



PORT OF WEIPA LONG-TERM SEAGRASS MONITORING PROGRAM: 2000 - 2018

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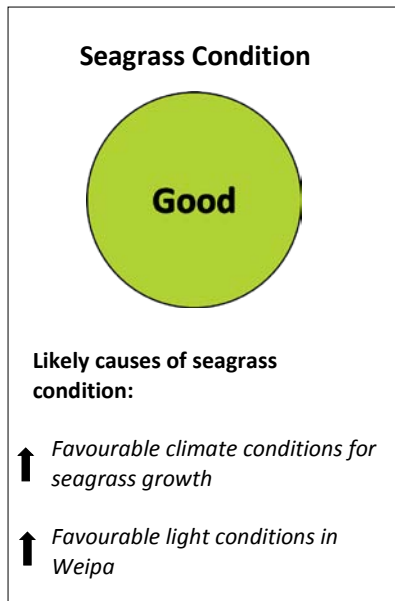
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KEY FINDINGS



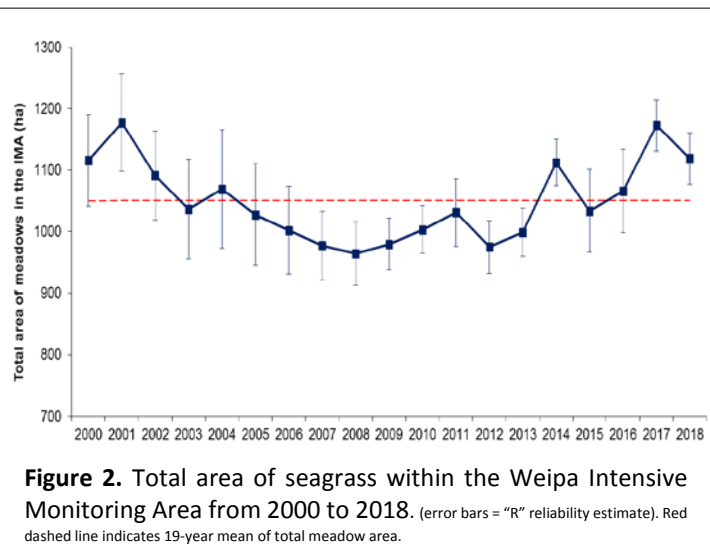
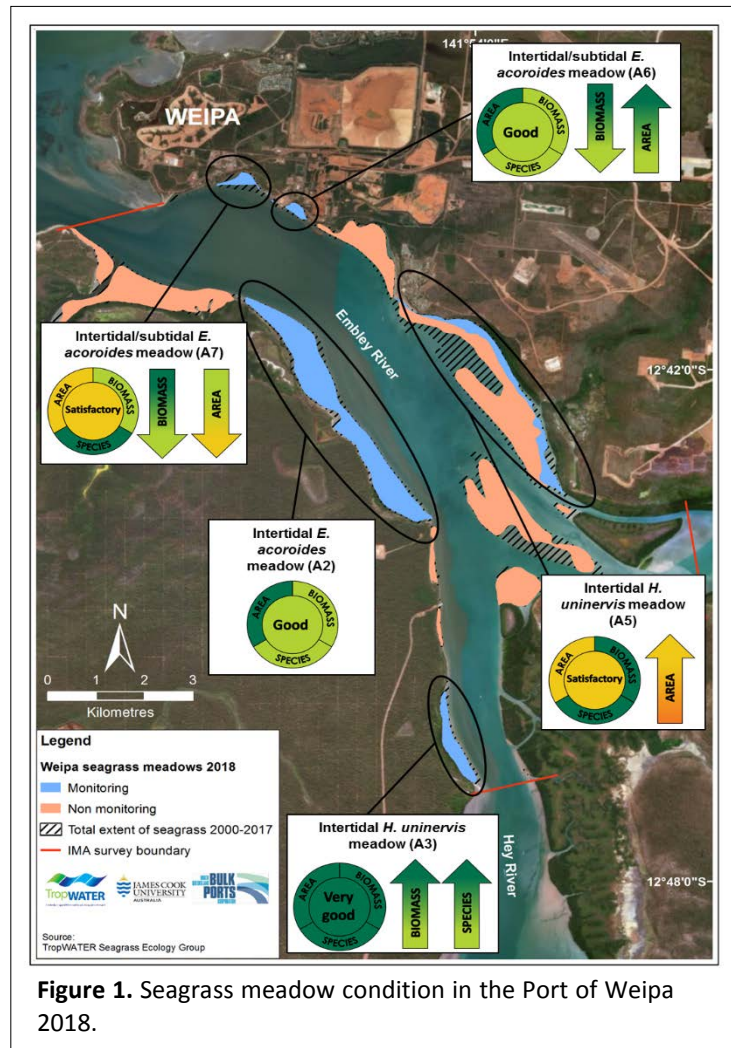
- Monitoring in 2018 found seagrasses in the Port of Weipa were in an overall good condition.
 - Individual seagrass monitoring meadows ranged in condition from satisfactory to very good.
 - Total area of seagrass meadows in the region closest to the port (Intensive Monitoring Area (IMA)) remained at one of the highest recorded in the 19 years monitoring has been conducted.
 - Extensive flowering of the large growing seagrass species *Enhalus acoroides* was observed in the meadows on the eastern bank of the Embley River.
- The recovery of coastal meadows between Lorim Point and Evans Landing recorded in 2017 (meadows A6 and A7) was largely sustained in 2018. The exception was loss of a small area of seagrass closest to the Evans Landing boat ramp.
- Environmental conditions that can effect seagrass growth; rainfall, tidal exposure and light were generally favourable for seagrass growth during 2018. The light available to seagrasses changes with season and 2018 followed a typical pattern with low levels of light during the wet season associated with high rainfall and river flow, followed by higher light levels supporting seagrass growth during the dry season.
- At the end of 2018 seagrasses were likely to have a high level of resilience to pressures. But subsequent to this survey, in early 2019, several weather events including cyclones and flooding of local rivers had the potential to impact seagrasses and their resilience. NQBP have since commissioned an additional seagrass assessment in May 2019 to check on the status of seagrasses post these wet-season events.

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 and five core seagrass meadows representing the range of different seagrass community types found in Weipa are assessed for changes in biomass, area and species composition. Changes to biomass, area and species composition are then used to develop a seagrass condition index (see section 2.3). Every three years all seagrasses within the port limits are remapped; the last completed in 2017.

Seagrasses in the Port of Weipa were in an overall good condition in 2018. Seagrasses maintained an extensive footprint within the IMA with total area one of the highest recorded during the 19 year monitoring program (Figure 2). The species composition of meadows was maintained with the expected mix and dominance of foundation species occurring. While area and biomass of individual meadows varied, all were maintained at conditions rated between very good and satisfactory compared with their long-term baseline history (Figure 1).

During 2016 the two seagrass meadows between Lorim Point and Evans Landing (Meadows A6 and A7) underwent declines, most likely due to localised reductions in light (see McKenna et al. 2017). In 2017 these meadows had largely recovered and this recovery was sustained in 2018 (Figure 1). The exception was a loss of seagrasses in a small section of meadow A7, closest to the Evans Landing boat ramp which suggested some localised impacts to seagrasses were continuing in this area (see Discussion section 4). This resulted in a reduction in seagrass meadow area from 2018 and a change in overall rating for this meadow to being in satisfactory condition.



The light environment in the twelve months leading up to the 2018 survey followed typical seasonal patterns with extended low light periods occurring in the wet season, and generally favourable light conditions occurring for seagrasses outside of this during dry season months (see section 3.2).

Other environmental conditions that can effect seagrass growth were also generally favourable in the twelve months prior to the survey, and likely contributed to the sustained good condition of seagrass in the Weipa

area (Figure 3). Tidal exposure was below average likely reducing air exposure stress including “burning” of seagrass leaves that has been observed in the region during the monitoring program. Rainfall was also below average and there were no major storms or cyclones that impacted the area in the twelve months leading up to the 2018 survey.

The key climax seagrass species *Enhalus acoroides* appears well adapted to cope with wet season reductions in light. Quarterly assessments of seagrass change at light (PAR) monitoring sites suggest that *E. acoroides* copes with several weeks and up to two months of extremely low light levels during high rainfall and river flow events, with seagrass biomass remaining relatively stable. This suggests that natural periods of low light in Weipa are generally not sustained long enough to considerably degrade *E. acoroides*, a species that has a large storage of carbohydrate energy reserves in below ground structures. However, the losses of *E. acoroides* that occurred in 2015 and 2016 when there were additional localised reductions in light, outside of the wet season, show that the species can be vulnerable, particularly when there are multiple occurrences of sustained low light within a year.

The good condition of seagrass in 2018 suggests that they are likely to remain resilient to planned annual maintenance dredging during 2019. However, since the completion of the 2018 survey, Weipa has experienced several weather events during early 2019 that have the potential to impact on their condition. Previous experience from the monitoring program has shown that generally seagrasses have been able to persist in Weipa following weather events but a closer examination of seagrass condition may be warranted in early 2019 to ensure they have been able to maintain their condition. NQBP have committed to an additional seagrass assessment in May 2019 to check on the status of seagrasses post wet-season.

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

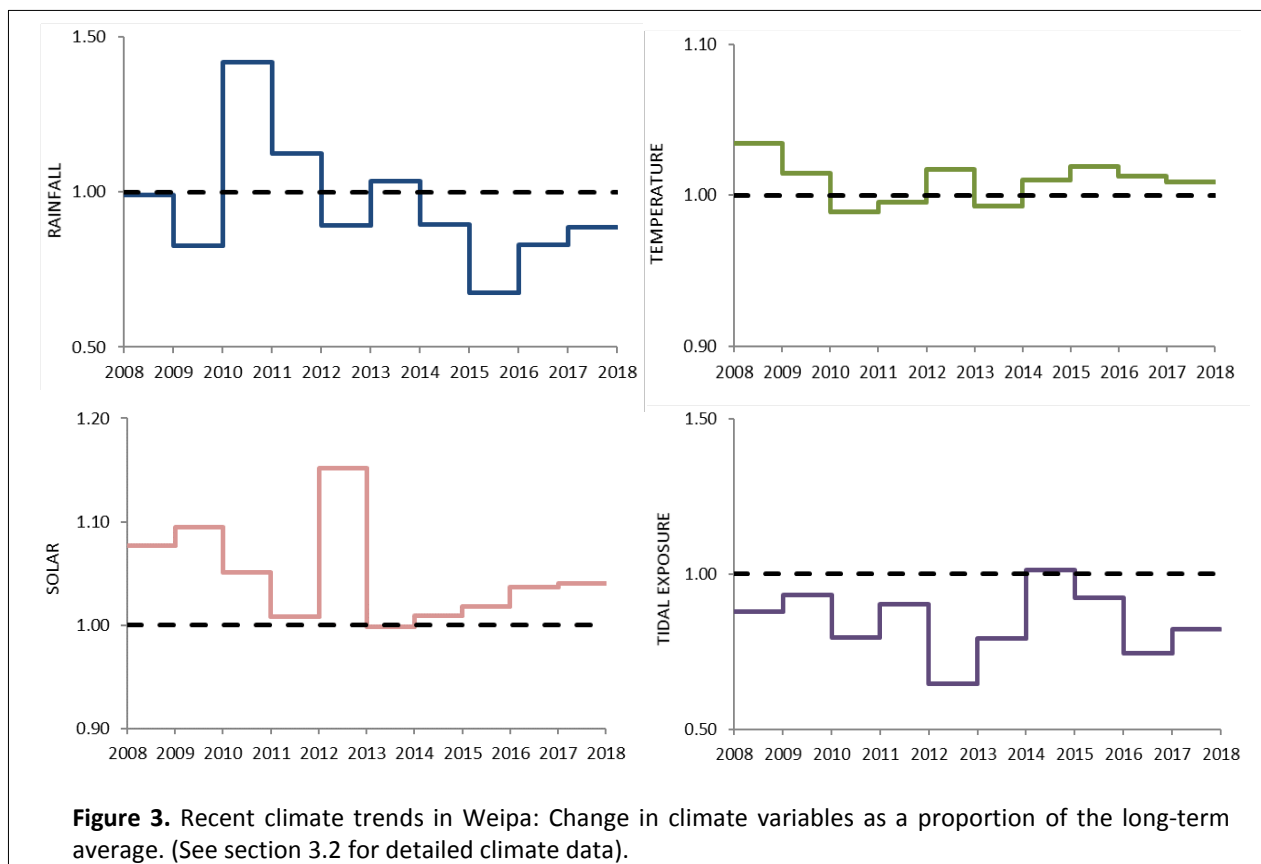


TABLE OF CONTENTS

KEY FINDINGS	i
IN BRIEF	ii
1 INTRODUCTION	1
1.1 Queensland Ports Seagrass Monitoring Program	1
1.2 Weipa Seagrass Monitoring Program	2
2 METHODS	4
2.1 Annual monitoring within the Intensive Monitoring Area.....	4
2.2 Habitat mapping and Geographic Information System	5
2.3 Seagrass meadow condition index.....	7
2.4 Environmental data.....	8
2.5 Light (PAR) and intertidal seagrass change	8
3 RESULTS.....	10
3.1 Seagrass species in the Port of Weipa	10
3.1.1 Seagrass in the Intensive Monitoring Area.....	10
3.1.2 Seagrass condition in the core annual monitoring meadows	14
3.2 Weipa climate data	22
3.2.1 Rainfall	22
3.2.2 Daytime tidal exposure.....	23
3.2.3 Solar Radiation.....	24
3.2.4 Benthic daily Photosynthetically active radiation (PAR (light)) and temperature	25
3.2.5 Water temperature	25
3.3 Light (PAR) and intertidal seagrass change	28
4 DISCUSSION	29
5 APPENDICES.....	31
Appendix 1. Seagrass meadow condition index.....	31
Baseline Calculations	31
Meadow Classification.....	31
Threshold Definition	31
Grade and Score Calculations	32
Score Aggregation.....	34
Appendix 2. Calculating meadow scores.....	36
Appendix 3. Detailed species composition; 2000 – 2018.	37
Appendix 4. Meadow above-ground biomass and area	38
Appendix 4. Meadow above-ground biomass and area	39
6 REFERENCES.....	40

1 INTRODUCTION

Seagrasses provide a range of critically important and economically valuable ecosystem functions and services including nutrient cycling and particle trapping that improves water quality, coastal protection, support of fisheries production and the capture and storage of carbon (Hemminga and Duarte 2000; Orth et al. 2006; Barbier et al. 2011; Fourqurean et al. 2012; Costanza et al. 2014). Seagrass meadows show measurable responses to changes in water quality, making them ideal candidates for monitoring the long term health of marine environments (Dennison et al. 1993; Abal and Dennison 1996; Orth et al. 2006).

Globally, seagrasses have been declining due to both natural and anthropogenic causes (Waycott et al. 2009). 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). The hot spots with highest threat exposure for seagrasses occur in areas where multiple threats accumulate including urban, port, industrial and agricultural runoff (Grech et al. 2012). These hot spots arise as seagrasses preferentially occur in the same sheltered coastal locations that 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 and ensure impacts are minimised (Coles et al. 2015).

1.1 Queensland Ports Seagrass Monitoring Program

A long-term seagrass monitoring and assessment program has been established in the majority of Queensland commercial ports. The program was developed by the Seagrass Ecology Group at James Cook University's Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) in partnership with the various Queensland Port Authorities. Each location is funded separately, but the common methods and rationale between locations provides a network of seagrass monitoring locations comparable across the State (Figure 4).

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 also has 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 <https://www.tropwater.com>



Figure 4. Location of Queensland Port seagrass assessment sites.

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 the TropWATER Seagrass Ecology Group 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 IIMA represent the range of seagrass meadow communities identified in the region. Every three years (i.e., 2000, 2002, 2005, 2008, 2011, 2014, 2017) seagrass monitoring surveys are extended to cover all meadows in the greater port limits, with a focus on mapping seagrass meadow distribution, meadow cover type and species composition (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 quarterly since September 2010 at three sites; now at four sites (Figure 14). In 2015, the program was expanded to incorporate quarterly seagrass assessments at permanent transects sites alongside the logging stations in Meadow A2 (Figure 14). The aim of conducting seagrass assessments coupled with collecting light and temperature data is to produce biologically relevant light requirement values for the dominant seagrass species in the Weipa area that can be used as a management tool for future port activities.

This report presents the results of the long-term seagrass monitoring assessments conducted in September 2018. The objectives were to:

1. Map seagrass distribution and determine biomass and meadow area in core monitoring meadows;
2. Assess changes in seagrass meadows with previous monitoring surveys;
3. Assess light and temperature conditions within seagrass meadows;
4. Assess light alongside the dominant seagrass species *Enhalus acoroides* to better understand light requirements;
5. Incorporate the results into the Geographic Information System (GIS) database for the Port of Weipa.

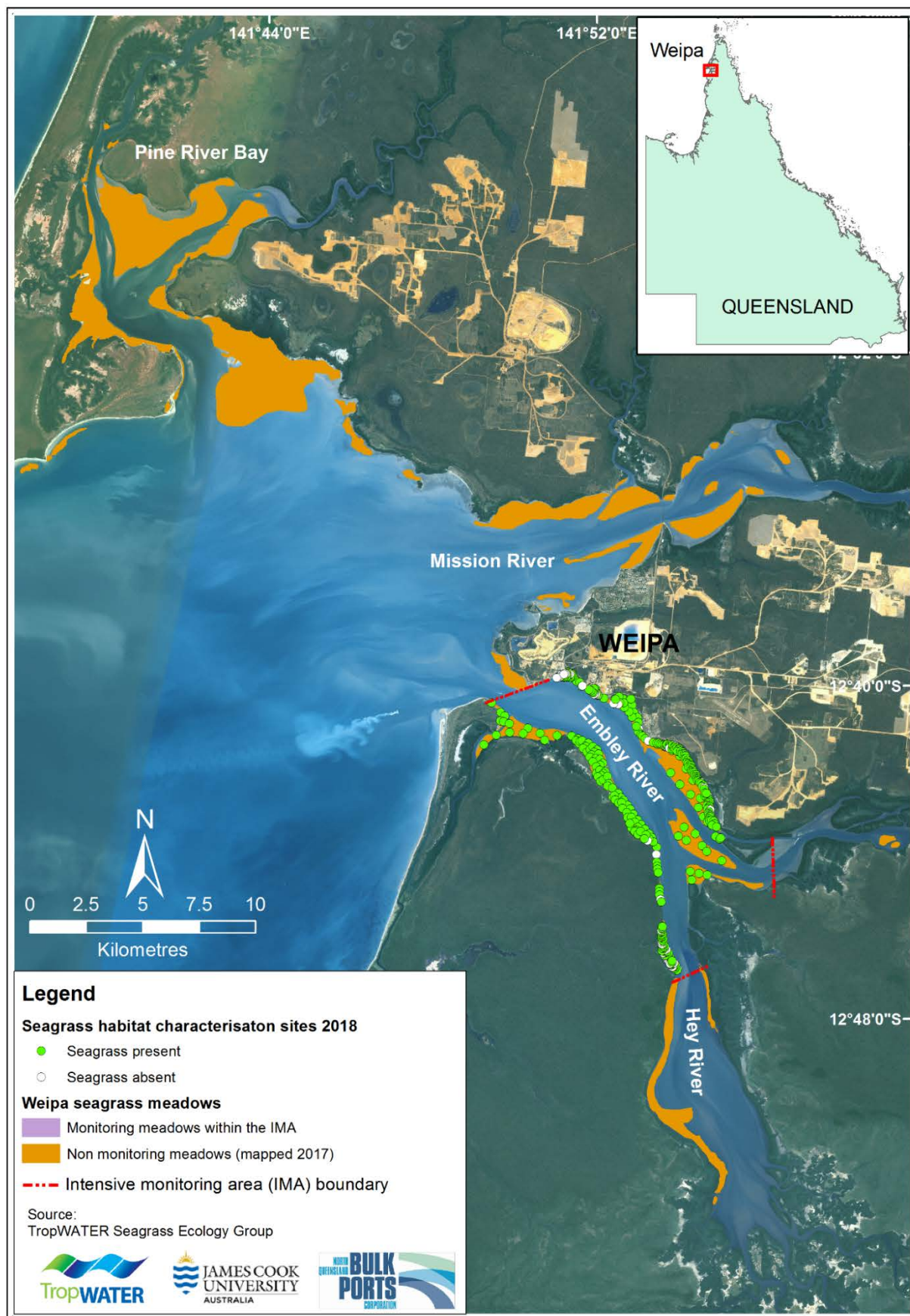


Figure 5. Location of 2018 seagrass survey sites and seagrass meadows in the Port of Weipa.

2 METHODS

2.1 Annual monitoring within the Intensive Monitoring Area

Annual monitoring of seagrass within the Port of Weipa was conducted September 7th – 9th 2018. Annual monitoring over the past 17 years has focused on five core monitoring meadows selected from baseline surveys within the Intensive Monitoring Area (IMA) (Figure 5 & 13) (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 survey, 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 September 2018 survey:

1. Assess and map seagrass distribution, species composition and biomass in the five core monitoring meadows (A2, A3, A5, A6, and A7; Figure 14);
2. Map seagrass distribution and species composition in non-core monitoring meadows within 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; $\pm 5\text{m}$) 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).

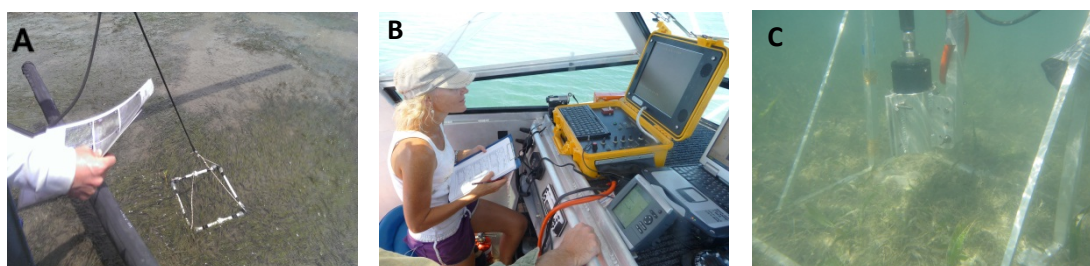


Figure 6. Seagrass methods using (A) helicopter aerial surveillance, and (B, C) boat-based camera surveillance.

Results from previous baseline surveys suggested the analysis of biomass for meadows where the large growing species *E. acoroides* was present but not dominant required 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. Historically therefore, isolated *E. acoroides* plants occurring within the *Halodule* dominated meadows A3 and A5 were excluded from all biomass and species composition analyses in order to track the dynamics of the morphologically distinct *Halodule* species in these two meadows.

Seagrass biomass (above-ground) was determined using a “visual estimates of biomass” technique (as described by Kirkman 1978 and Mellors 1991). This technique involves an observer ranking seagrass biomass in the field in three random placements of a 0.25m² 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 estimates in grams dry weight per square metre (g dw m²). At the completion of sampling, each observer ranks a series of calibration quadrats that represented 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 estimates.

2.2 Habitat mapping and Geographic Information System

All survey data were entered into a Geographic Information System (GIS) using ArcGIS 10.4[®]. Three GIS layers were created to describe seagrass in the survey area: a site layer, meadow layer and 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, longitude, depth below mean sea level (dbMSL; metres) for subtidal sites.
 - Habitat information – Sediment type; seagrass information including presence/absence, above-ground biomass (total and for each species) and biomass standard error (SE); site benthic cover (percent cover of algae, seagrass, benthic macro-invertebrates, open substrate); dugong feeding trail (DFT) presence/absence.
 - Sampling method and any relevant comments.
- *Meadow layer:* The meadow (polygon) layer provides summary information for all sites within each meadow, including:
 - Meadow ID number – A unique number assigned to each meadow to allow comparisons among surveys
 - Temporal details – Survey date.
 - Habitat information – Mean meadow biomass \pm standard error (SE), meadow area (hectares) \pm reliability estimate (R) (Table 3), number of sites within the meadow, seagrass species present, meadow density and community type (Tables 1 & 2), meadow landscape category (Figure 14).
 - 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.

Meadows were described using a standard nomenclature system developed for Queensland's seagrass meadows. Seagrass community type was determined using the dominant and other species' percent contribution to mean meadow biomass (for all sites within a meadow) (Table 1). Community density was based on mean biomass of the dominant species within the meadow (Table 2).

Table 1. Nomenclature for Queensland seagrass 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. Density categories and mean above-ground biomass ranges for each species used in determining seagrass community type in Weipa.

Density	Mean above ground biomass (grams dry weight per meter square (gdw m ²))				
	<i>H. uninervis</i> (narrow)	<i>H. ovalis</i> <i>H. decipiens</i>	<i>H. uninervis</i> (wide) <i>S. isoetifolium</i>	<i>T. hemprichii</i>	<i>E. acoroides</i>
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 determined from a combination of techniques. Exposed inshore boundaries were mapped directly from helicopter and guided by recent satellite imagery of the region (Source: ESRI; Google Earth). Subtidal boundaries were interpreted from a combination of subtidal survey sites and the distance between sites, field notes, depth contours and recent satellite imagery.

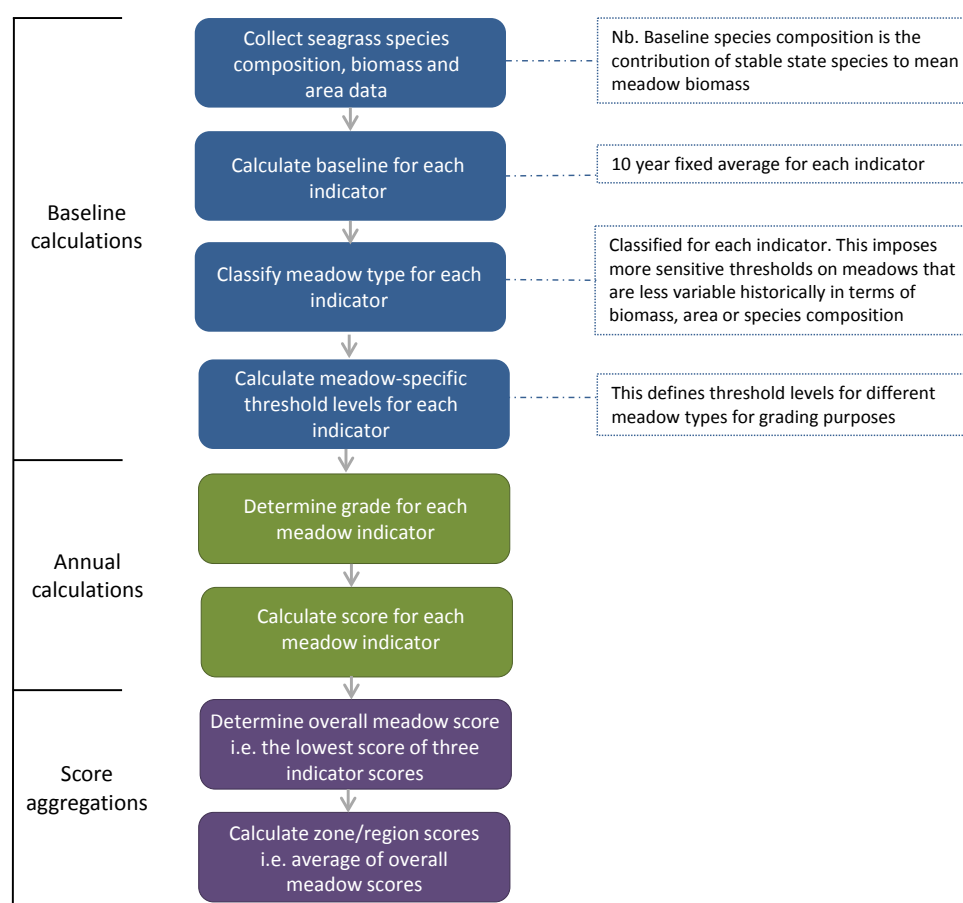
Meadow area was determined using the calculate geometry function in ArcGIS®. Meadows were assigned a mapping precision estimate (in metres) based on mapping methods used for that meadow (Table 3). The mapping precision estimate was used to calculate a buffer around each meadow representing error; the 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 2018.

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 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 assess seagrass monitoring meadow condition.

2.4 Environmental data

Environmental data was collated for the twelve months preceding each 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) $\text{mol photons m}^{-2} \text{ day}^{-1}$) conditions and temperature within the seagrass meadows at Weipa have been assessed at a northern and southern site within the intertidal A2 meadow, and at one site in the subtidal/intertidal A7 meadow (Figure 14) since September 2010 using custom built benthic data logging stations (Figure 9). An additional site was set up in meadow A6 in 2017. 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 2 π 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 recorded seabed temperature every 30 minutes. During 2018 we transitioned to Bluetooth HOBO® loggers for a period, however these were found to be not robust enough for the Weipa area. iBTag's were redeployed in September 2018.

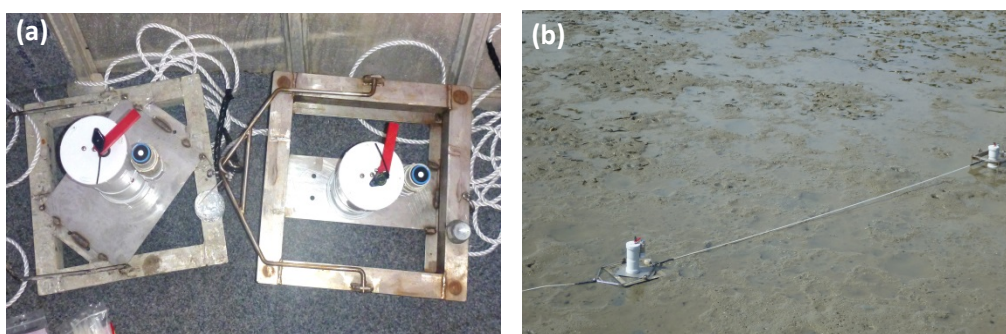


Figure 9. (a) Logging station consisting of a stainless steel frame with PAR loggers and temperature loggers attached, and wiper units (b) deployment of logging stations on the A2 meadow.

2.5 Light (PAR) and intertidal seagrass change

Quarterly seagrass assessments at permanent transect sites were established in 2015 to monitor the dominant species in the Weipa area; *E. acoroides*, coupled with the already established PAR and temperature monitoring. The goal of these assessments is to produce a better understanding of the local biologically relevant light requirements for *E. acoroides*.

Three permanent transect sites are located alongside logging stations in meadow A2; two sites at the northern end of the meadow (A2-1a and A2-1b) and one at the south end (A2-2) (Figure 14). For further information, see McKenna et al. (2017).

Key information collected for seagrass at the quarterly assessment sites includes:

- Above-ground biomass
- Percent cover
- Species composition
- Notes taken of the presence of *E. acoroides* reproductive structures.

To avoid damaging seagrass from repeated sampling in highly muddy sites such as Weipa, the methodology was adapted to use a helicopter/boat (camera drops) to sample the intertidal sites. Each permanent transect site comprised a 50m x 50m area of a relatively homogenous section of the seagrass meadow. The site contained three 50m transects which were monitored to determine the above listed key information. Eleven 0.25 m² quadrats were examined on each transect. Photos of each quadrat were also taken for further assessment.

3 RESULTS

3.1 Seagrass species in the Port of Weipa

A total of 370 seagrass habitat characterisation sites were surveyed in the IMA in 2018, with seagrass present in 85% of sites (Figure 5). Four species of seagrass were identified in the survey (Figure 10).

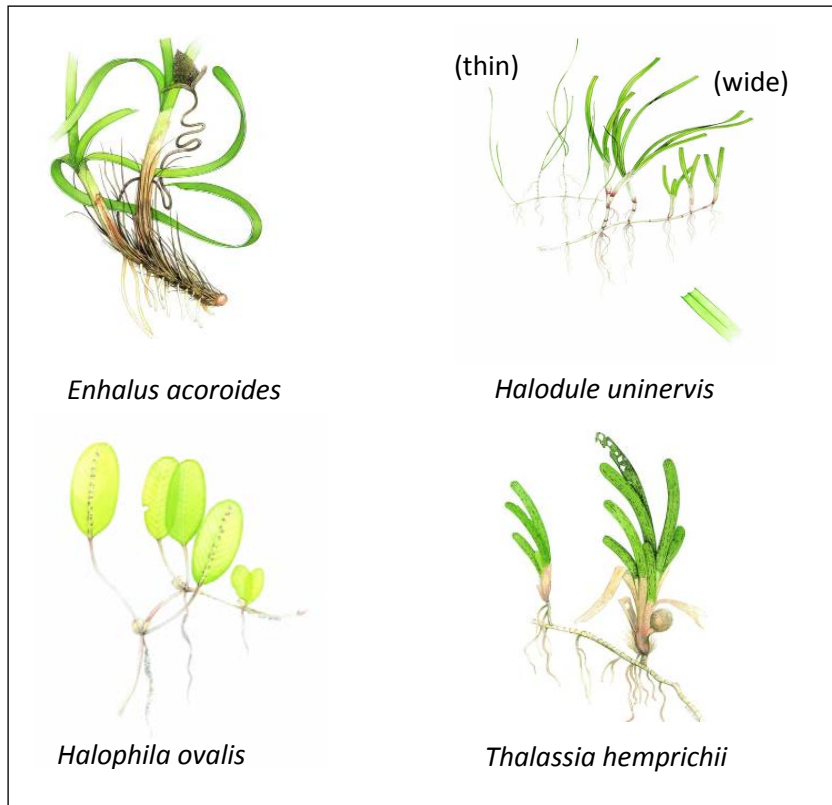


Figure 10. Seagrass species present in the Port of Weipa 2018.

3.1.1 Seagrass in the Intensive Monitoring Area

Fourteen seagrass meadows were mapped in 2018 within the Intensive Monitoring Area (IMA) (Figure 14). The total combined seagrass meadow area was 1119 ± 42 ha, one of the highest areas that has been recorded in the 19 years of monitoring in Weipa (Figure 11). Area has been above the IMA long-term average for the last three years (Figure 11).

Enhalus acoroides dominated nine out of the fourteen meadows within the IMA (Figure 14), all with light density cover. *Halodule uninervis* was the dominant species in three of the fourteen meadows, two of those being core monitoring meadows A5 and A3, consisting of continuous cover and aggregated patches respectively (Figure 14). *Thalassia hemprichii* was the dominant species in two of the IMA meadows, meadow A1 and the meadow above A1, both at the mouth of Leithen Creek (Figure 14).

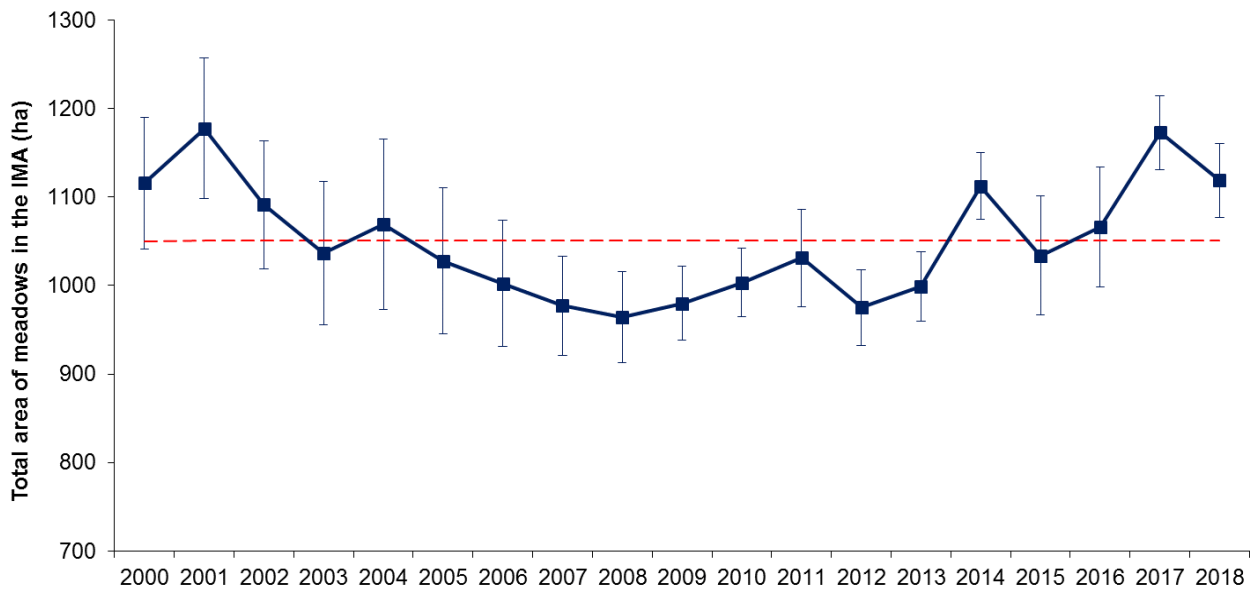


Figure 11. Total area of seagrass within the Weipa Intensive Monitoring Area from 2000 to 2018 (error bars = “R” reliability estimate). Red dashed line indicates 19-year mean of total meadow area.

The condition known as burning, i.e. the browning and subsequent death of seagrass blades (Figure 12), was observed at 18% of sites across all meadows within the IMA in 2018; a slight increase from 2017. 2013 had the lowest occurrence of burning observed since the condition was first formally recorded in 2010 (Figure 12).

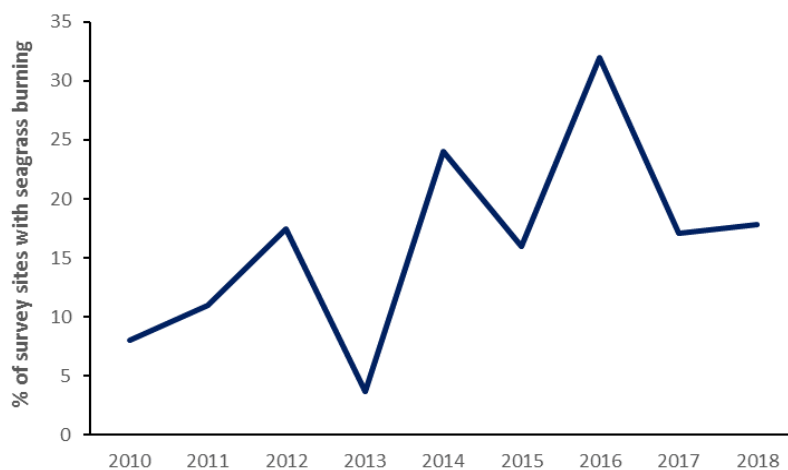
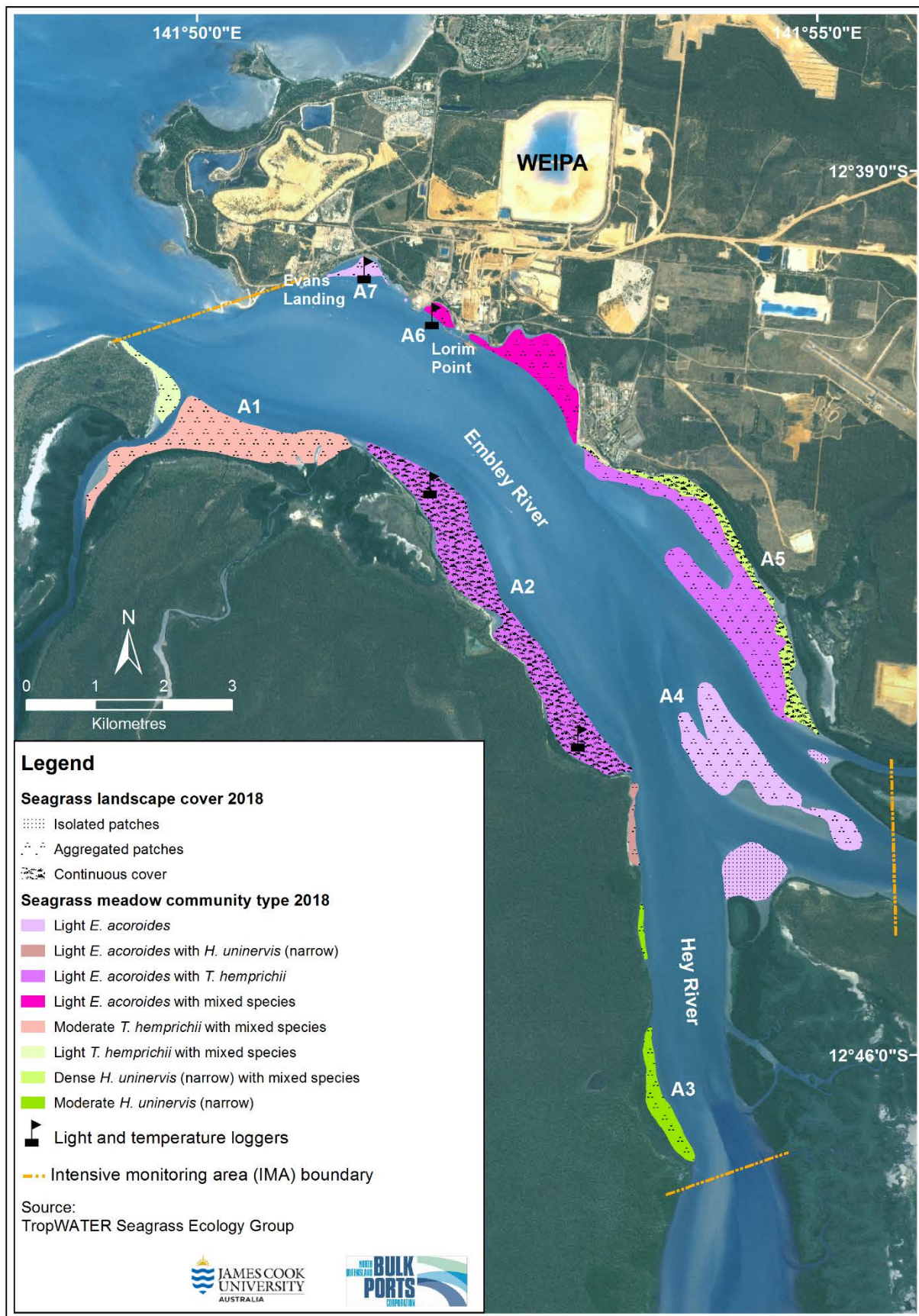


Figure 12. Percentage of sites within the IMA that have evidence of *Enhalus acoroides* burning in the Weipa IMA meadows.

Dugong feeding trails (Figure 13) are not commonly observed within the IMA having only been recorded in one previous survey in 2016 in meadows A3, A5 and the large meadow between Lorim Point and Napranum (Figure 14). In 2018 Dugong feeding trails were observed in meadow A5 and in one area of A2 (southern end) where a higher density of *H. uninervis* was recorded in the meadow. This is the first time feeding trails were observed in the A2 meadow. No dugong feeding trails were recorded in the IMA in 2017.



Figure 13. Examples of Dugong feeding trails in the A5 Weipa monitoring meadow in 2016.



3.1.2 Seagrass condition in the core annual monitoring meadows

The overall condition of seagrass monitoring meadows in Weipa was classed as good in 2018 (Table 4), similar to 2017. The last two years have been an improvement in condition from 2016 when meadows were classed as satisfactory overall. For all monitoring meadows seagrass biomass, area and species composition was in a good or very good condition, with the exception of monitoring meadow A5 and meadow A7 where area was classed as satisfactory.

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

All *E. acoroides* dominated meadows had a light seagrass cover that was continuous for meadow A2, and consisted of aggregated patches for meadows A6 and A7 closest to port infrastructure (Figure 14). *E. acoroides* maintained its dominance of the species composition for all of these meadows (Figures 16; 19; 20).

Meadow A2:

Biomass, area and species composition for meadow A2 remained in a good condition for 2018; similar to the previous two years (Figure 16). Meadow area has been at or above the long-term average for the last six years (Figure 16). Biomass has varied spatially through time, with denser patches of seagrass occurring towards the northern end of the meadow, similar to previous years (Figure 21). Dugong feeding trails were recorded for the first time in this meadow, towards its southern end where a higher density of *H. uninervis* occurred; a species often targeted by dugong. An unprecedented number of *E. acoroides* female and male flowers were seen throughout this meadow during the survey (Figure 15).



Figure 15. (a) Male *E. acoroides* flowers/pollen sacs and (b) female flowers in the A2 meadow.

Meadow A6:

Area was classed in a very good condition, while biomass and species composition was classed as being in a good condition (Table 4). A decline in seagrass area for meadow A6 (along with neighbouring meadow A7) was noted in 2015 and 2016 (Figure 19). Between 2016 and 2017 meadow area increased, leading to condition increasing from satisfactory to good. Through 2018, there was a further 14.5% increase in meadow area leading to condition increasing from good to very good (Figure 19). Biomass declined leading up to 2018, and is likely due to an increase in smaller species of seagrass contributing to the overall species composition of the meadow (Figure 19).

Meadow A7:

The area of this meadow has recovered over the last couple of years after declines that occurred through 2015 and 2016 (Figure 20). Species composition has remained very good for the past five years while biomass has varied through time (Figure 20). Between 2017 and 2018 there was a decline in biomass leading to a decrease from very good (16.61 ± 2.09 g DW m⁻²) to good condition (5.36 ± 1.13 g DW m⁻²) (Table 4; Figure

20). Most of the biomass decline occurred at the Evans Landing end of the meadow, where the meadow has become very patchy and there were also localised losses in meadow area resulting in a satisfactory score for area in 2018 (Figure 20).

***Halodule uninervis* dominated meadows (A3, A5)**

Both *Halodule uninervis* dominated monitoring meadows consisted of aggregated patches to a continuous cover of seagrass, with a moderate to dense biomass for the species (Figure 14). Both meadows had other species of seagrass in the meadows including *E. acoroides*, *Thalassia hemprichii* and *Halophila ovalis* (Figure 10). Dugong feeding trails were observed throughout Meadow A5.

Meadow A3:

The overall condition of monitoring meadow A3, in the Hey River, continued to increase from a satisfactory condition in 2016, a good condition in 2017, to a very good condition in 2018 (Table 4; Figure 17). Improved condition between 2016 and 2017 was due to an increase in area from 31.1 ± 2.2 ha to 41.0 ± 2.2 ha (Figure 17). Improved condition leading up to the 2018 survey was due to biomass and species composition returning to very good condition (Figure 17).

Meadow A5:

The overall condition of meadow A5, south of Napranum, increased from poor condition to a satisfactory condition in 2018 (Table 4; Figure 18). This improvement in condition was due the meadow recovering in area, principally at the southern end of the meadow (Figure 18). Area increased by 21% between surveys. Seagrass has fluctuated in its patchiness at the southern end of the meadow throughout the monitoring program. Biomass and species composition has remained in very good condition for at least the last four years (Figure 18).

Table 4. Grades and scores for seagrass indicators (biomass, area and species composition) for 2018 in the Port of Weipa.

Meadow	Biomass	Area	Species Composition	Overall Meadow Score
A2	0.81	0.86	0.74	0.78
A3	0.85	0.88	0.85	0.85
A5	0.93	0.58	0.97	0.58
A6	0.73	0.92	0.75	0.73
A7	0.66	0.54	0.85	0.54
Overall Score for the Port of Weipa				0.70

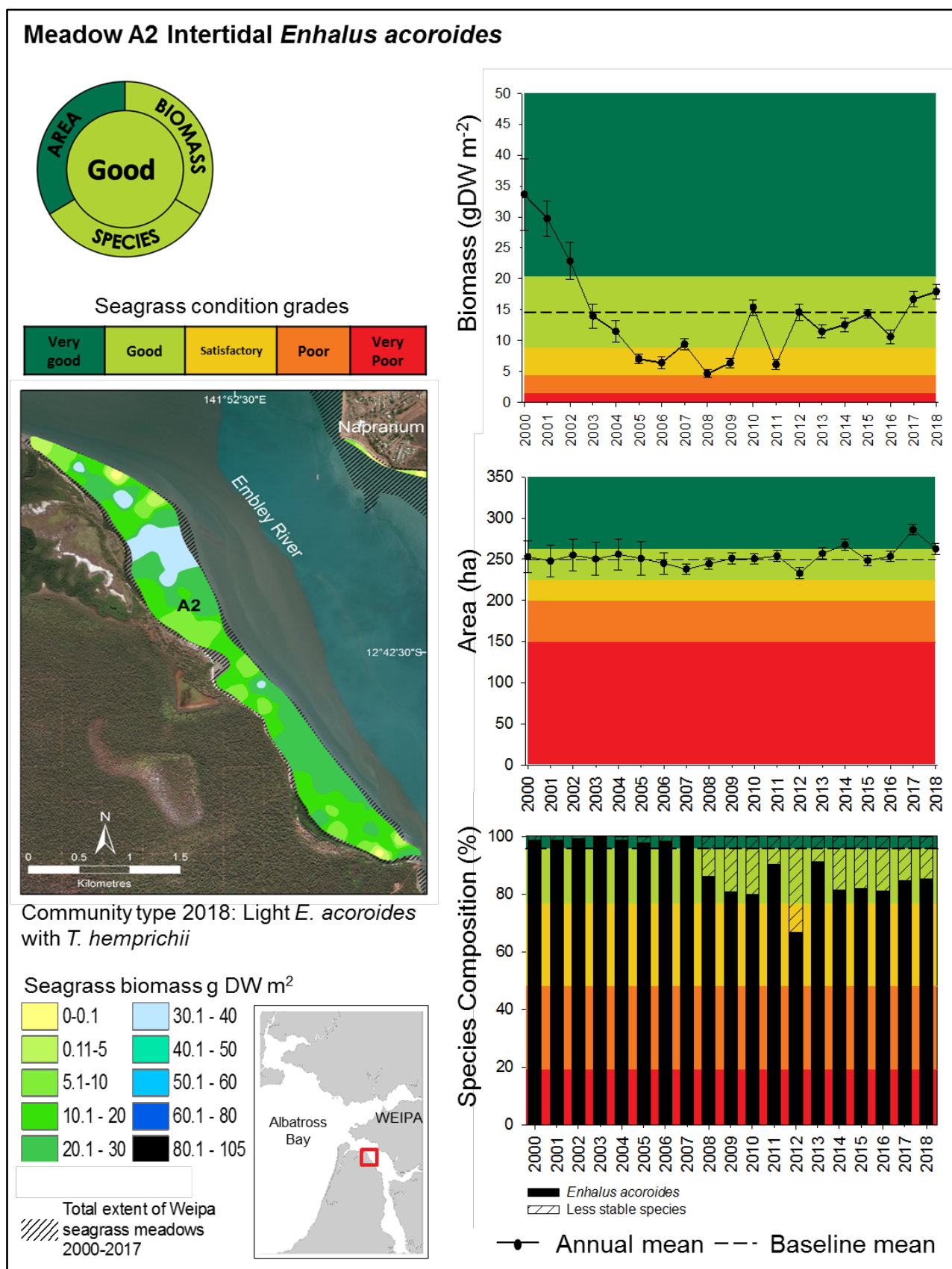


Figure 16. Changes in biomass, area and species composition for the *E. acoroides* dominated core monitoring meadow A2 in Weipa; 2000 to 2018 (biomass error bars = SE; area error bars “R”).

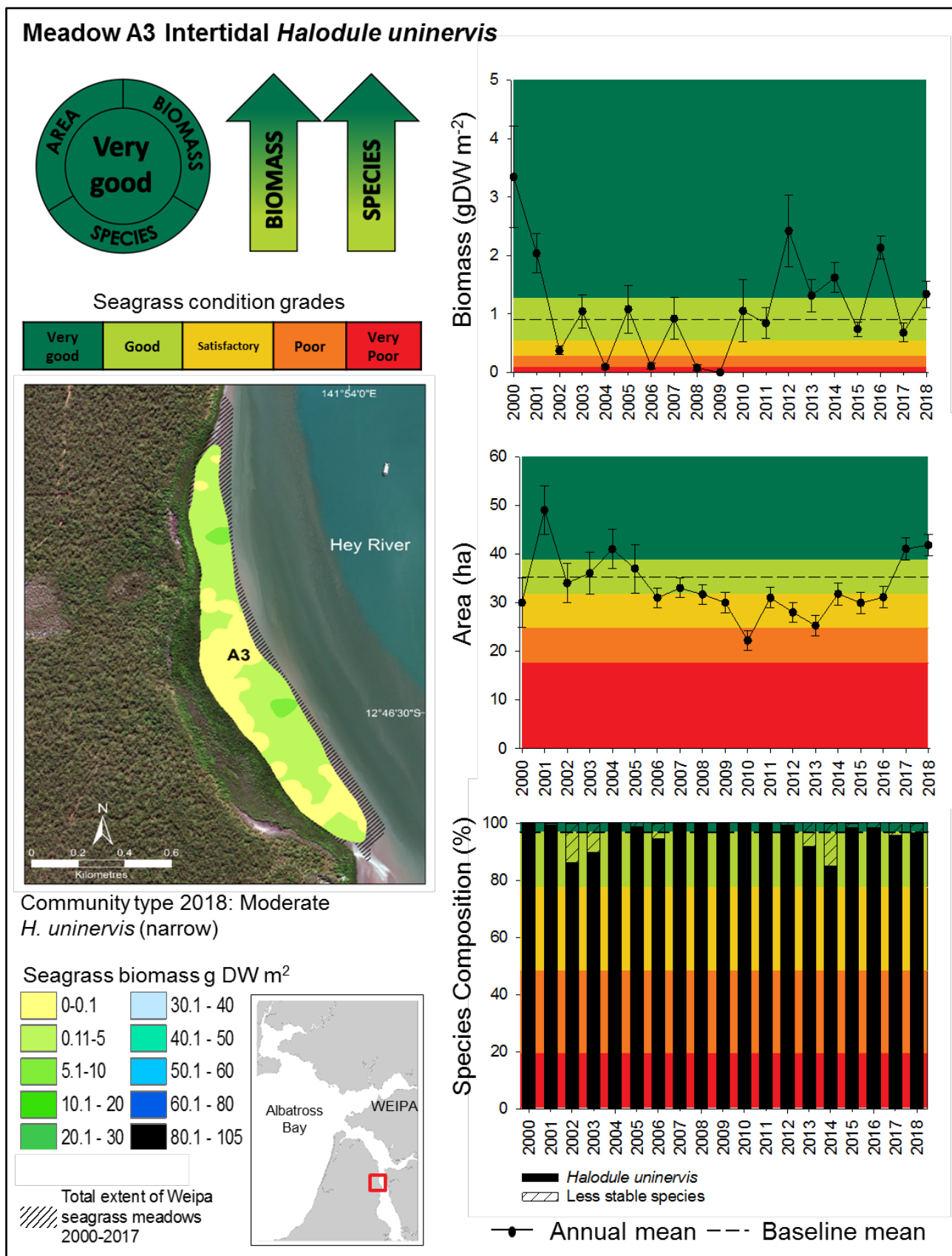


Figure 17. Changes in biomass, area and species composition for the *H. uninervis* dominated core monitoring meadow A3 in Weipa; 2000 to 2017 (biomass error bars = SE; area error bars “R”).

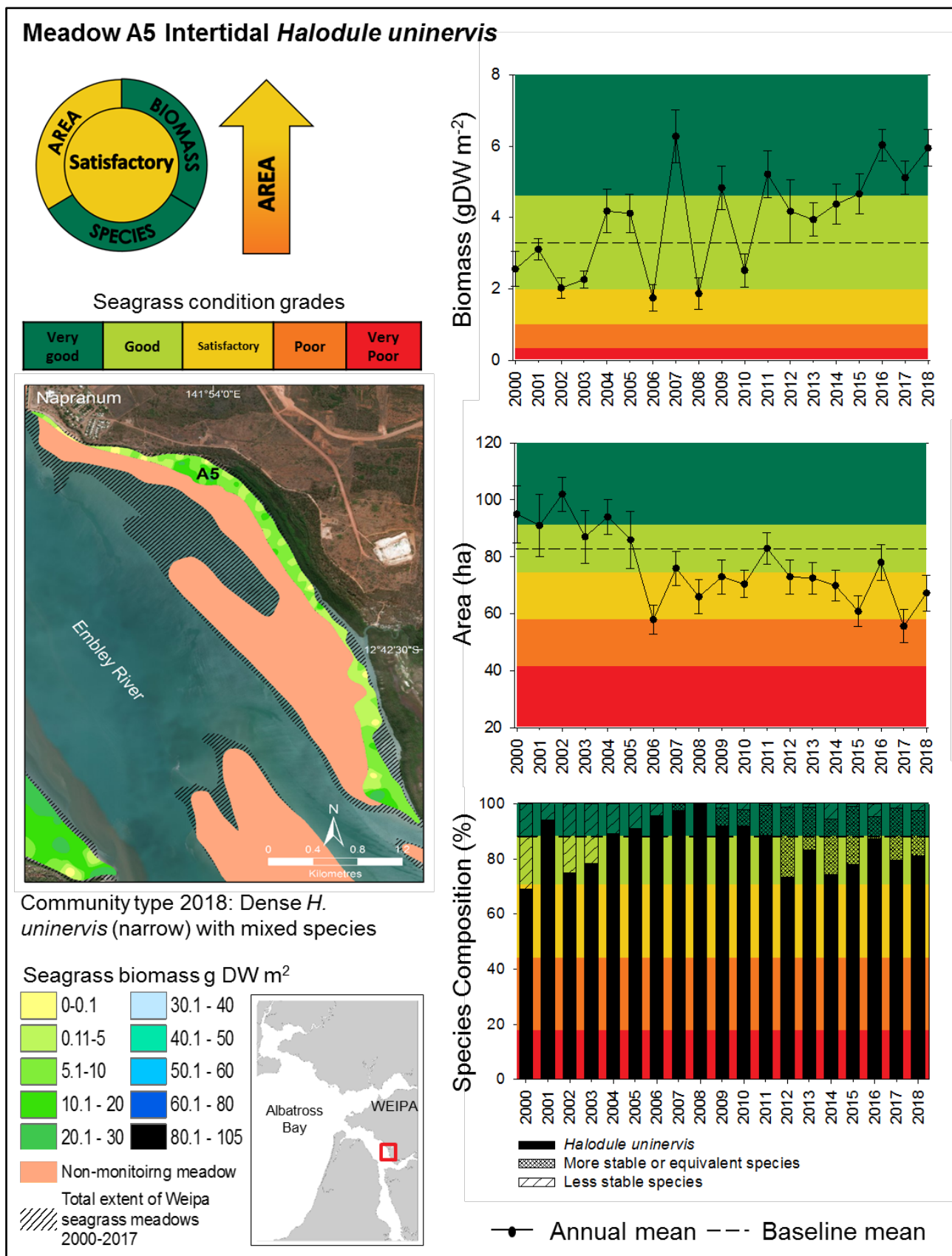


Figure 18. Changes in biomass, area and species composition for the *H. uninervis* dominated core monitoring meadow A5 in Weipa; 2000 to 2016 (biomass error bars = SE; area error bars "R").

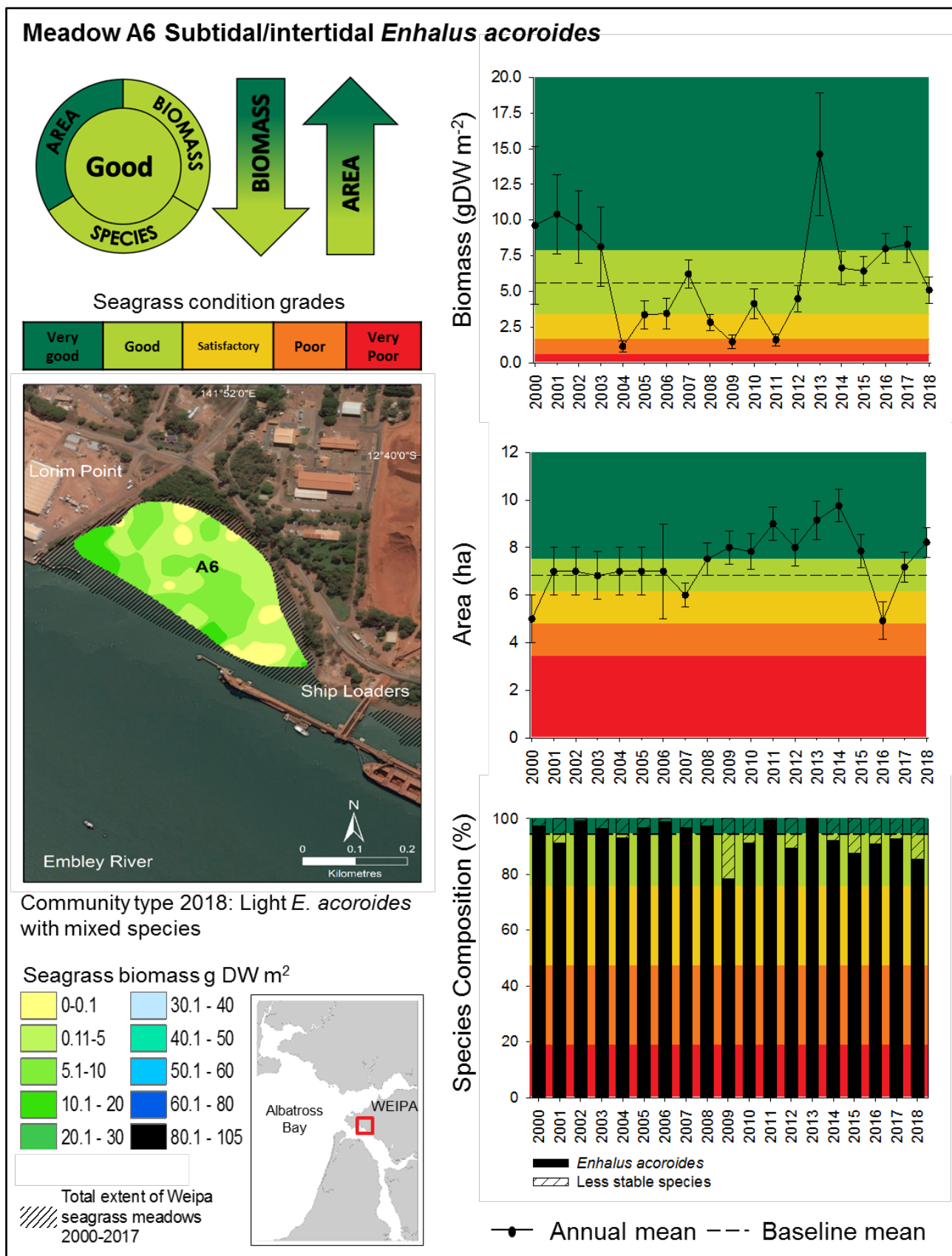


Figure 19. Changes in biomass, area and species composition for the *E. acoroides* dominated core monitoring meadow A6 in Weipa; 2000 to 2018 (biomass error bars = SE; area error bars "R").

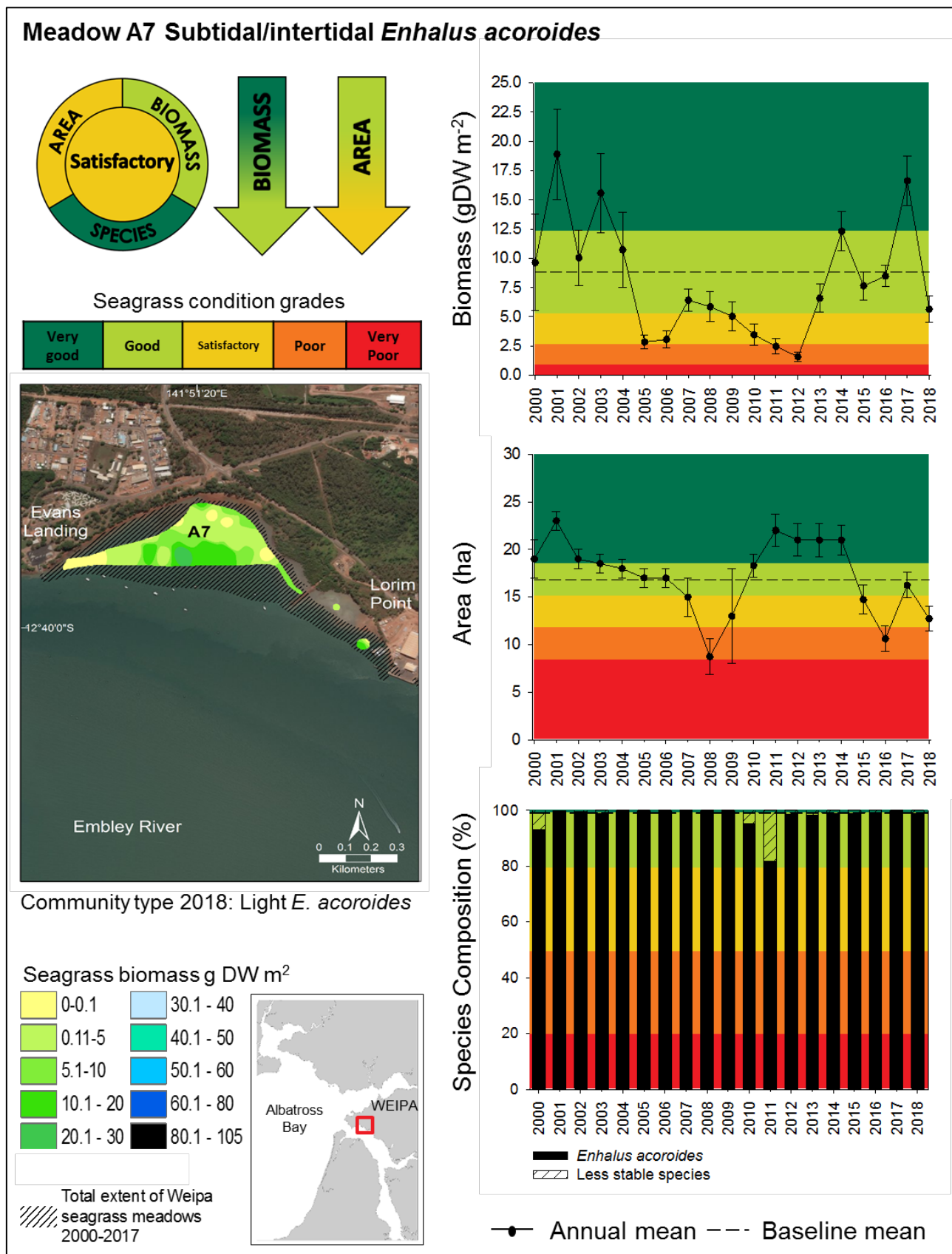


Figure 20. Changes in biomass, area and species composition for the *E. acoroides* dominated core monitoring meadow A7 in Weipa; 2000 to 2017 (biomass error bars = SE; area error bars “R”).

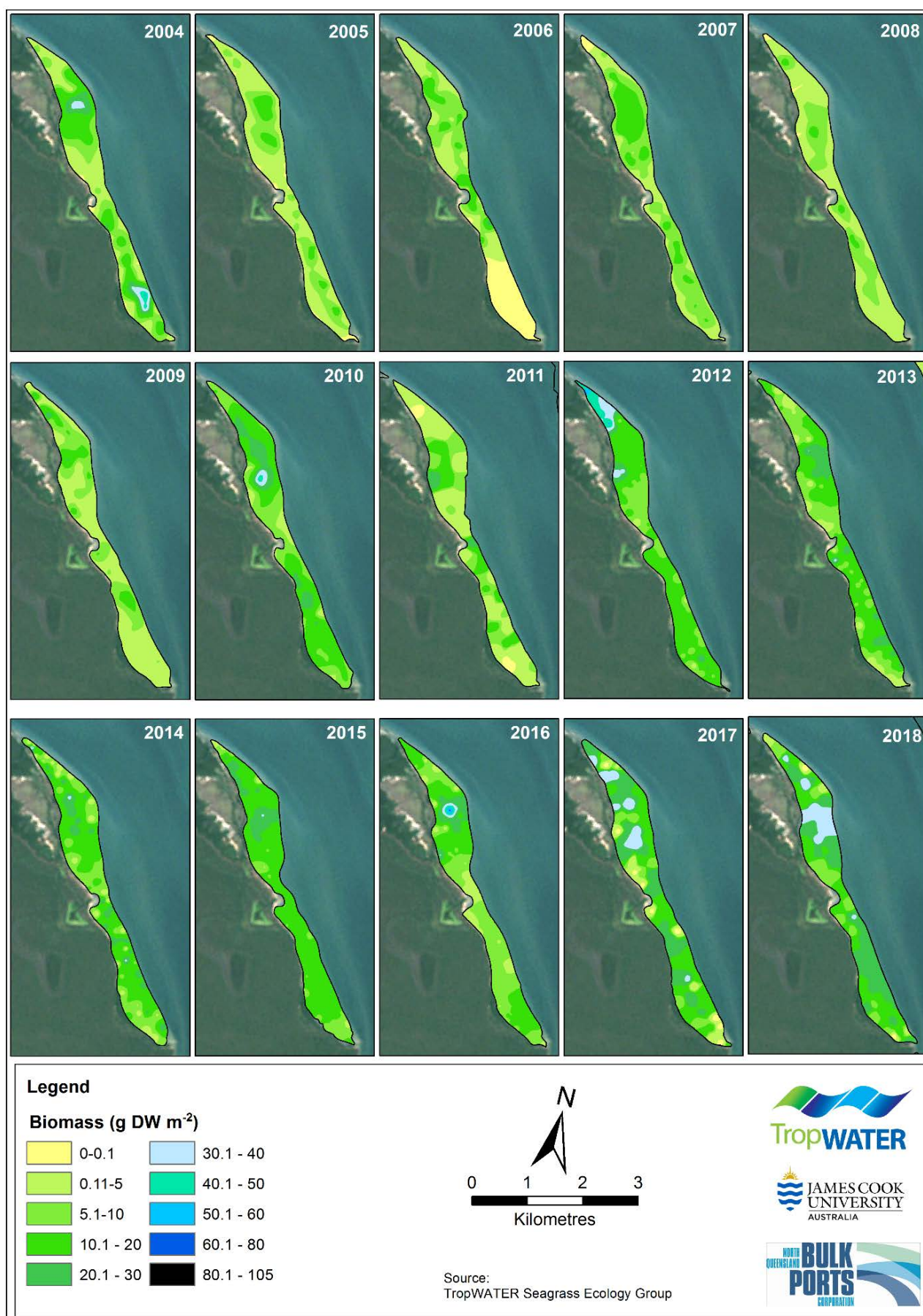


Figure 21. Seagrass biomass changes in the A2 monitoring meadow; 2004-2018.

3.2 Weipa climate data

3.2.1 Rainfall

Total annual rainfall in Weipa (2017/18) was 1714 mm and has been below the long-term average for the last four years (Figure 22a). Rainfall followed similar wet season trends leading up to the annual survey, with January having the highest rainfall of 704 mm (Figure 22b). January rainfall was the only month that exceeded the historical monthly long-term average (Figure 22b). Between May and August 2018 only 2.0 mm of rainfall was recorded (Figure 22b).

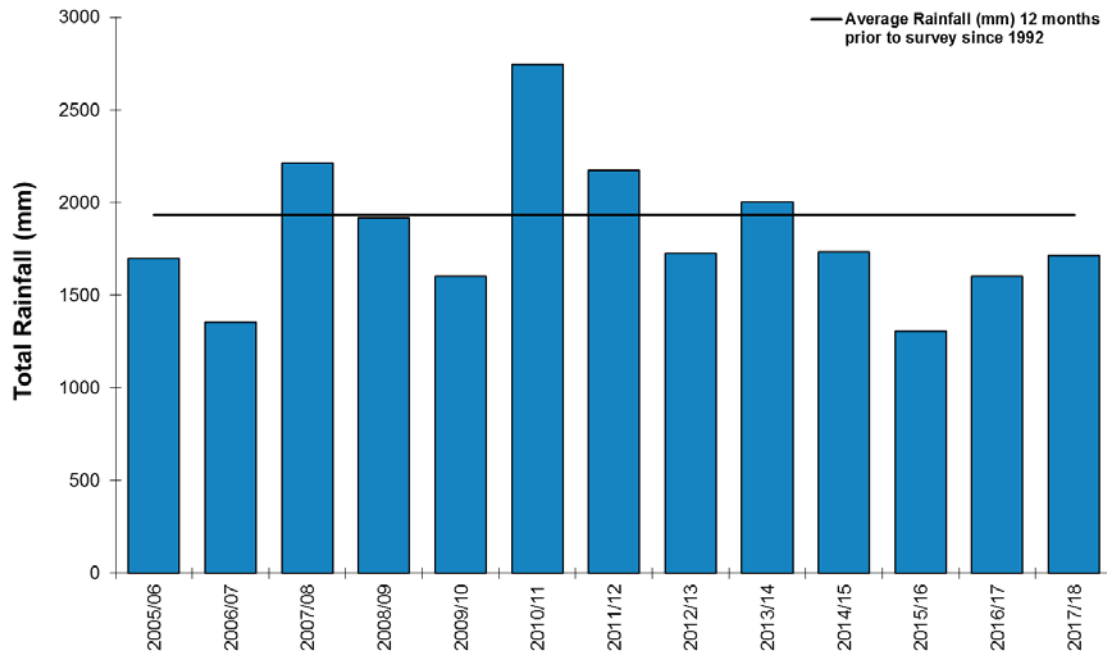


Figure 22a. Total annual rainfall recorded at Weipa Airport; 2005-2018. Data is twelve months prior to survey.

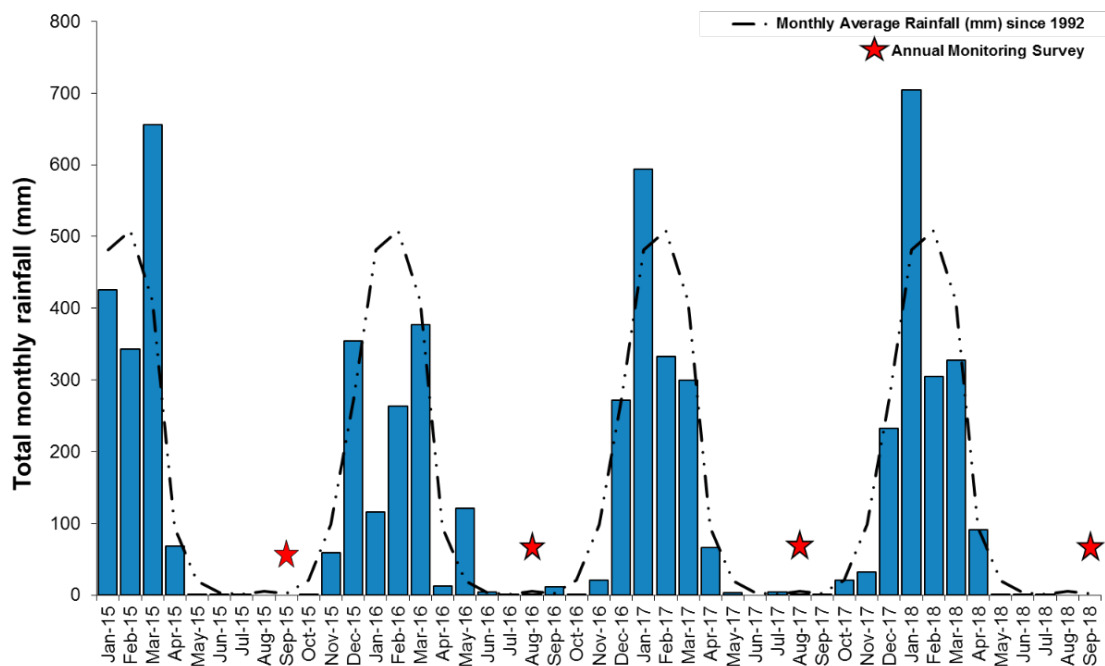


Figure 22b. Total monthly rainfall (mm); January 2015 – September 2018.

3.2.2 Daytime tidal exposure

The amount of tidal exposure to daytime air for intertidal meadows in the twelve months prior to survey (327 hours) was below the long-term average (Figure 23a). Daytime tidal exposure has been below or similar to the long-term average since 2008/09 (Figure 23a). Intertidal seagrass meadows generally 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 23b). In the critical times closer to the monitoring survey daytime tidal exposure, one month and three months prior to the 2018 survey was also below the long-term average (Figure 23c). One month and three month tidal exposure values have been below the respective long term average for the last three years (Figure 23c)

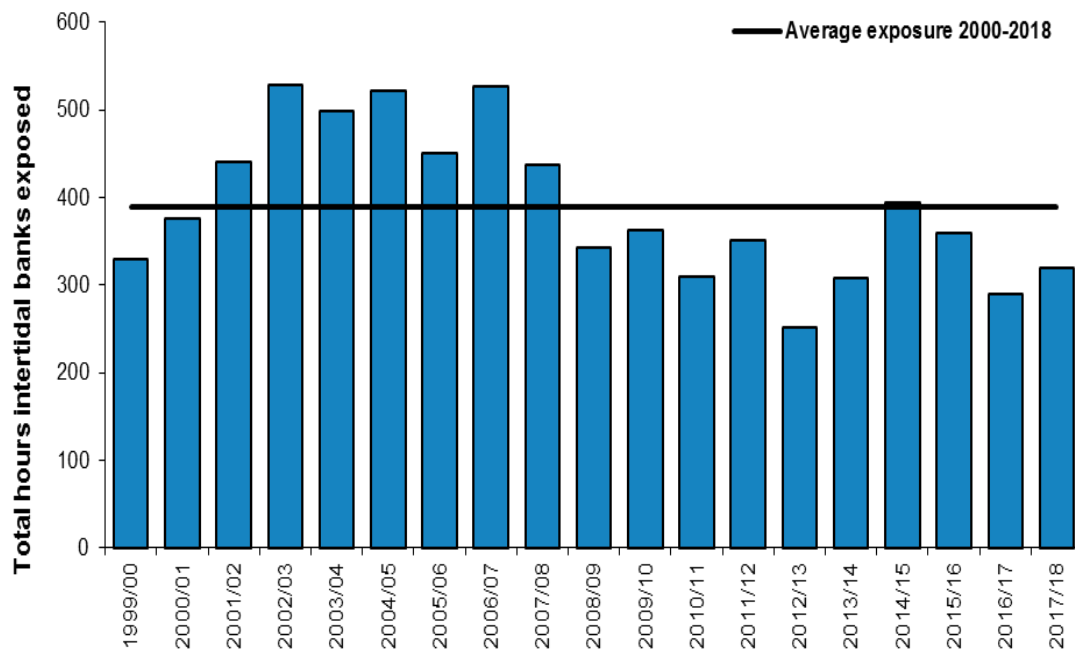


Figure 23a. Total daily tidal exposure to air 1999/00 -2017/18. Data is twelve months prior to survey.

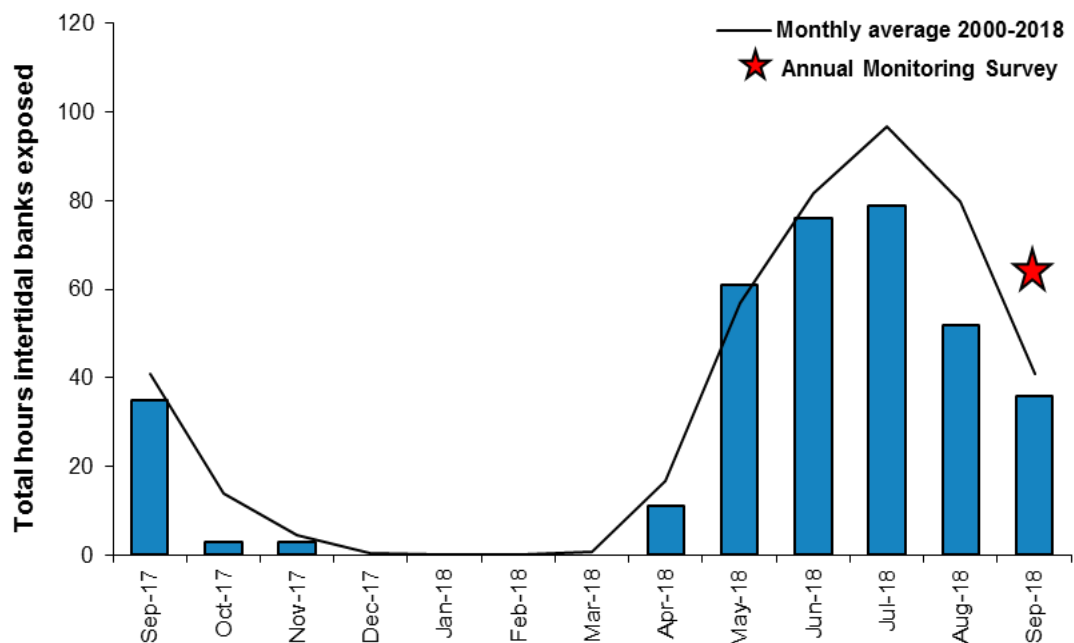


Figure 23b. Monthly total daytime tidal exposure to air (hours; $\leq 0.9\text{m}$ tidal height); September 2017 – September 2018.

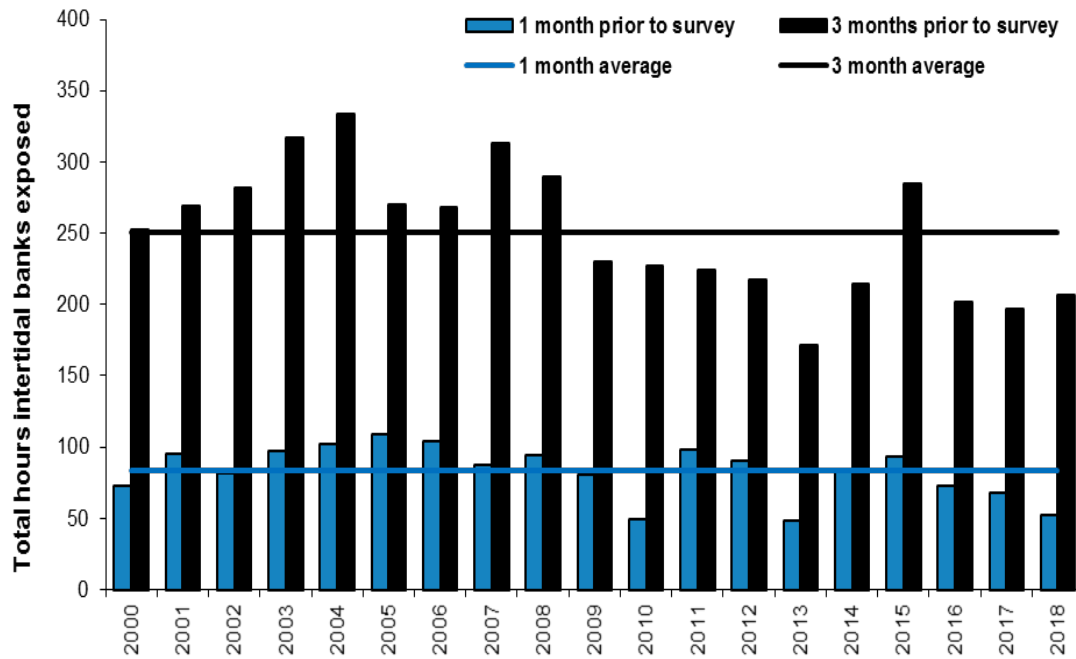


Figure 23c. Total daytime tidal exposure to air (hours; ≤0.9m tidal height) 1 and 3 months preceding each survey; 2000-2018.

3.2.3 Solar Radiation

Daily global solar exposure (megajoules per square metre) is a measure of the total amount of solar energy falling on a horizontal surface in one day. Values are highest in clear sun conditions and lowest on cloudy days and typically range between 1 to 35 MJ/m². Mean daily solar exposure has been increasing above the long-term average over the last four years (Figure 24). 2017/18 recorded the highest solar exposure since 2012/13 (Figure 24).

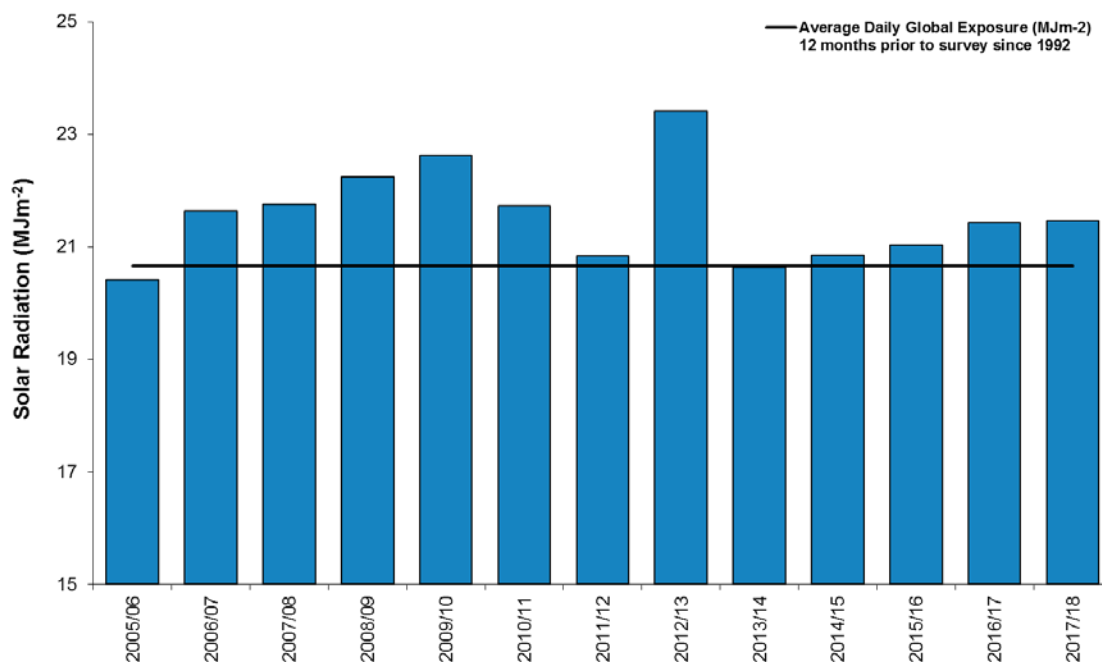


Figure 24. Average annual solar radiation (MJ/m²) for the 12 months preceding each survey; 2005/06 – 2017/18. Data is twelve months prior to survey.

3.2.4 Benthic daily Photosynthetically active radiation (PAR (light)) and temperature

Total daily PAR is measured at two locations in the shallow intertidal meadow on the south-western bank of the Embley River (A2), and in the deeper meadows between Evans Landing and Lorim Point (meadows A6 and A7) (Figure 14). The A6 logging station was established in 2017 and preliminary data from that site indicated the placement of the loggers was not in a suitable place for meaningful light recordings. The logging station was relocated to a more appropriate position in September 2018; as such, data for A6 has not been included in this annual report.

PAR was less in the deeper meadow (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;

- Control logger (above water): 2.38 to 45.10 mol m⁻² day⁻¹;
- A2 intertidal meadow: 0.03 to 36.45 mol m⁻² day⁻¹ (Figure 25 a & b);
- A7 intertidal/subtidal meadow: 1.38 to 18.01 mol m⁻² day⁻¹ (Figure 25c).

While no specific light requirement growth thresholds for *E. acoroides* have been developed, it is likely that both *E. acoroides* and *H. uninervis* require at least 5 mol m⁻² day⁻¹ over an integration time of 14 days (Collier et al. 2016) to maintain effective growth as an acute management trigger. For the long-term maintenance of seagrass, they may need as much as ~10-13 mol m⁻² day⁻¹ (Collier et al. 2016). The longest ongoing integration period (14-day rolling average) that PAR fell below the acute threshold suggested in Collier et al. (2016) (5 mol m⁻² day⁻¹) during 2018 was:

- 72 consecutive days in the shallow intertidal A2 meadow (Figure 25a & b – Figure 27). These extended low light periods coincided with wet season/high rainfall weather between January and March 2018 (Figure 22a & b).
- Over 100 consecutive days in the deeper A7 meadow between December and April 2018 (Figure 25c & d; Figure 26), also coinciding with wet season/high rainfall in the region.

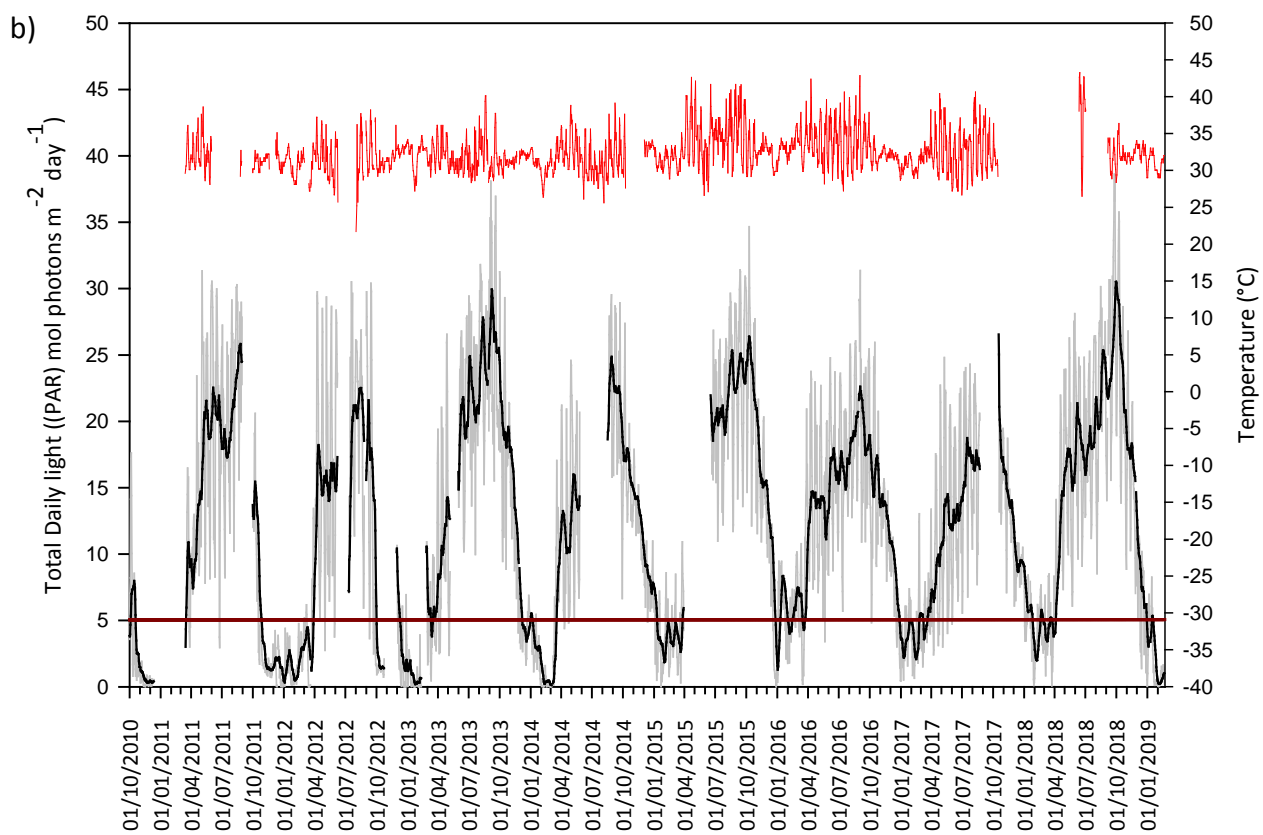
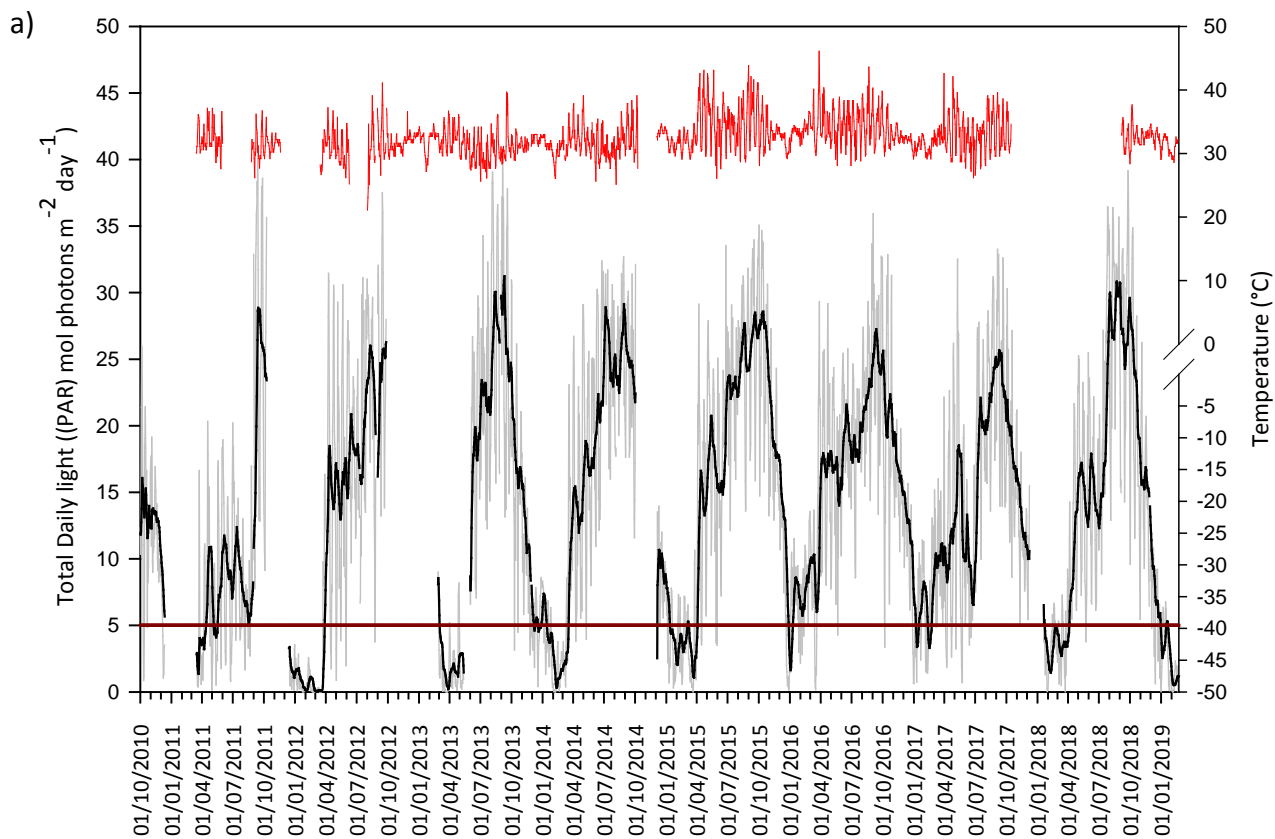
The last time the A2 meadow had such extended low light conditions was the 2015 wet season (January – March 2015); 76 consecutive days (Figures 25a & b – Figure 27).

3.2.5 Water temperature

In 2018, we transitioned the temperature data loggers from Thermodata® iBTag submersible loggers to widely used Bluetooth HOBO® data loggers. The HOBO® loggers did not perform well Weipa, often being destroyed by animals (mud crabs suspected) causing water inundation and resulting in data loss. We re-deployed iBTag temperature loggers in September 2018, and have been collecting complete data sets since the iBTag's were re-deployed.

For the temperature data available in the twelve months prior to the survey, the overall water temperatures at the seagrass meadows in 2018 remained similar to the previous two years (Figure 25a-c). Mean and maximum daily water temperature at the sites was (Figures 25a-c):

- A2 meadow:
 - Mean daily water temperature: 28.2 °C for the northern site and 27.6 for the southern site;
 - Maximum daily water temperature: peaked at over 40 °C and was sustained for a least three consecutive days in the intertidal A2 meadow on two separate occasions in June 2018.
- A6 & A7 meadows:
 - Mean daily water temperature: 28.5 °C and 28.4 °C respectively;
 - Maximum daily water temperature: The highest maximum temperature recorded in the twelve months prior to survey was 41.6 °C, with temperatures over 35 °C sustained for three days in June 2018.



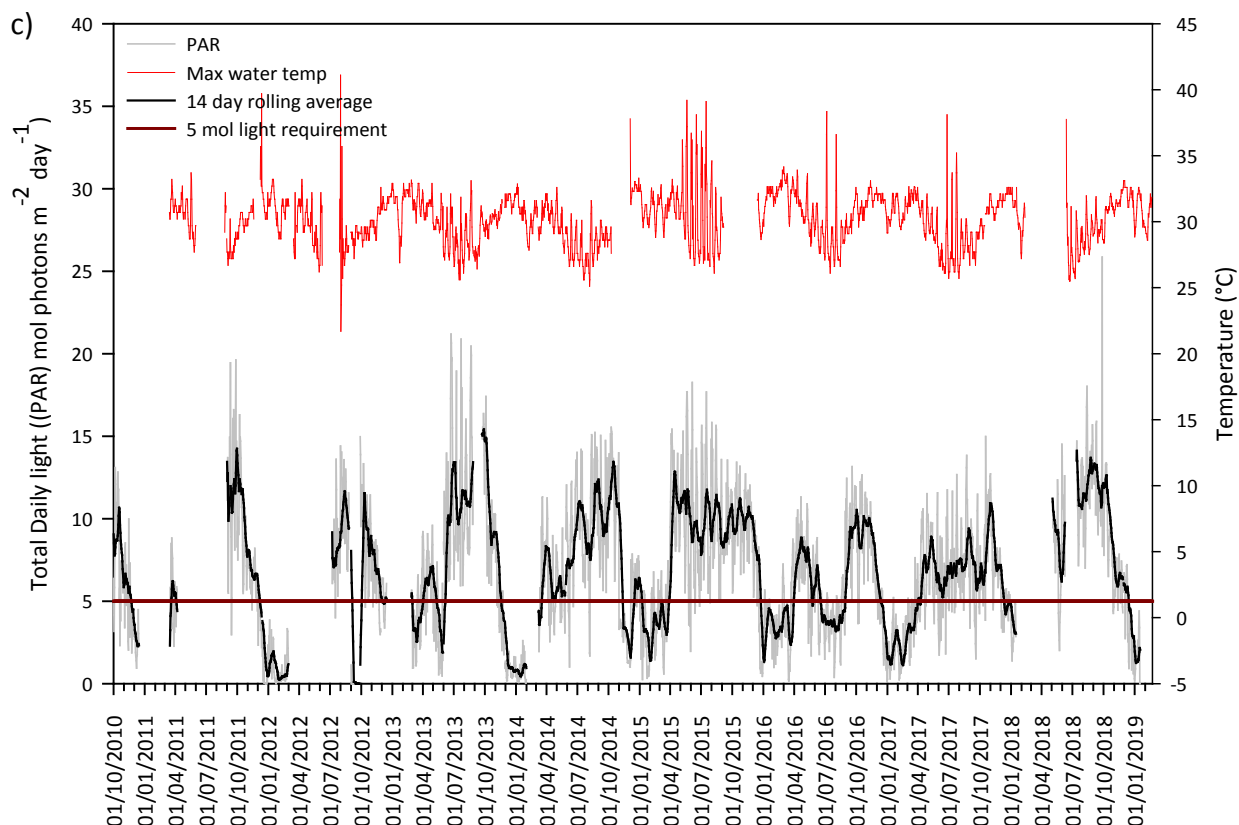


Figure 25. Daily photosynthetically active radiation (PAR mol photons $\text{m}^{-2} \text{day}^{-1}$), 14-day rolling average, 5 mol light threshold, and mean maximum daily water temperature ($^{\circ}\text{C}$) at Weipa; 2010 – 2018, at meadow A2 (a & b) and meadow A7 (c)

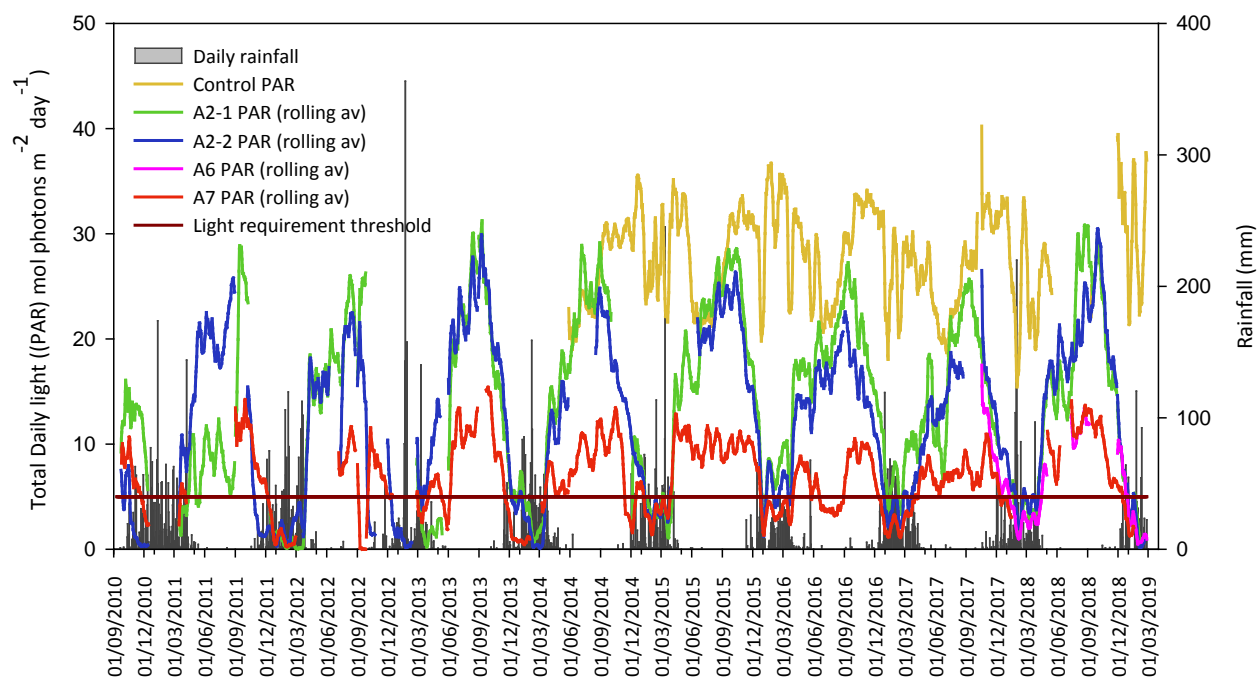


Figure 26. Daily photosynthetically active radiation (PAR; mol photons $\text{m}^{-2} \text{day}^{-1}$) and total daily rainfall (mm) at Weipa; October 2010 – October 2017, at Meadow A2 northern (A2-1) and southern (A2-2), Meadow A7, control logger and preliminary data from Meadow A6.

3.3 Light (PAR) and intertidal seagrass change

Quarterly seagrass assessments in Meadow A2 were incorporated into the established PAR and temperature program in 2015 to track the persistent species *E. acoroides* in relation to light levels. In 2018, quarterly assessments were conducted in January, May, July and September and November. Seagrass biomass ranged from 15.49 ± 0.93 g DW m⁻² to 25.35 ± 2.07 g DW m⁻² (Figure 27). Since quarterly biomass monitoring has been established, there have been some variations in biomass; however, there seems to be little impact from periods of natural wet season low light levels on *E. acoroides* in the intertidal A2 meadow. PAR on the intertidal A2 meadow has followed ‘typical’ patterns of high and low light levels during dry and wet seasons, and tidal exposure (Figure 27). As mentioned above, during each wet season PAR reaches very low levels and fell below 5 mol m⁻² day⁻¹ (light threshold) for up to 72 consecutive days between January and March 2018 in the A2 meadow. However, *E. acoroides* in intertidal meadows appears to have a good capacity to resist these wet season low light periods, with biomass being maintained at similar pre-wet season levels following these low light events (Figure 27).

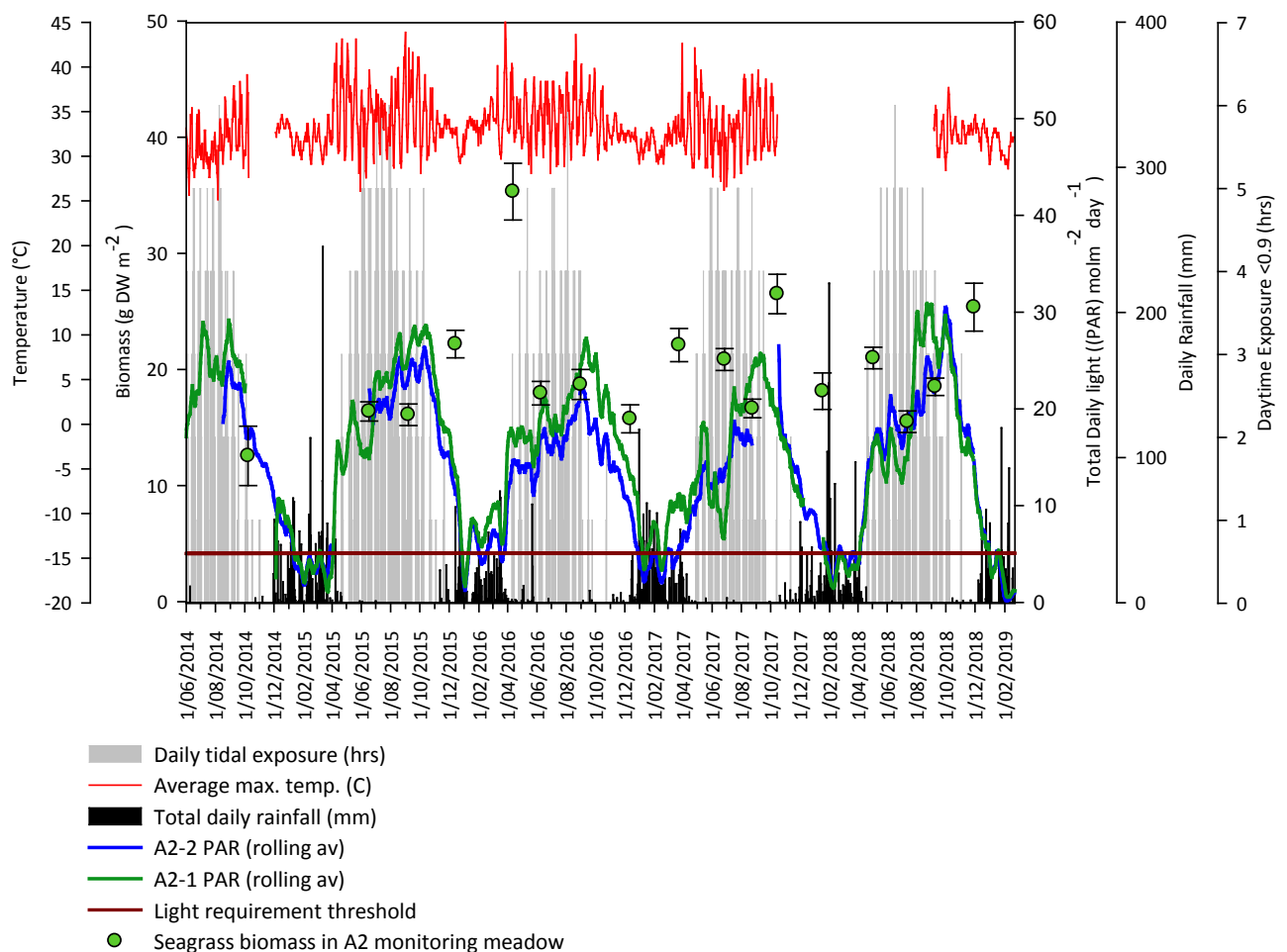


Figure 27. Total daily light (14 day rolling average (PAR; mol photons m⁻² day⁻¹)), seagrass biomass (g dw m⁻²), maximum sea temperature within the seagrass canopy (°C), total daily rainfall (mm) and total daily hours intertidal banks are exposed to air (hrs) in Weipa June 2014 – February 2019 in the A2 intertidal monitoring meadow.

4 DISCUSSION

Seagrasses in the Port of Weipa were in an overall good condition in 2018. Seagrasses maintained an extensive footprint in the region closest to the port (IMA) with total area one of the highest recorded during the 19 year monitoring program history. The species composition of meadows was maintained with the expected mix and dominance of foundation species occurring. While area and biomass of individual meadows varied all were maintained at levels rated between very good and satisfactory compared with their long-term baseline history. The presence of dugong feeding trails in meadows and extensive flowering of seagrass recorded during the survey were further signs of a healthy and productive seagrass ecosystem in 2018.

Results of the 2018 seagrass survey suggests that Weipa's seagrass meadows were likely to have a high level of resilience to impacts and stress at the end of 2018. As such they are likely to be resilient to annual maintenance dredging during 2019, assuming the duration of dredging remains relatively short and that there are no major seagrass losses associated with climate or other impacts leading up to the 2019 maintenance dredging campaign. However, since the completion of the 2018 survey, Weipa has experienced several weather events during early 2019 including Tropical Cyclone (TC) Penny and high rainfall associated with ex TC Oma that had the potential to impact on seagrass condition. Previous experience from the monitoring program has shown that generally seagrasses have been able to persist in Weipa following weather events but a closer examination of seagrass condition may be warranted in early 2019 to ensure they have been able to maintain their condition. NQBP have committed to an additional seagrass assessment in May 2019 to check on the status of seagrasses post wet-season to assist in informing potential management actions should they be required. Results of this survey will be provided to NQBP shortly after the survey has been completed.

In 2017, the seagrass meadows between Evans Landing and Lorim Point (Meadows A6 & A7) had recovered from localised declines recorded leading up to 2016 (McKenna et al. 2017). Additional interim monitoring of these meadows conducted in May and June 2017 showed improvements in seagrass had started to occur, and by the annual monitoring in August 2017 seagrass had recovered. Light levels at the monitoring station within this region (meadow A7) during 2016 revealed an unusual period of low light in the dry season (McKenna et al. 2017), which was the likely cause of the observed declines in seagrass area. This low light period was only recorded locally at this station, and while the exact cause of the decline in benthic light in the affected area is unclear, there were a range of activities and events in this area of the port that had the potential for short term impacts on local water quality. These included:

- Development of the new recreational boat ramp at Evans Landing;
- Expansion of the Humbug Terminal for a roll on/roll off barge facility to service the Amrun project;
- Increased localised boating/barge activity;
- Temporary issues with sewerage treatment discharge adjacent to the meadows.

In 2018 the seagrass recovery for these meadows had been largely sustained with only a small area of meadow A7, closest to the Evans Landing boat ramp, reducing between surveys. Despite this very localised decline, the meadow stayed in a satisfactory condition overall. This suggests there may be a very local impact to seagrass occurring in this area as overall light and climate conditions have remained favourable for seagrass growth in 2018, and seagrass in other sections of the meadow seem unaffected.

Light is one of the primary drivers of seagrass condition and resilience (Dennison et al. 1993; Collier et al. 2012; Petrou et al. 2013; Collier and Waycott 2014; Chartrand et al. 2017). The availability of light limits their spatial and temporal distribution, and light limitation can drive seagrass loss (Collier et al. 2012; Rasheed et al. 2014; Chartrand et al. 2017). While critically important, the knowledge of how much light different seagrass species require to maintain their growth and reproductive requirements, and how this requirement varies seasonally is limited for many tropical species. This lack of specific knowledge extends to the dominant large growing species in Weipa, *Enhalus acoroides* (Collier et al. 2016). Results of the quarterly seagrass monitoring in Weipa have found *E. acoroides* appears adapted to cope with several weeks and up to two and a half months of extremely low light levels during high rainfall and river flow events during the wet season months, with seagrass biomass remaining relatively stable. This suggests that natural periods of low light are generally not low enough or sustained long enough to considerably degrade *E. acoroides*, a persistent species

that has a large storage of carbohydrate energy reserves in below ground structures (Kilminster et al. 2015). While seemingly being able to resist extended periods of low light during the wet season, the losses of *E. acoroides* that occurred in 2015 and 2016 between Evans Landing and Lorim Point, when there were additional uncharacteristic localised reductions in light during the dry season, show that the species can be vulnerable. Particularly when there are multiple occurrences of sustained low light within a year. It is likely that *E. acoroides* is relying on the generally good light conditions that typically occur in the dry season to recover their energy reserves and resilience each year.

Through 2017 and 2018 light in the Weipa area, particularly between Evans Landing and Lorim Point, returned to a more normal range and was once again consistent with light trends in the broader port. Other environmental conditions that can effect seagrass growth were also generally favourable in the twelve months prior to the survey and likely contributed to the sustained good condition of seagrass in the Weipa area. Tidal exposure was below average, likely reducing air exposure stress including “burning” of seagrass leaves that has been observed in the region previously during the monitoring program and led to seagrass declines (Unsworth et al. 2012). Below average rainfall also likely contributed to the light environment for seagrasses being above requirements for the majority of the year, and there were no major storms or cyclones that impacted the area in the twelve months leading up to the 2018 survey.

Similar seagrass monitoring to the Port of Weipa is conducted to the north in the Torres Strait (Carter et al. 2018; McKenna et al. 2018) and further south in the Gulf of Carpentaria around Karumba (Van de Wetering et al. 2019). Seagrasses in the Torres Strait were in a similarly good condition to those in Weipa in 2018 (McKenna et al. 2018). However to the south in Karumba, seagrasses were impacted by flooding associated with TC Nora in 2018 and for the first time in fifteen years declined from very good/good to a satisfactory condition, illustrating the effect that large weather events can have on seagrass condition. Along the eastern coast of Queensland there is still a general trend of recovery in seagrass meadows since large scale losses of seagrasses occurred in the years leading up to 2011, associated with extended La Niña climate conditions and severe storms.

The persistent occurrence of seagrass in the Port of Weipa is a reflection of the resilience of seagrasses in the region to periodic low light, tidal exposure and ‘typical’ port activities such as maintenance dredging. While generally resilient, previous localised declines of some meadows, and large losses of seagrasses in nearby regions in response to climate events illustrate the potential of this resilience to be eroded. The Weipa seagrass monitoring program provides a timely assessment of current seagrass condition to ensure the continued health of this important habitat and an excellent indicator of overall marine environmental health in the port.

5 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 $\geq 80\%$ 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.


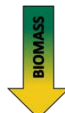
Table A1. Coefficient of variation (CV; %) thresholds used to classify historical stability or variability of meadow biomass, area and species composition.

Indicator	Class			
	Highly stable	Stable	Variable	Highly variable
Biomass	-	$< 40\%$	$\geq 40\%$	-
Area	$< 10\%$	$\geq 10, < 40\%$	$\geq 40, < 80\%$	$\geq 80\%$
Species composition	-	$< 40\%$	$\geq 40\%$	-

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
		<div> <div>Increase above threshold from previous year</div> <div>  </div> <div>Decrease below threshold from previous year</div> <div>  </div> </div>				

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 2017 values against meadow-specific thresholds for each grade, then scaling biomass, area and species composition values against the prescribed score range for that grade.

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

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 report card.

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

Where species composition was determined to be anything less than in “perfect” condition (i.e. a score < 1), a decision tree was used to determine whether equivalent and/or more persistent species were driving this grade/score (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).

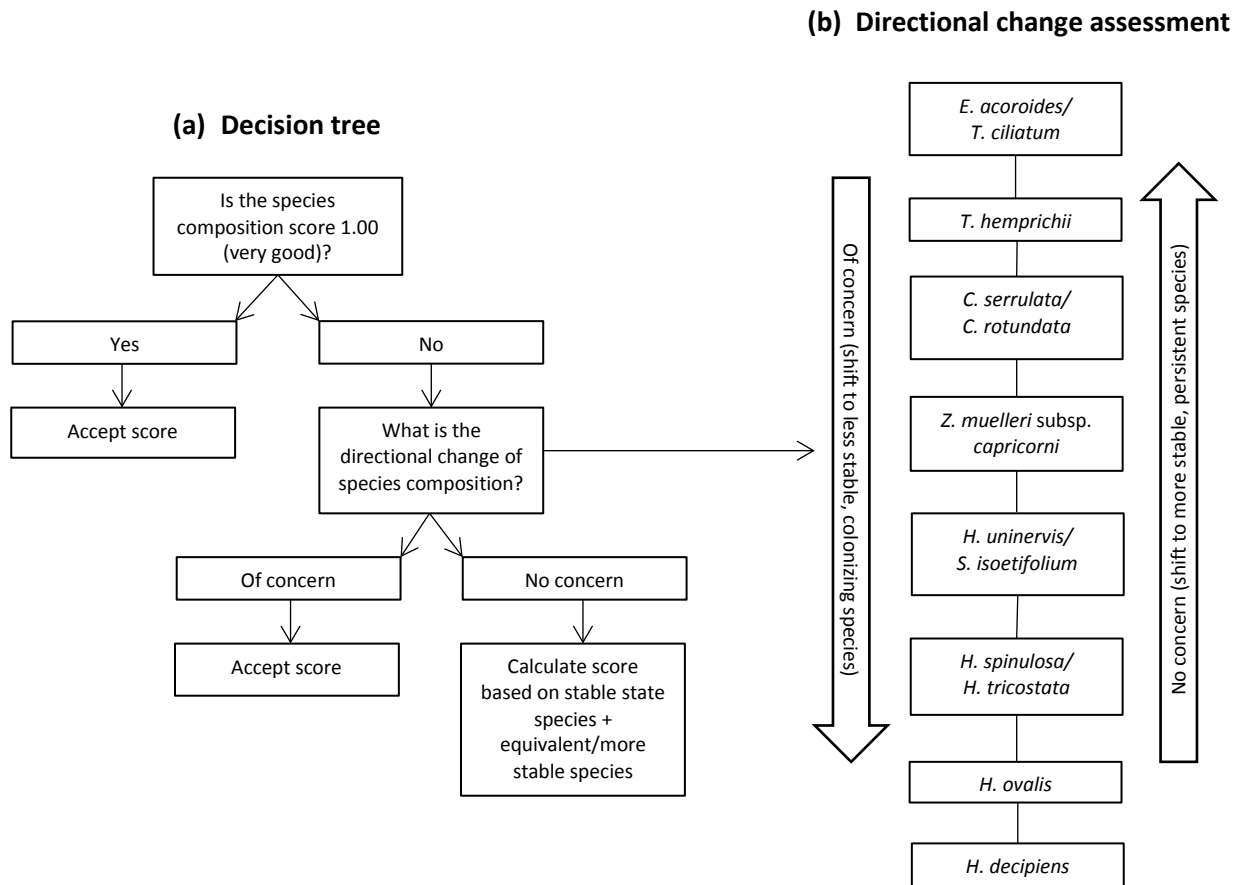


Figure A1. (a) Decision tree and (b) directional change assessment for grading and scoring species composition in the Port of Weipa.

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. 2014b).

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

The change in weighting approach for species composition was tested across all previous years and meadows in 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:

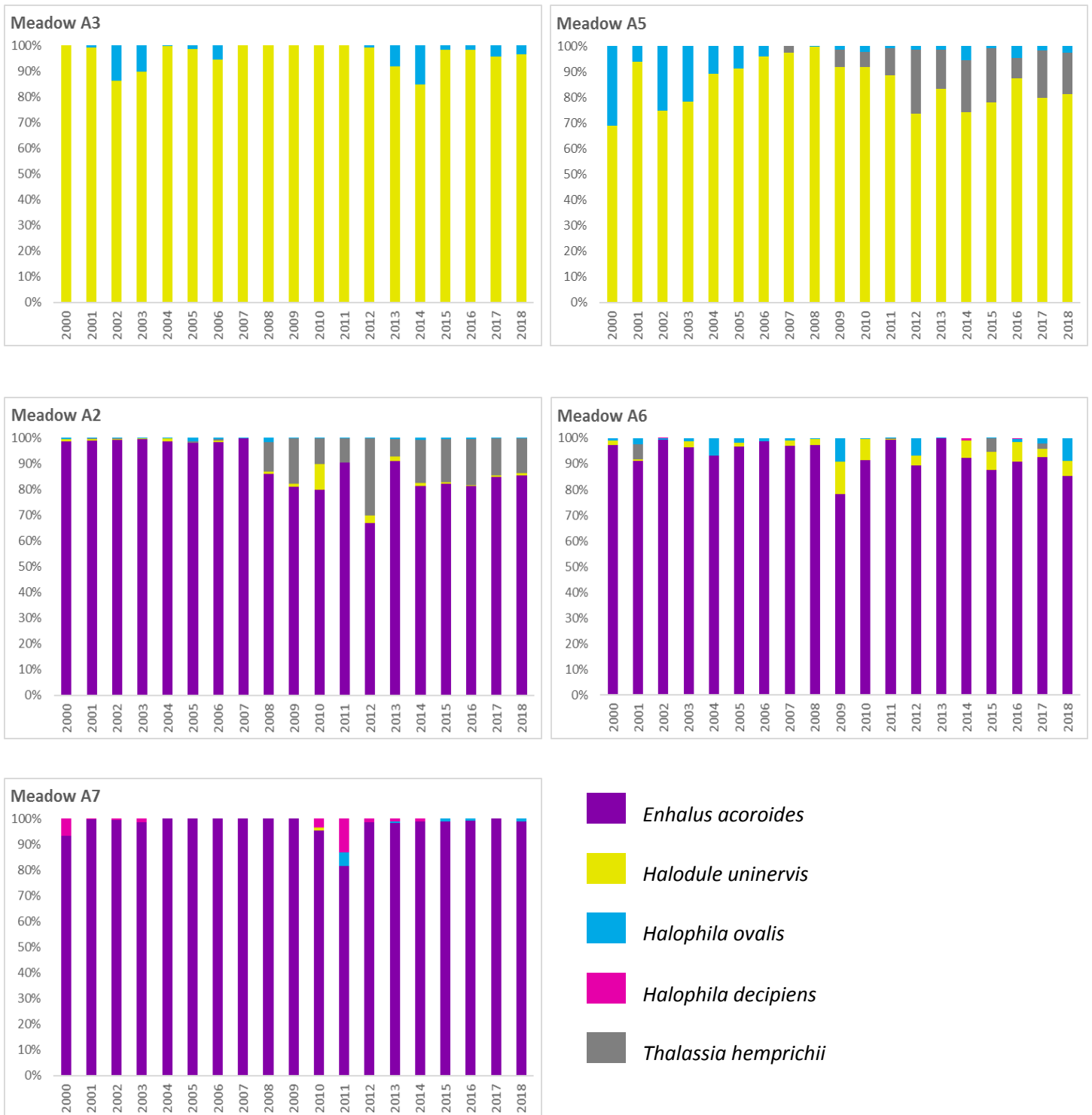
$$B_{prop} = \frac{B_{diff}}{B_{range}}$$

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 – 2018.



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 – 2018.

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	Sep-10	Aug-11	Aug-12	Sep-13	Aug-14	Sept-15	Aug-16	Aug-17	Sept-18
A2 Intertidal <i>Enhalus</i> 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)
A3 Intertidal <i>Halodule</i> 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)
A5 Intertidal <i>Halodule</i> 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)
A6 Intertidal/ subtidal <i>Enhalus</i> 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)
A7 Intertidal/ subtidal <i>Enhalus</i> 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)

Appendix 4. Meadow above-ground biomass and area

Total meadow area \pm R (ha) for each core monitoring meadow within the Port of Weipa, 2000 – 2018.

Monitoring Meadow	Total meadow area \pm 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
A2 Intertidal <i>Enhalus</i> dominated	253.0 \pm 19.0	248.0 \pm 19.0	255.0 \pm 19.0	250.4 \pm 19.7	256.0 \pm 19.0	251.0 \pm 20.0	245.0 \pm 13.0	238.0 \pm 6.0	244.5 \pm 6.6	251.0 \pm 7.0	250.7 \pm 6.5	254.0 \pm 6.5	233.0 \pm 7.0	256.9 \pm 6.6	267.7 \pm 6.5	248.3 \pm 6.5	253.59 \pm 6.56	285.82 \pm 6.51	262.63 \pm 6.62
A3 Intertidal <i>Halodule</i> dominated	30.0 \pm 5.0	49.0 \pm 5.0	34.0 \pm 4.0	36.1 \pm 4.3	41.0 \pm 4.0	37.0 \pm 5.0	31.0 \pm 2.0	33.0 \pm 2.0	31.7 \pm 2.0	30.0 \pm 2.1	22.2 \pm 2.1	31.0 \pm 2.1	28.0 \pm 2.0	25.3 \pm 2.2	31.8 \pm 2.3	30.0 \pm 2.2	31.11 \pm 2.2	41.04 \pm 2.22	41.82 \pm 2.22
A5 Intertidal <i>Halodule</i> dominated	95.0 \pm 10.0	91.0 \pm 11.0	102.0 \pm 6.0	87.0 \pm 9.3	94.0 \pm 6.0	86.0 \pm 10.0	58.0 \pm 5.0	76.0 \pm 6.0	66.0 \pm 6.0	73.0 \pm 6.0	70.5 \pm 4.7	83.0 \pm 5.5	73.0 \pm 6.0	72.6 \pm 5.5	69.9 \pm 5.3	60.9 \pm 10.8	78.06 \pm 6.34	55.63 \pm 5.82	67.26 \pm 6.19
A6 Intertidal/ subtidal <i>Enhalus</i> dominated	5.0 \pm 1.0	7.0 \pm 1.0	7.0 \pm 1.0	6.8 \pm 1.0	7.0 \pm 1.0	7.0 \pm 1.0	7.0 \pm 2.0	6.0 \pm 0.5	7.5 \pm 0.7	8.0 \pm 0.7	7.8 \pm 0.8	9.0 \pm 0.7	8.0 \pm 3.0	9.2 \pm 1.6	9.8 \pm 1.4	7.9 \pm 1.4	4.92 \pm 3.34	7.19 \pm 2.61	8.22 \pm 2.61
A7 Intertidal/ subtidal <i>Enhalus</i> dominated	19.0 \pm 2.0	23.0 \pm 1.0	19.0 \pm 1.0	18.5 \pm 1.0	18.0 \pm 1.0	17.0 \pm 1.0	17.0 \pm 1.0	15.0 \pm 2.0	8.7 \pm 1.9	13.0 \pm 5.0	18.3 \pm 1.2	22.0 \pm 3.4	21.0 \pm 7.0	21.0 \pm 3.5	21.0 \pm 6.4	14.7 \pm 6.0	10.62 \pm 5.53	16.23 \pm 5.56	12.74 \pm 1.26
Total	402.0\pm 37.0	418.0\pm 37.0	417.0\pm 31.0	398.8\pm 35.3	416.0\pm 31.0	398.0\pm 37.0	358.0\pm 23.0	368.0\pm 16.5	358.4\pm 17.0	375.0\pm 20.8	369.4\pm 15.3	399.0\pm 18.2	363.0\pm 25.0	384.9\pm 19.4	400.1\pm 21.8	361.8\pm 27.0	378.31 \pm 23.97	405.91 \pm 22.72	392.67 \pm 16.92

6 REFERENCES

- Abal, E. and Dennison, W. 1996. Seagrass depth range and water quality in southern Moreton Bay, Queensland, Australia. *Marine and Freshwater Research*, 47: 763-771.
- Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81, 169-193.
- Bryant, C., Jarvis, J. C., York, P. and Rasheed, M. 2014. Gladstone Healthy Harbour Partnership Pilot Report Card; ISP011: Seagrass. Final Report, no. 14/53. Centre for Tropical Water & Aquatic Research, Cairns, 74 pp.
- Carter AB, Jarvis JC, Bryant CV & Rasheed MA 2015, 'Development of seagrass indicators for the Gladstone Healthy Harbour Partnership Report Card, ISP011: Seagrass', Centre for Tropical Water & Aquatic Ecosystem Research Publication 15/29, James Cook University, Cairns, 71 pp.
- Carter AB, Bryant CV, Davies JD & Rasheed MA (2016). 'Gladstone Healthy Harbour Partnership 2016 Report Card, ISP011: Seagrass'. Centre for Tropical Water & Aquatic Ecosystem Research Publication 16/23, James Cook University, Cairns, 62 pp.
- Carter AB, Mellors JM & Rasheed MA (2018). 'Torres Strait Seagrass 2018 Report Card'. Centre for Tropical Water & Aquatic Ecosystem Research Publication 18/25, James Cook University, Cairns, 65 pp.
- Chartrand K.M., Bryant C.V., Sozou S., Ralph P.J. and Rasheed M.A. 2017, 'Final Report: Deep-water seagrass dynamics - Light requirements, seasonal change and mechanisms of recruitment', Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication, James Cook University, Report No 17/16. Cairns, 68 pp.
- Coles R. G, Rasheed M. A, McKenzie L. J., Grech, A., York, P.H., Sheaves, M.J., McKenna, S. and Bryant, C. V. 2015. The Great Barrier Reef World Heritage Area seagrasses: managing this iconic Australian ecosystem resource for the future. *Estuarine, Coastal and Shelf Science*, 153: A1-A12.
- Collier, C. J., Waycott, M. and McKenzie, L. J. 2012. Light thresholds derived from seagrass loss in the coastal zone of the northern Great Barrier Reef, Australia. *Ecological Indicators*, 23: 211-219.
- Collier CJ & Waycott, M 2014, 'Temperature extremes reduce seagrass growth and induce mortality', *Marine Pollution Bulletin*, vol. 83, pp. 483-490.
- Collier, C.J., Chartrand, K., Honchin, C., Fletcher, A. Rasheed, M. 2016. Light thresholds for seagrasses of the GBR: a synthesis and guiding document. Including knowledge gaps and future priorities. Report to the National Environmental Science Programme. Reef and rainforest Research Centre Limited, Cairns (41pp.).
- Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. *Global Environmental Change* 26, 152-158.
- Dennison, W., Orth, R., Moore, K., Stevenson, J., Carter, V., Kollar, S., Bergstrom, P. and Batiuk, R. 1993. Assessing water quality with submersed aquatic vegetation: Habitat requirements as barometers of Chesapeake Bay health. *BioScience*, 43: 86-94.
- Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marba, N., Holmer, M., Mateo, M. A., Apostolaki, E. T., Kendrick, G. A., Krause-Jensen, D., McGlathery, K. J. and Serrano, O. 2012. Seagrass ecosystems as a globally significant carbon stock. *Nature Geoscience*, 5: 505-509.

- Grech, A., Coles, R., Marsh, H. 2012. A broad-scale assessment of the risk to coastal seagrasses from cumulative threats Marine Policy, 35: 560-567.
- Hemminga, M. A. and Duarte, C. M. 2000. Seagrass Ecology. Cambridge University Press, Cambridge.
- Kilminster, K., McMahon, K., Waycott, M., Kendrick, G.A., Scanes, P., McKenzie, L., O'Brien, K.R., Lyons, M., Ferguson, A., Maxwell, P., 2015. Unravelling complexity in seagrass systems for 712 management: Australia as a microcosm. Science of The Total Environment 534, 97-109.
- Kirk, JTO 1994, 'Light and photosynthesis in aquatic ecosystems', Cambridge University Press.
- Kirkman, H 1978, 'Decline of seagrass in northern areas of Moreton Bay, Queensland', Aquatic Botany, vol. 5, pp. 63-76.
- McKenna, SA, Carter, AB, Sozou, AM & Rasheed MA 2017, 'Port of Weipa long-term seagrass monitoring program, 2000-2016'. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) Publication 17/02, JCU Cairns.
- McKenna, S.A. & Rasheed, M. 2018, 'Long-term Seagrass Monitoring in the Port of Thursday Island: April 2018. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook University, Cairns.
- Mellors, JE 1991, 'An evaluation of a rapid visual technique for estimating seagrass biomass', Aquatic Botany vol. 42, pp. 67-73.
- Orth, R. J., Carruthers, T. J. B., Dennison, W. C., Duarte, C. M., Fourqurean, J. W., Heck, K. L., Hughes, A. R., Kendrick, G. A., Kenworthy, W. J., Olyarnik, S., Short, F. T., Waycott, M. and Williams, S. L. 2006. A global crisis for seagrass ecosystems. BioScience, 56: 987-996.
- Petrou K, Jimenez-Denness I, Chartrand K, McCormack C, Rasheed M and Ralph PJ 2013 Seasonal heterogeneity in the photophysiological response to air exposure in two tropical intertidal seagrass species. Mar. Ecol. Prog. Ser. 482 93–106.
- Rasheed, MA. 2004, 'Recovery and succession in a multi-species tropical seagrass meadow following experimental disturbance: the role of sexual and asexual reproduction', Journal of Experimental Marine Biology and Ecology, vol. 310, pp. 13-45.
- Rasheed, MA, McKenna, S, Carter, A and Coles, RG 2014, 'Contrasting recovery of shallow and deep water seagrass communities following climate associated losses in tropical north Queensland, Australia', Marine Pollution Bulletin, vol. 83, pp. 491-499.
- Roelofs, A. J., Rasheed, M. A. and Thomas, R. 2001. Port of Weipa Seagrass Monitoring Baseline Surveys, April & September 2000. Ports Corporation of Queensland, Brisbane, 38 pp.
- Roelofs, A. J., Rasheed, M. A. and Thomas, R. 2003. Port of Weipa seagrass monitoring, 2000 - 2002. Ports Corporation of Queensland, Brisbane, 32 pp.
- Roelofs, A. J., Rasheed, M. A. and Thomas, R. 2005. Port of Weipa Long-Term Seagrass Monitoring, Progress Report - September 2004. Report to Ports Corporation Queensland. Queensland Department of Primary Industries and Fisheries, Northern Fisheries Centre, Cairns, 15 pp.
- Short, FT. & Wyllie-Echeverria, S. 1996. Natural and human-induced disturbance of seagrasses. Environmental Conservation 23, 17–27.

Unsworth, R. K. F., Rasheed, M. A., Chartrand, K. M. and Roelofs, A. J. 2012. Solar radiation and tidal exposure as environmental drivers of *Enhalus acoroides* dominated seagrass meadows. PLoS ONE, 7: e34133.

Van De Wetering, C, Scott, AL & Rasheed, MA 2019, 'Port of Karumba Long-term Annual Seagrass Monitoring: November 2018, James Cook University Publication, Centre for Tropical Water & Aquatic Ecosystem Research, Cairns, 28pp.

Waycott, M., Duarte, CM., Carruthers, TJB., Orth, R. Dennison, WC., Olyarnik, S., Calladine, A., Fourqurean, JW., Heck Jr., KL., Hughes, AR., Kendrick, GA., Kenworthy, WJ., Short, FT., Williams, SL., 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proceedings of the National Academy of Sciences of the United States of America 106, 12377–12381.