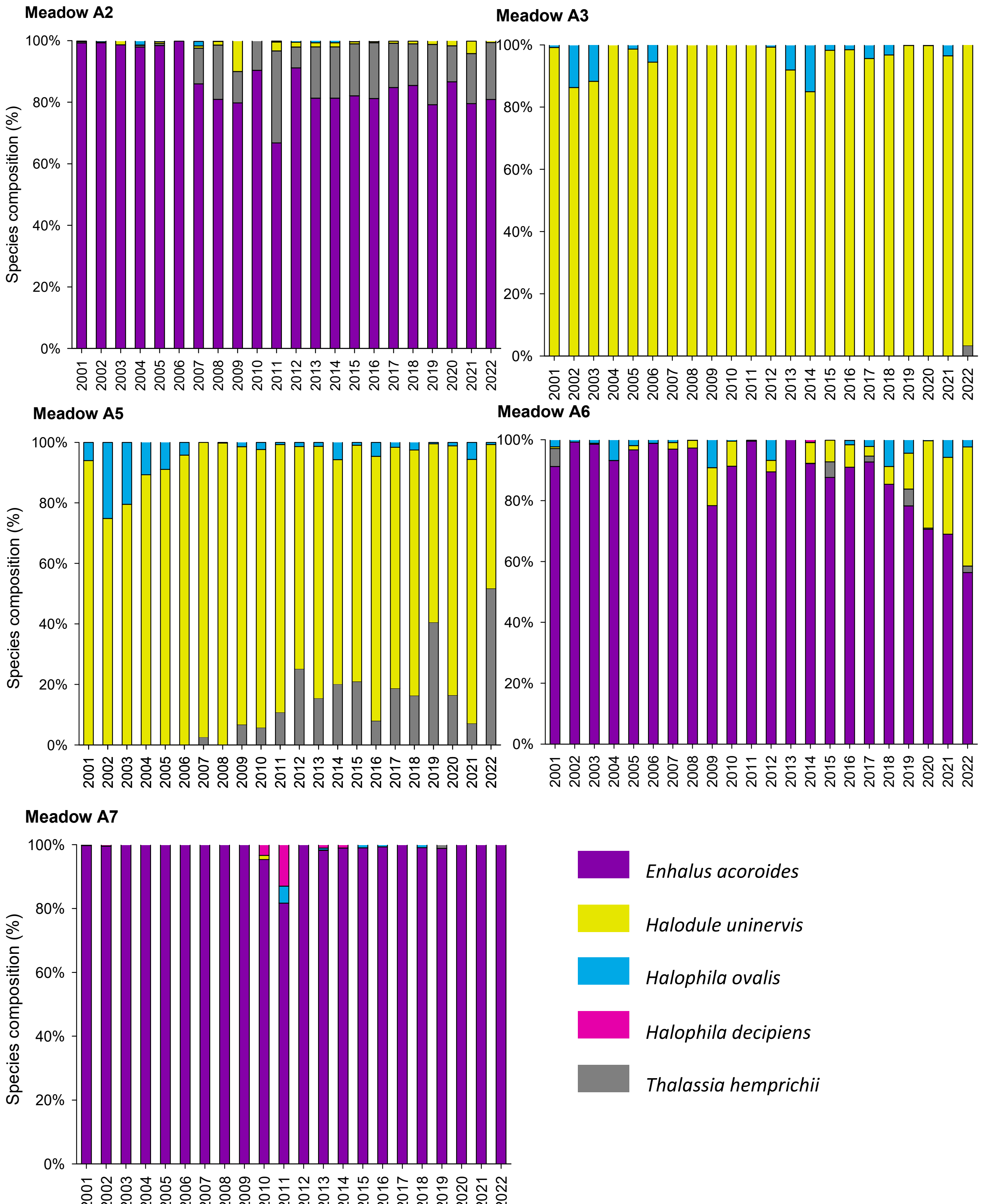
$$B_{prop} = \frac{B_{diff}}{B_{range}}$$

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

$$Score_{2016} = LB_{satisfactory} + (B_{prop} \times SR_{satisfactory})$$

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

Appendix 3. Detailed species composition; 2000 – 2022



Appendix 4. Meadow above-ground biomass and area

Mean above-ground seagrass biomass (g DW m^{-2}) ± standard error and number of biomass sampling sites (in brackets) for each core monitoring meadow within the Port of Weipa, 2000 – 2022.

Monitoring Meadow	Mean Biomass ± SE (g DW m^{-2}) (no. of sites)																						
	Sep 00	Sep 01	Sep 02	Sep 03	Aug 04	Aug 05	Aug 06	Sep 07	Sep 08	Sep 09	Se 10	Aug 11	Aug 12	Sep 13	Aug 14	Sept 15	Aug 16	Aug 17	Sept 18	Sept 19	Aug 20	Aug 21	Aug 22
A2 Intertidal *Enhalus* dominated	33.63 ± 5.82 (17)	29.73 ± 2.88 (51)	22.84 ± 2.99 (50)	13.99 ± 1.96 (54)	11.47 ± 1.77 (51)	7.04 ±0.72 (51)	6.43 ±1.03 (54)	9.40 ±0.90 (46)	4.65 ±0.63 (48)	6.39 ±0.77 (70)	15.36 ± 1.23 (52)	6.13 ±0.82 (51)	14.60 ± 1.36 (65)	11.47 ± 1.01 (76)	12.55 ± 1.15 (81)	14.37 ±0.66 (91)	10.62 ± 1.13 (66)	16.70 ±1.28 (72)	17.92 ± 1.18 (68)	14.19 ± 0.98 (62)	14.27 ±0.89 (64)	14.78 ±0.99 (74)	15.40 ±1.14 (76)
A3 Intertidal *Halodule* dominated	3.34 ±0.87 (11)	2.04 ±0.33 (26)	0.38 ±0.07 (30)	1.04 ±0.29 (26)	0.10 ±0.04 (26)	1.08 ±0.41 (25)	0.11 ±0.05 (31)	0.92 ±0.36 (31)	0.08 ±0.05 (28)	0.0002 ± 0.0001 (31)	1.05 ± 0.53 (26)	0.84 ±0.26 (44)	2.42 ±0.61 (34)	1.31 ±0.28 (69)	1.62 ±0.25 (71)	0.74 ±0.12 (77)	2.13 +0.19 (42)	0.68 ±0.16 (71)	1.34 ±0.23 (56)	2.30 ±0.54 (45)	1.55 ±0.33 (42)	3.71 ±0.53 (58)	2.75 ±0.45 (51)
A5 Intertidal *Halodule* dominated	2.55 ±0.49 (9)	3.11 ±0.31 (51)	2.03 ±0.29 (51)	2.26 ±0.23 (49)	4.18 ±0.61 (50)	4.11 ±0.54 (50)	1.75 ±0.38 (57)	6.27 ±0.74 (48)	1.87 ±0.45 (48)	4.83 ±0.61 (76)	2.52 ±0.46 (62)	5.21 ±0.66 (78)	4.17 ±0.88 (60)	3.94 ±0.47 (70)	4.38 ±0.57 (67)	4.66 ±0.55 (67)	6.03 +0.44 (95)	5.12 ±0.47 (69)	5.94 ±0.51 (91)	5.52 ±0.67 (60)	9.51 ±0.81 (58)	12.07 ±0.98 (57)	10.17 ±1.11 (53)
A6 Intertidal/ subtidal *Enhalus* dominated	9.63 ±5.52 (9)	10.4 ±2.79 (26)	9.5 ±2.54 (25)	8.13 ±2.90 (25)	1.14 ±0.40 (26)	3.37 ±1.00 (26)	3.45 ±1.09 (26)	6.22 ±1.01 (31)	2.83 ±0.55 (25)	1.47 ±0.47 (29)	4.14 ±1.04 (25)	1.61 ±0.41 (49)	4.49 ±0.94 (28)	14.61 ± 4.29 (32)	6.64 ±1.19 (32)	6.43 ±1.03 (32)	7.99 +1.05 (19)	8.30 ±1.26 (32)	5.1 ±0.91 (33)	7.91 ±1.30 (40)	9.67 ±1.1 (33)	8.30 ±0.1.2 (33)	7.45 ±1.14 (32)
A7 Intertidal/ subtidal *Enhalus* dominated	9.63 ±4.12 (14)	18.89 ± 3.88 (30)	10.03 ± 2.34 (33)	15.57 ± 3.39 (31)	10.71 ± 3.19 (24)	2.84 ±0.58 (30)	3.06 ±0.73 (33)	6.41 ±0.97 (33)	5.85 ±1.28 (21)	5.03 ±1.22 (24)	3.46 ±0.92 (21)	2.47 ±0.65 (35)	1.58 ±0.42 (36)	6.58 ±1.20 (45)	12.31 ± 1.65 (39)	7.64 ±1.20 (34)	8.48 +0.91 (28)	16.61 ± 2.08 (30)	5.63 ±1.13 (28)	12.99 ± 1.82 (38)	10.01 ± 1.25 (41)	13.66 ± 2.19 (41)	10.2 ±1.52 (40)

Appendix 4. Meadow above-ground biomass and area

Total meadow area + R (ha) for each core monitoring meadow within the Port of Weipa, 2000 – 2022.

Monitoring Meadow	Total meadow area ± R (ha)																						
	Sep 00	**Sep 01**	**Sep 02**	**Sep 03**	**Aug 04**	**Aug 05**	**Aug 06**	**Sep 07**	**Sep 08**	**Sep 09**	**Sep 10**	**Aug 11**	**Aug 12**	**Sep 13**	**Aug 14**	**Sep 15**	**Aug 16**	**Aug 17**	**Sept 18**	**Sep 19**	**Aug 20**	**Aug 21**	**Aug 22**
A2 Intertidal *Enhalus* dominated	253.0 ±19.0	248.0 ±19.0	255.0 ±19.0	250.4 ±19.7	256.0 ±19.0	251.0 ±20.0	245.0 ±13.0	238.0 ± 6.0	244.5 ± 6.6	251.0 ± 7.0	250.7 ± 6.5	254.0 ± 6.5	233.0 ± 7.0	256.9 ± 6.6	267.7 ± 6.5	248.3 ± 6.5	253.59 ± 6.56	285.82 ± 6.51	262.63 ± 6.62	248.32 ± 6.61	261.85 ± 6.49	266.27 ± 6.39	264.14 ± 6.80
A3 Intertidal *Halodule* dominated	30.0 ±5.0	49.0 ±5.0	34.0 ±4.0	36.1 ±4.3	41.0 ±4.0	37.0 ±5.0	31.0 ±2.0	33.0 ±2.0	31.7 ±2.0	30.0 ±2.1	22.2 ±2.1	31.0 ±2.1	28.0 ±2.0	25.3 ±2.2	31.8 ±2.3	30.0 ±2.2	31.11 ± 2.2	41.04 ± 2.22	41.82 ± 2.22	37.21 ± 2.22	45.57 ± 2.37	36.73 ± 2.27	37.83 ± 2.26
A5 Intertidal *Halodule* dominated	95.0 ± 0.0	91.0 ±11.0	102.0 ±6.0	87.0 ±9.3	94.0 ±6.0	86.0 ±10.0	58.0 ±5.0	76.0 ±6.0	66.0 ±6.0	73.0 ±6.0	70.5 ±4.7	83.0 ±5.5	73.0 ±6.0	72.6 ±5.5	69.9 ±5.3	60.9 ±10.8	78.06 ± 6.34	55.63 ± 5.82	67.26 ± 6.19	77.67 ± 6.03	83.33 ± 6.14	79.76 ± 6.28	85.20 ± 6.36
A6 Intertidal/ subtidal *Enhalus* dominated	5.0 ±1.0	7.0 ±1.0	7.0 ±1.0	6.8 ±1.0	7.0 ±1.0	7.0 ±1.0	7.0 ±2.0	6.0 ±0.5	7.5 ±0.7	8.0 ±0.7	7.8 ±0.8	9.0 ±0.7	8.0 ±3.0	9.2 ±1.6	9.8 ±1.4	7.9 ±1.4	4.92 ±3.34	7.19 ±2.61	8.22 ±2.61	7.62 ±0.68	8.13 ±0.67	7.89 ±0.66	8.60 ± 0.68
A7 Intertidal/ subtidal *Enhalus* dominated	19.0 ±2.0	23.0 ±1.0	19.0 ±1.0	18.5 ±1.0	18.0 ±1.0	17.0 ±1.0	17.0 ±1.0	15.0 ±2.0	8.7 ±1.9	13.0 ±5.0	18.3 ±1.2	22.0 ±3.4	21.0 ±7.0	21.0 ±3.5	21.0 ±6.4	14.7 ±6.0	10.62 ± 5.53	16.23 ± 5.56	12.74 ± 1.26	15.28 ± 1.37	15.69 ± 1.12	15.93 ± 1.51	14.63 ± 1.41
Total	**402.0 ±37.0**	**418.0 ±37.0**	**417.0 ±31.0**	**398.8 ±35.3**	**416.0 ±31.0**	**398.0 ±37.0**	**358.0 ±23.0**	**368.0 ±16.5**	**358.4 ±17.0**	**375.0 ±20.8**	**369.4 ±15.3**	**399.0 ±18.2**	**363.0 ±25.0**	**384.9 ±19.4**	**400.1 ±21.8**	**361.8 ±27.0**	**378.31 ±23.97**	**405.91 ± 2.72**	**392.67 ± 6.92**	**386.09 ± 5.00**	**412.58 ±16.79**	**406.58 ±17.11**	**410.41 ±17.50**

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