Port of Karumba long-term annual seagrass monitoring 2022

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KEY FINDINGS

Seagrass Condition 2022

VERY GOOD

1. In 2022 all seagrass condition indicators in the Karumba monitoring meadow remained in very good condition.

2. Seagrass condition at the Alligator Bank long-term monitoring meadow improved again in 2022, continuing the trajectory of increases after the 2019 flood related declines. Overall meadow score was the highest since this scoring system was implemented in 2015.

3. There was a large increase in seagrass biomass, with the third highest biomass since monitoring began recorded in 2022.

4. Above average numbers of *Halodule uninervis* seeds were found in the meadow indicating a stable seed bank is present.

5. Environmental conditions were favourable in 2022, enabling continued improvements in condition of the Alligator Bank seagrass meadow.

6. Biomass, area and percentage composition of the more stable seagrass species remain at very high levels with a seed bank also present. This confers good levels of resilience for the seagrass meadow in 2023.

IN BRIEF

Seagrasses have been monitored annually in the Port of Karumba since 1994. Each year, the monitoring meadow between the Norman and Bynoe Rivers at Alligator Bank (Figure 1) is assessed for changes in biomass (density), distribution (area), species composition, and reproductive capacity (seed bank, fruits and flowers). Changes to area, biomass and species composition are assessed using a seagrass condition index (see 2.3 and Appendix 1 of this report for further details).

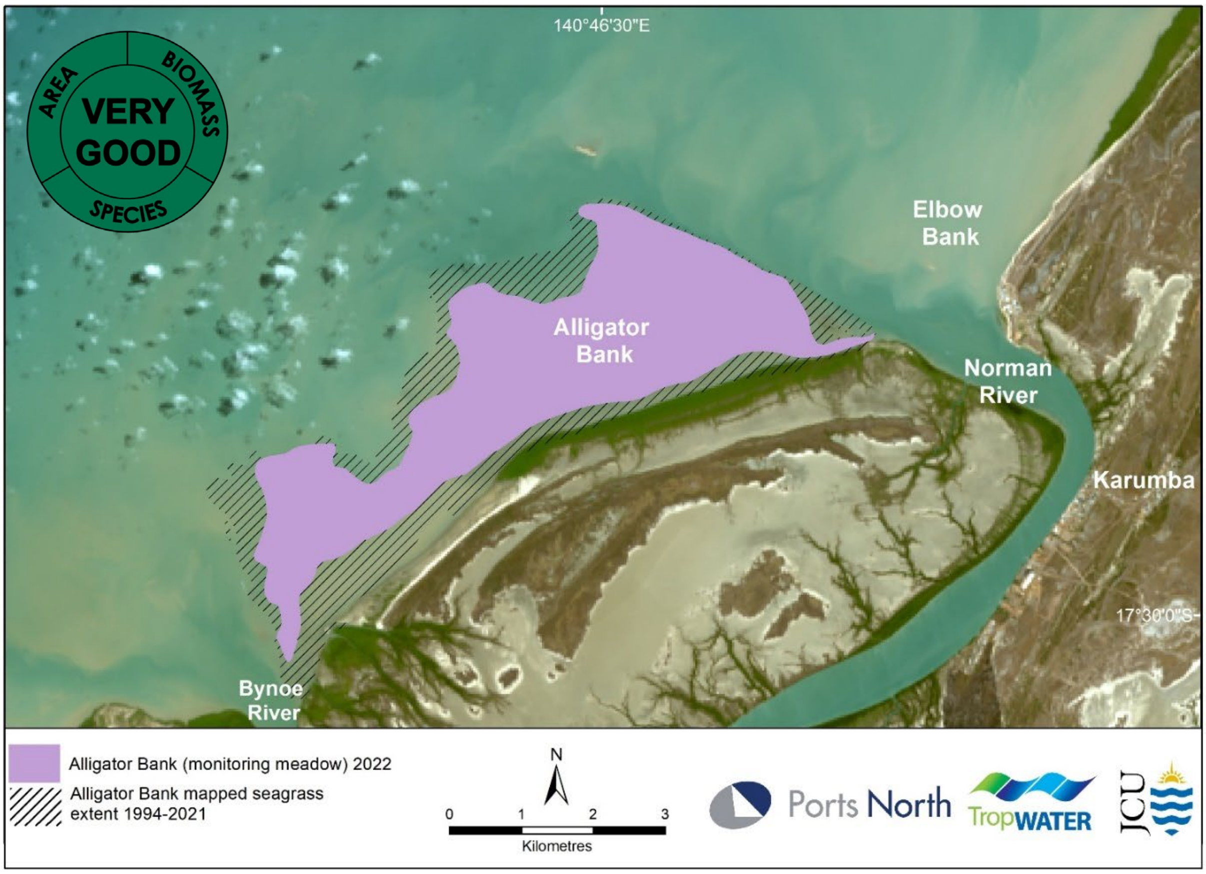

FIGURE 1. SEAGRASS CONDITION AT ALLIGATOR BANK, KARUMBA, 2022.

Seagrass in the Alligator Bank monitoring meadow continued to improve in condition in 2022 maintaining the trajectory of increases seen after flood related declines in 2019 and the recovery from these in 2021. Seagrass biomass, area and species composition improved in 2022 and were all in very good condition. The largest increase was seen in seagrass biomass, with the third highest meadow biomass recorded since monitoring began. This, combined with the dramatic improvement in area in 2021, puts the meadow in a condition similar to pre-flooding levels. There was a small increase in the more stable species *Halodule uninervis,* and in 2022 this species made up 99% of seagrass biomass. There were above average numbers of *Halodule uninervis* seeds in the below-ground seed bank with some pericarps (seed casings) also found, indicating the seed bank is present and is being used to support meadow expansion. Dugong feeding activity was once again observed throughout the Alligator Bank monitoring meadow in 2022.

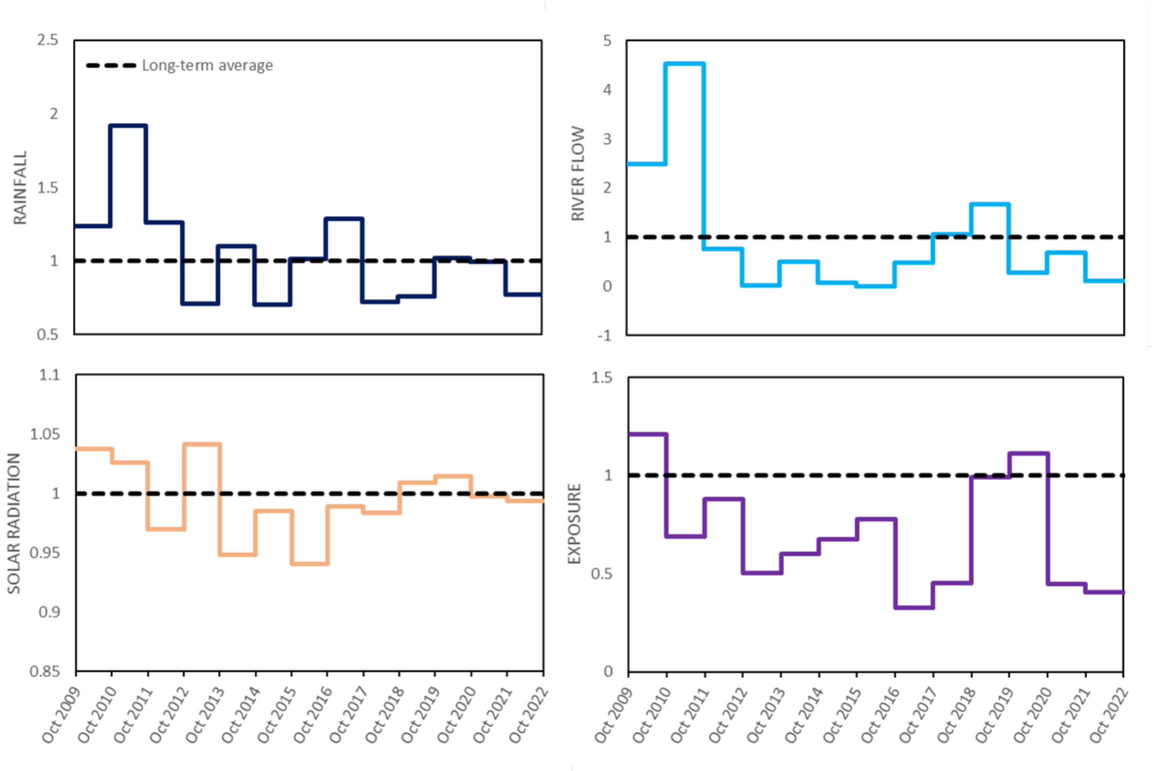

FIGURE 2. CHANGE IN CLIMATE VARIABLES AS A PROPORTION OF THE LONG-TERM AVERAGE IN KARUMBA. SEE SECTION 3.5 FOR DETAILED CLIMATE DATA.

Favourable environmental conditions for seagrass growth in 2022 have allowed continued improvement in seagrass condition, with rainfall, river flow and the amount of daytime air exposure of the meadow all below the long-term average in 2022 (Figure 2). The maintenance of very good meadow condition and presence of the below-ground seed bank in 2022, means Karumba seagrasses have some resilience leading into 2023 and an ability to recover via the seed bank if faced with large scale climate or anthropogenic impacts.

Karumba seagrass monitoring is part of a broader seagrass program that examines the condition of seagrasses in the majority of Queensland commercial ports and areas of high anthropogenic activity, and is a component of TropWATER's broader seagrass assessment and research program. Overall seagrass condition was good at Weipa in 2022, which is the closest location to Karumba. For full details of the Queensland ports seagrass monitoring program, see https://www.tropwater.com/project/management-of-ports-and-coastal-facilities/

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1 INTRODUCTION

Seagrasses provide a range of critically important and economically valuable ecosystem services including coastal protection, support of fisheries production, nutrient cycling and particle trapping (Costanza et al. 2014; Hemminga & Duarte 2000; Costanza et al. 1997). Seagrass meadows show measurable responses to changes in water quality, making them ideal candidates for monitoring the long-term health of marine environments (Orth et al. 2006; Abal & Dennison 1996; Dennison et al. 1993).

1.1 QUEENSLAND PORTS SEAGRASS MONITORING PROGRAM

A long-term seagrass monitoring and assessment program has been established in the majority of Queensland's 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 3).

FIGURE 3. LOCATION OF QUEENSLAND PORT SEAGRASS ASSESSMENT SITES.

A strategic long-term assessment and monitoring program for seagrasses provides port managers and regulators with key information to ensure that seagrasses and ports can co-exist. These results are useful for planning and implementing port development and maintenance programs to ensure minimal impact on seagrasses. The program also provides an ongoing assessment of many of the most threatened seagrass communities in Queensland.

The data collected as part of this program has resulted in significant advances in the science and knowledge of tropical seagrass ecology. This data has been instrumental in developing tools, indicators and thresholds for the protection and management of seagrasses. The program also provides an understanding of the drivers of tropical seagrass change. It provides local information for individual ports as well as feeding into regional assessments of the status of seagrasses.

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

1.2 KARUMBA SEAGRASS MONITORING PROGRAM

The Karumba port entrance and the Norman River channel are naturally shallow and require periodic maintenance dredging to allow the passage of vessels. Dredging has the potential to cause a high level of environmental risk to marine habitats such as seagrass meadows (Erftemeijer and Lewis 2006) unless management strategies are adopted to minimise potential risks. Ports North is responsible for dredging in the port and for managing and monitoring Karumba's port environment. Seagrass meadows are the key marine habitat that occur within the Port of Karumba that can be affected by port activities.

Seagrasses form a key ecological habitat in the Karumba region and Ports North have funded a long-term seagrass monitoring program since 1994. The initial six-year (1994-2000) seagrass monitoring program was commissioned as part of a wider range of environmental studies to assess and monitor the impacts of dredging and other port developments (Rasheed et al. 2001). Following this, a long-term seagrass monitoring program for the Port of Karumba was developed.

Results from the monitoring program are used by Ports North to assess the health of the ports' marine environment and help identify possible effects of port operations and developments on seagrasses. The program also provides an assessment of the resilience of seagrass meadows to withstand a range of potential influences, e.g., land runoff and dredging impacts, and provides a simple assessment of condition to confirm that port activities are not impacting the seagrass. The program also satisfies environmental monitoring requirements as part of the port's long-term dredge management plan and is used by management agencies to assess the status and condition of seagrass resources in the region.

This report presents results from the November 2022 monitoring survey. The objectives of the survey were:

1. Map seagrass distribution in the Alligator Bank monitoring meadow between the Norman and Bynoe River;
2. Determine seagrass species composition and biomass within the monitoring meadow;
3. Measure the reproductive capacity of the monitoring meadow;
4. Assess seagrass condition in the Alligator Bank monitoring meadow by comparing results with previous monitoring surveys.

2 METHODS

2.1 SAMPLING APPROACH

The 2022 survey was designed to provide updated information on seagrass habitats within the Port of Karumba, including seagrass distribution, density and species composition. The sampling method used followed those established for the Karumba long-term seagrass monitoring program as well as other seagrass programs established in Queensland Ports including Weipa, Cairns, Mourilyan Harbour, Townsville, Gladstone, Mackay, Thursday Island and Abbot Point.

For more details see: https://www.tropwater.com/project/management-of-ports-and-coastal-facilities/

2.2 SAMPLING METHODS

The Karumba seagrass survey was conducted on 1st November 2022. The survey area covered the intertidal area of Alligator Bank. Detailed monitoring program methods are available in previous reports (Rasheed et al. 1996; Rasheed et al. 2001; McKenna and Rasheed 2011).

Seagrass meadow boundaries were mapped from a helicopter survey conducted during the spring low tide when intertidal banks were exposed. Waypoints were recorded around the edge of the meadow using a global positioning system (GPS) and digitised into a Geographic Information System (GIS).

Seagrass metrics were recorded at survey sites scattered haphazardly within the mapped meadow. The number of sites was based on a power analysis that considered within-meadow variability (Unsworth et al. 2009). Site characteristics including seagrass species composition and above-ground biomass, epiphyte cover, algae and other benthic cover were recorded at each site.

Seagrass above-ground biomass was measured using a visual estimate of biomass technique (as described by Kirkman 1978 and Mellors 1991). This method has been used in surveys throughout Queensland (e.g. Rasheed et al. 2008; Rasheed and Unsworth 2011; Rasheed et al. 2014; McKenna et al. 2015; York et al. 2015). The method involves an observer ranking above-ground seagrass biomass within three randomly placed 0.25m^2 quadrats at each site. Observer measurements are calibrated against biomass values from quadrats harvested and dried to determine mean above-ground biomass in grams dry weight per square metre (g DW m^{-2}) at each site. The percent contribution of each seagrass species to total biomass within each quadrat also was recorded.

Sampling of the seagrass seed bank (seeds stored in the sediments) and other seagrass reproductive structures (fruit and flowers) was conducted at 17 sites within the Alligator Bank monitoring meadow. A Van Veen sediment grab ($0.0625m^{-2}$) was used to collect samples at sites haphazardly scattered throughout the meadow. Seagrass and sediment/seed samples were sorted by passing the sample through a 1 mm sieve. Any seagrass reproductive structures in the 1 mm fraction were identified and counted. The 1 mm mesh size was small enough to retain seeds/pericarps of *H. uninervis* and fruits and flowers of *H. uninervis* and *H. ovalis*. Seeds of *H. ovalis* were not measured because their small size allows them to pass through the sieve mesh and requires a microscope to locate them.

2.3 HABITAT MAPPING AND GEOGRAPHIC INFORMATION SYSTEM

All survey data was entered into a GIS for presentation of seagrass spatial data. Satellite imagery of the Karumba region plus information recorded during the monitoring survey was used to map seagrass meadows. Three seagrass GIS layers were created in ArcMap® 10.8:

2.3.1 Site layer

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

- Site number.
- Temporal details – Survey date and time.
- Spatial details – Latitude and longitude.
- 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).
- Sampling method and any relevant comments.

2.3.2 Biomass interpolation

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

2.3.3 Meadow Layer

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

- Meadow ID number – A unique number assigned to each meadow to allow comparisons among surveys.
- Temporal details – Survey date.
- Habitat information – Mean meadow biomass ± standard error (SE), meadow area (hectares) ± reliability estimate (R), number of sites within the meadow, seagrass species present, meadow density and community type (Tables 1, 2), meadow landscape category (Figure 4).
- Sampling method and any relevant comments.

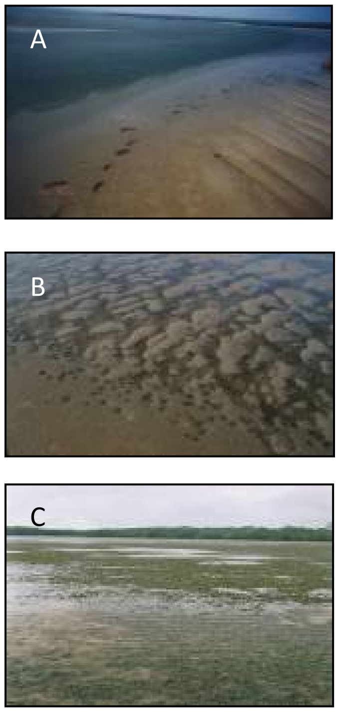
Meadow boundaries were constructed using GPS marked meadow boundaries, seagrass presence/absence site data, field notes, and aerial photographs taken during helicopter surveys. Meadow area was determined using the calculate geometry function in ArcMap®. The meadow boundary was assigned a mapping precision estimate (in metres) based on mapping methodology used for that meadow. Mapping precision was estimated to be ±5 m due to the error associated with GPS fixes. 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 1. SEAGRASS MEADOW COMMUNITY TYPE NOMENCLATURE IN THE PORT OF KARUMBA.

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 BASED ON MEAN ABOVE-GROUND BIOMASS RANGES FOR EACH SPECIES IN THE PORT OF KARUMBA.

Density	Mean above-ground biomass (g DW m^{-2})	
	Halodule uninervis (narrow)	*Halophila ovalis*
Light	< 1	< 1
Moderate	1 - 4	1 - 5
Dense	> 4	> 5



Isolated seagrass patches

The majority of area within the meadows consisted of unvegetated sediment interspersed with isolated patches of seagrass.

Aggregated seagrass patches

Meadows are comprised of numerous seagrass patches but still feature substantial gaps of unvegetated sediment within the meadow boundaries

Continuous seagrass cover

The majority of area within the meadows comprised of continuous seagrass cover interspersed with a few gaps

FIGURE 4. SEAGRASS MEADOW LANDSCAPE CATEGORIES: (A) ISOLATED SEAGRASS PATCHES, (B) AGGREGATED SEAGRASS PATCHES, (C) CONTINUOUS SEAGRASS COVER.

2.4 SEAGRASS MEADOW CONDITION INDEX

A condition index was developed for seagrass monitoring meadows in Karumba 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 5 summarises the methods used to calculate seagrass condition. See Appendix 1 and 2 for full details of score calculation.

2.5 ENVIRONMENTAL DATA

Environmental data were collated for the 12 months preceding each survey:

- Tidal data was provided by Maritime Safety Queensland (MSQ) (© The State of Queensland Department of Transport and Main Roads 2022, Tidal Data) for Karumba (www.msq.qld.gov.au). Predicted data were used for five days in August and three days in September 2020 where the tidal guage was not working.
- Data for rainfall (mm), air temperature (°C), and global solar exposure (MegaJoules, MJ m^{-2}) were obtained for the nearest weather station from the Australian Bureau of Meteorology (BOM) (Normanton Airport, Station #029063; http://www.bom.gov.au/climate/data/).
- Norman River flow data (megalitres; ML) was obtained from the Queensland Government (Glenore Weir, Station #916001B; https://water-monitoring.information.qld.gov.au/).

2.6 SEAGRASS REPRODUCTION ANALYSIS

Halodule uninervis seeds and pericarps in the sediment were compared among years (2003-2022) using a negative binomial regression model in R (version 3.6.2) using the *MASS* package (Venables and Ripley 2002). Data exploration protocols prior to all analyses followed Zuur et al. (2010) and included checks for zero inflation and overdispersion. Statistical significance of year in each model was tested using a likelihood ratio test. Statistical analyses could not be performed on *H. uninervis* and *H. ovalis* fruit and flower counts due to the large number of zeros in the data; this data is presented graphically instead.

FIGURE 5. PROCESS USED TO DETERMINE KARUMBA SEAGRASS MONITORING MEADOW CONDITION GRADES AND SCORES EACH YEAR.

3 RESULTS

3.1 SEAGRASS SPECIES

Seagrass was present at 93 of the 95 sites surveyed in the Alligator bank monitoring meadow in 2022. Two seagrass species were present in Karumba: *Halodule uninervis* (narrow leaf form) was the dominant species recorded and accounted for approximately 99% of above-ground seagrass biomass in the meadow, while *Halophila ovalis* accounted for the remaining 1%, (Figures 6 and 7).

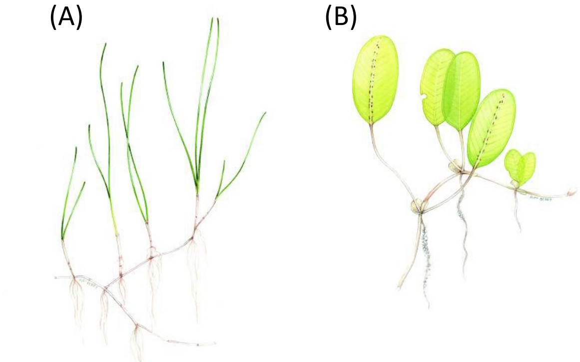


FIGURE 6. SEAGRASS SPECIES FOUND IN KARUMBA: (A) *HALODULE UNINERVIS*, FAMILY CYMODOCEACEAE (NARROW LEAF FORM); (B) *HALOPHILA OVALIS*, FAMILY HYDROCHARITACEAE.

3.2 SEAGRASS CONDITION IN THE ALLIGATOR BANK MONITORING MEADOW

Seagrass in the Alligator Bank monitoring meadow was in a very good condition in 2022 (Table 3, Figure 7). The Alligator Bank meadow has continued to improve after the losses in biomass and area documented in the 2019 survey. Above-ground biomass increased substantially from 6.8 $\pm$ 0.7 g DW m^{-2} in 2021 to 11.3 $\pm$ 0.7 g DW m^{-2} in 2022 and condition remained very good (Table 3, Figure 7). Meadow area increased slightly from 1324 $\pm$ 13 ha in 2021 to 1356 $\pm$ 13 ha in 2022 and also remined in very good condition (Table 3, Figures 7 and 8). Seagrass species composition remained in very good condition, with the meadow 99% dominated by the more stable species *H. uninervis* in 2022, an increase from 94% in 2021 (Table 3, Figure 7).

TABLE 3. GRADES AND SCORES FOR SEAGRASS INDICATORS (BIOMASS, AREA AND SPECIES COMPOSITION) FOR KARUMBA.

Meadow	Biomass	Area	Species Composition	Overall Meadow Condition
Alligator Bank	1	1	0.99	1

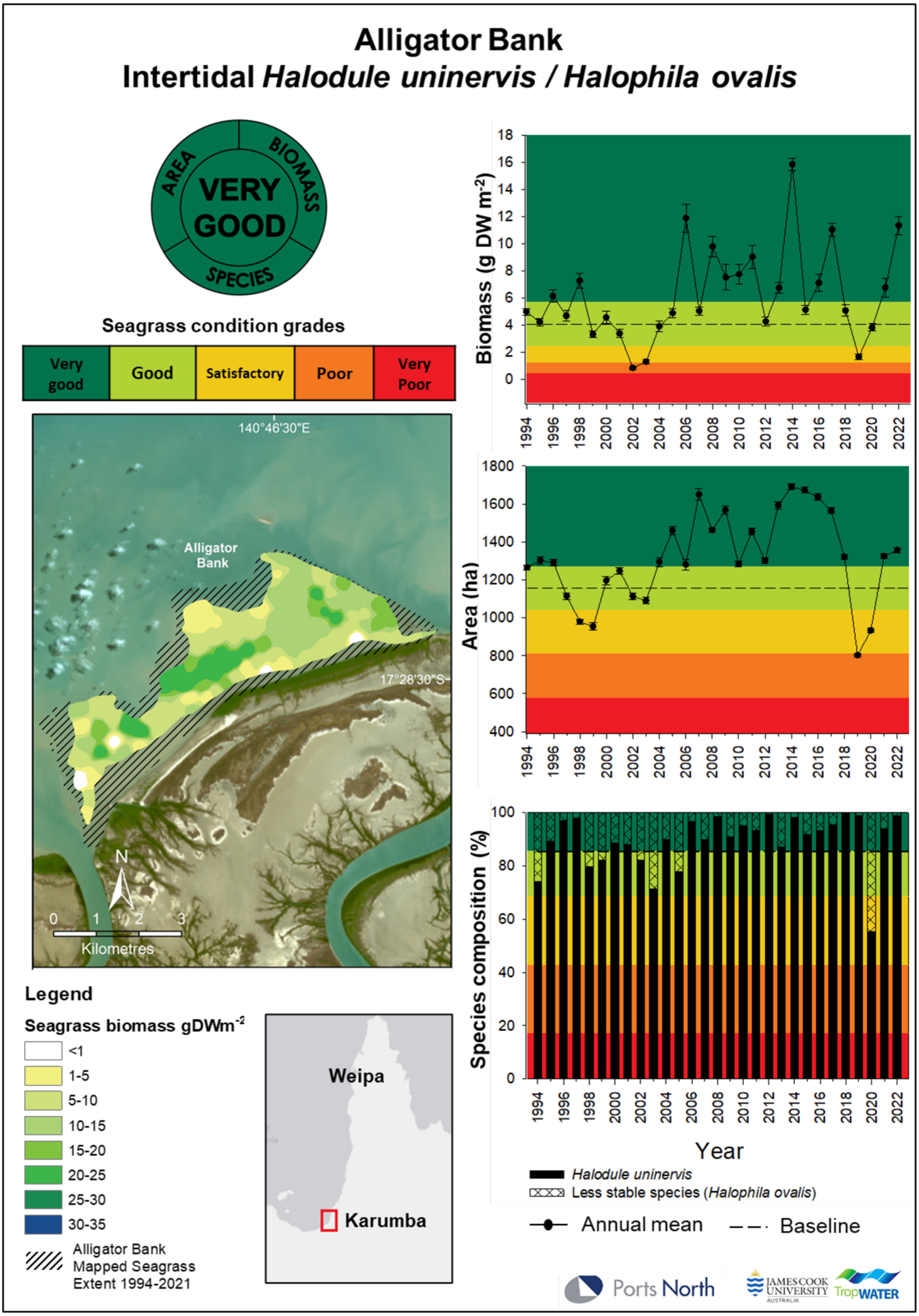


FIGURE 7. CHANGES IN BIOMASS, AREA AND SPECIES COMPOSITION FOR THE KARUMBA SEAGRASS MONITORING MEADOW FROM 1994 TO 2022 (BIOMASS ERROR BARS = SE; AREA ERROR BARS = "R" RELIABILITY ESTIMATE).

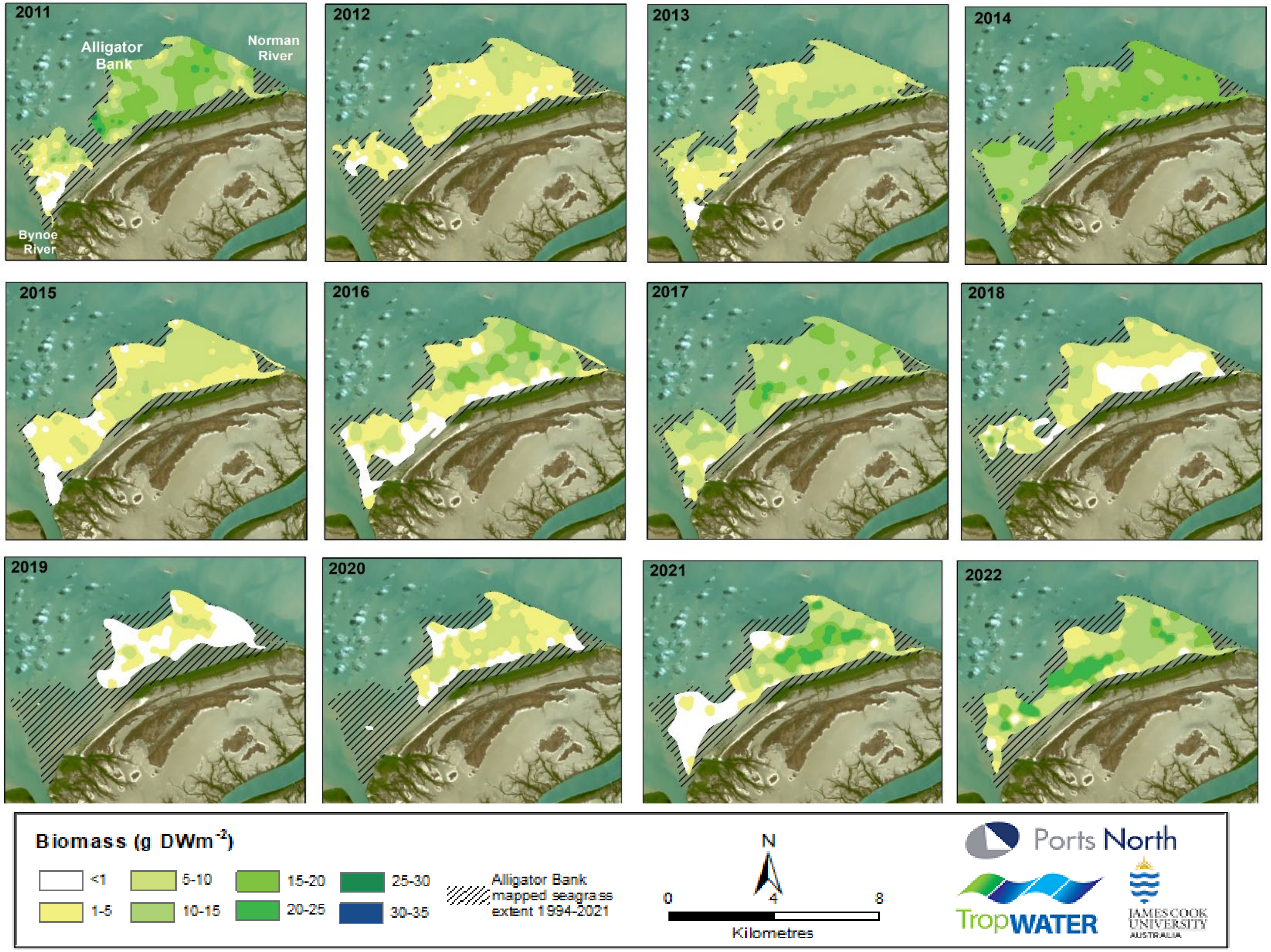


FIGURE 8. BIOMASS AND AREA CHANGE IN THE ALLIGATOR BANK MONITORING MEADOW, 2011 TO 2022.

3.3 COMPARISON WITH PREVIOUS MONITORING SURVEYS

Seagrass was maintained in very good condition in 2022, continuing the trajectory of improvement from poor in 2019 and satisfactory in 2020 (Table 3, Figure 7). Biomass and species composition scores both improved in 2022, while area was maintained at the highest score possible, this means the overall meadow score is the highest it has been since the current scoring methodology was implemented in 2015.

Above-ground biomass remained in very good condition for the second year in a row in 2022 (Figure 7). Average meadow above-ground biomass increased by 4.6 g DW m^{-2} from 2021 to 2022 and was the third highest recorded since monitoring began (Figure 7). This trend continues the improvement in above-ground biomass from 2020 onwards, from the low levels in 2019. This increase in above-ground biomass occurred throughout the expanded meadow area on Alligator Bank documented in 2021 (Figure 8).

Seagrass meadow area increased by 32 ha in 2022, maintaining the large improvement seen in 2021 and the very good condition documented in this survey (Figure 7). There have been some small increases in the seagrass meadow boundary in 2022 and no significant areas of loss (Figure 8).

Seagrass species composition also improved and maintained a very good condition in 2022, reaching a score similar to pre disturbance levels. The meadow was once again dominated by the more stable species *H. uninervis*, making up 99% of biomass in the meadow (Figure 7).

3.4 SEAGRASS REPRODUCTIVE CAPACITY

Halodule uninervis seeds and pericarps (outer casings of seeds) were found throughout the monitoring meadow in 2022 (Figure 9), with a mean density of 61 seeds m^{-2} and 16 pericarps m^{-2} across the meadow. *Halodule uninervis* seed density varied significantly among years at the .05 level (Chi square=86, df=18, p=<0.001) when compared against the NULL model, post-hoc analysis showed that in 2022 the number of seeds was significantly higher than in 2004 (p=<0.05) but did not differ from any other year (Figure 11A). *Halodule uninervis* pericarp density varied significantly among years at the .05 level (Chi square=165, df=18, p=<0.001) when compared against the NULL model, post-hoc analysis showed that pericarp densities in 2022 were significantly lower than 2003, 2009, 2011, 2013, 2017, 2018 and 2020 (p=<0.05) (Figure 11A). Similar to previous years, there were no *H. uninervis* fruits or flowers found in the Alligator Bank meadow at the time of the survey in 2022 (Figure 10A). In November 2022 there were no *H. ovalis* fruits or flowers found in the Alligator Bank meadow, this is a reduction from 2021 but similar to previous years (Figures 9 and 10C).

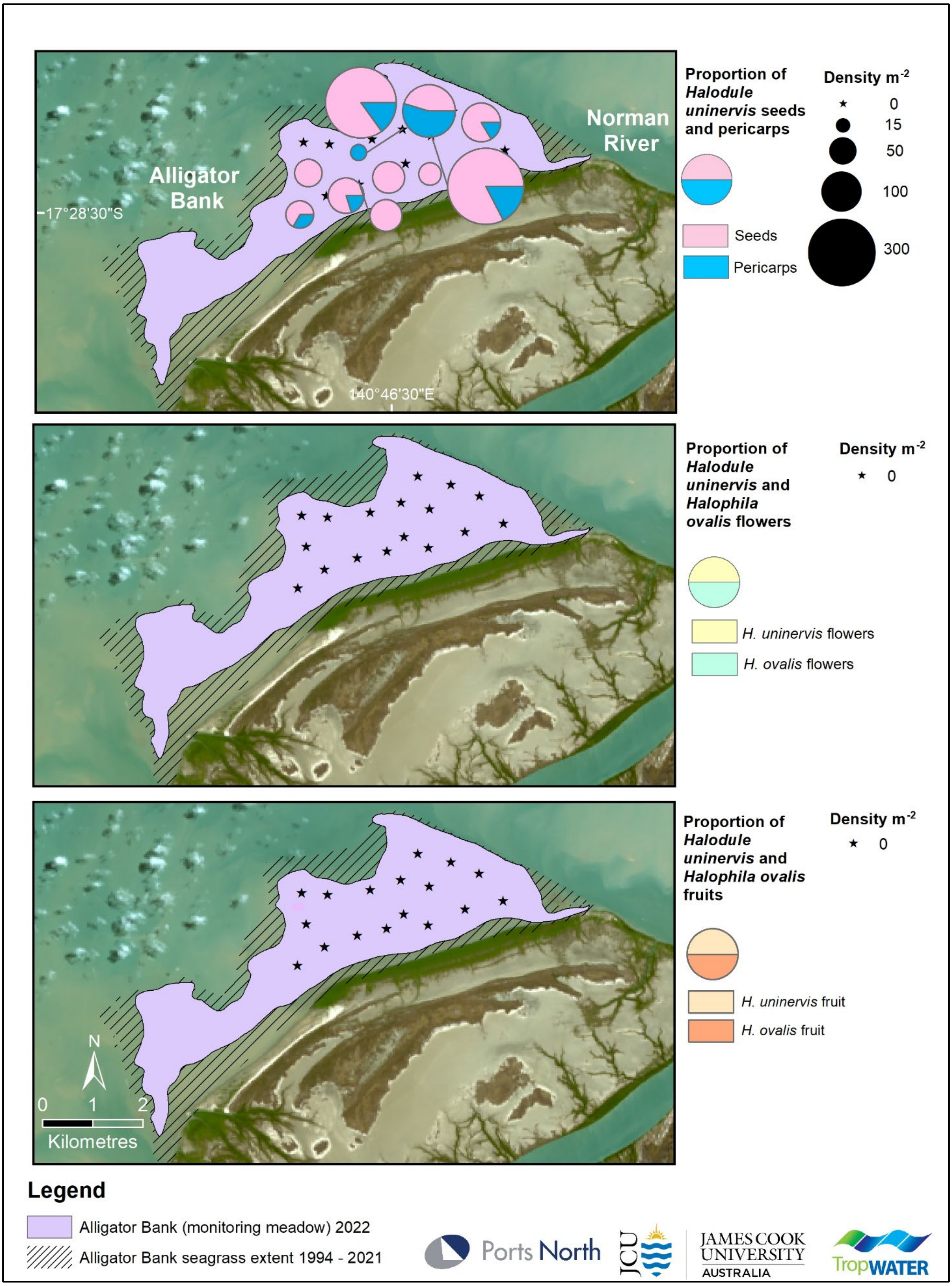


FIGURE 9. DENSITY OF *H. UNINERVIS* SEEDS AND PERICARPS, AND *H. UNINERVIS* AND *H. OVALIS* FLOWERS AND FRUITS IN 2022.

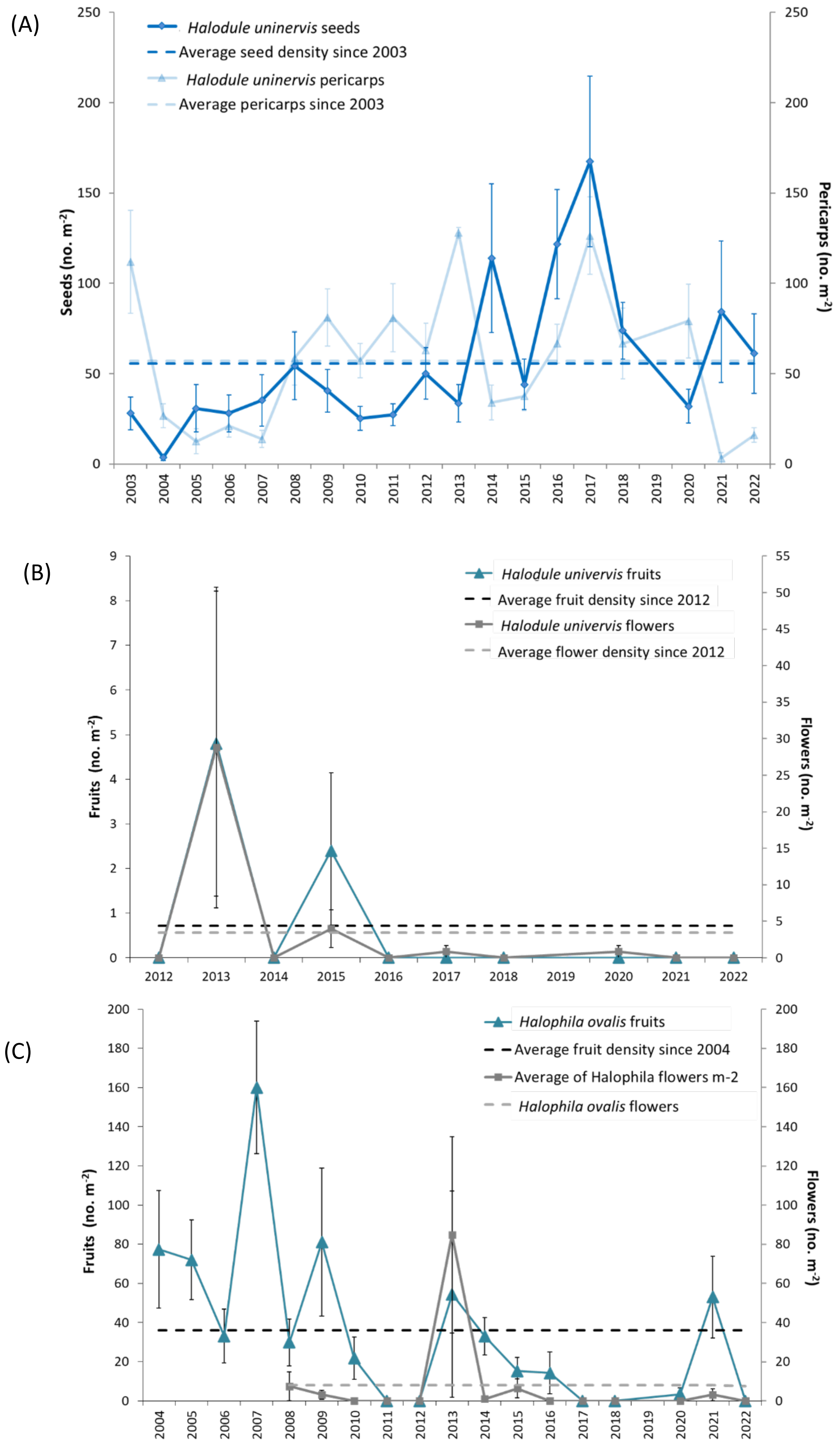


Figure 10. Mean density (± SE) of (A) *Halodule uninervis* seeds and pericarp pieces, (B) *H. uninervis* fruits and flowers, and (C) *Halophila ovalis* fruits sampled within the monitoring meadow. Data from 2019 have been excluded due to a different sampling method used.

3.5 DUGONG FEEDING ACTIVITY

Dugong feeding trails have been observed within seagrass meadows over the history of the Karumba monitoring program. Dugong feeding trails were observed throughout much of the Alligator Bank meadow in 2022, these were particularly concentrated in the higher biomass areas of the meadow.

3.6 KARUMBA ENVIRONMENTAL CONDITIONS

3.6.1 RAINFALL

Total annual rainfall for the Normanton area in the twelve months prior to the November 2022 survey was 609 mm, this was below the average annual rainfall for the area (Figure 12). The majority of the monthly rainfall during this 12 month period was below average, with only November 2021 and May 2022 recording slightly above average rainfall (Figure 13). During the survey month there was 41.3 mm of rain, and only 13.1 mm fell in the three months leading up to the survey (Figure 13).

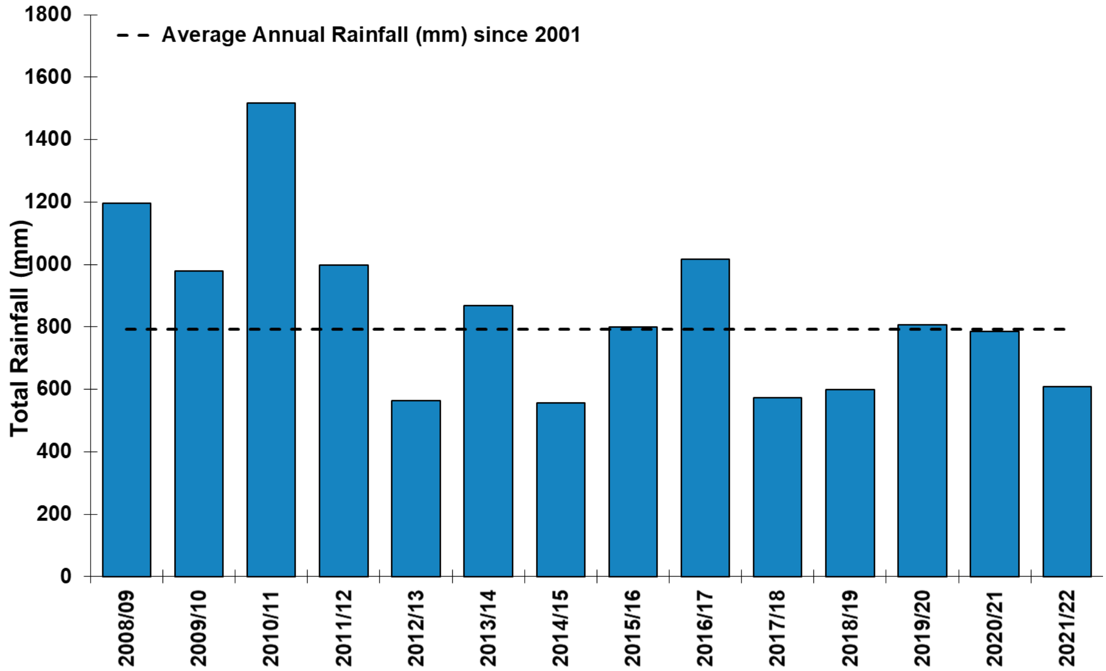


FIGURE 12. TOTAL ANNUAL RAINFALL (MM) RECORDED AT NORMANTON AIRPORT, 2008/09 – 2021/22, IN EACH 12 MONTHS PRIOR TO SEAGRASS SURVEY.

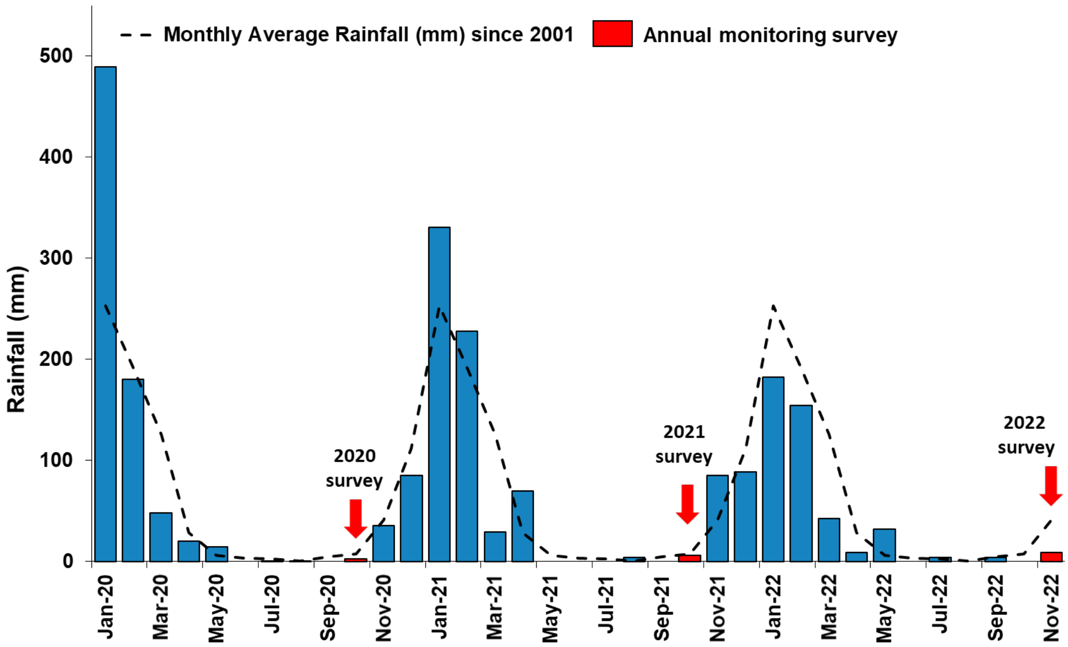


FIGURE 13. TOTAL MONTHLY RAINFALL (MM) RECORDED AT NORMANTON AIRPORT, JANUARY 2020 - NOVEMBER 2022.

3.6.2 River Flow

Total annual river flow 12 months prior to the seagrass survey was 194 GL, well below average and lower than recent years (Figure 14), monthly river flow also remained well below average in the 12 months prior to the survey (Figure 15).

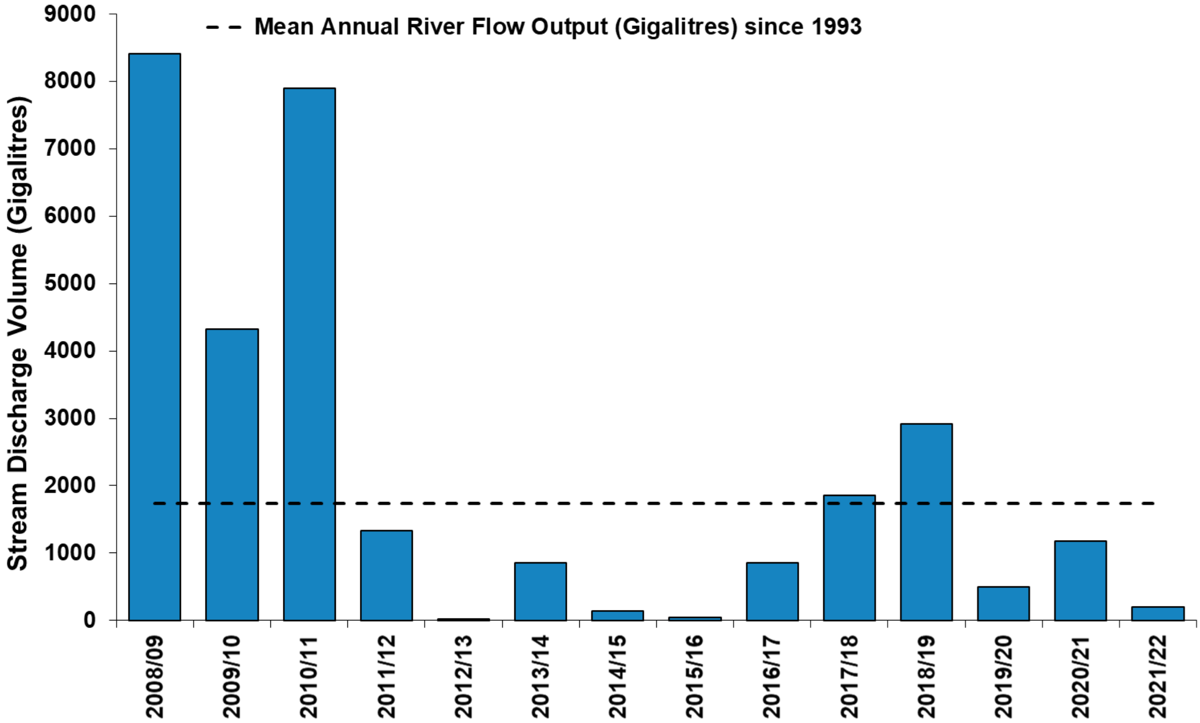


Figure 14. Total Norman River flow (measured as stream discharge volume in Gigalitres, GL) recorded at Glenore Weir, 1993/94 – 2021/22 twelve month year (2021/22) is twelve months prior to survey.

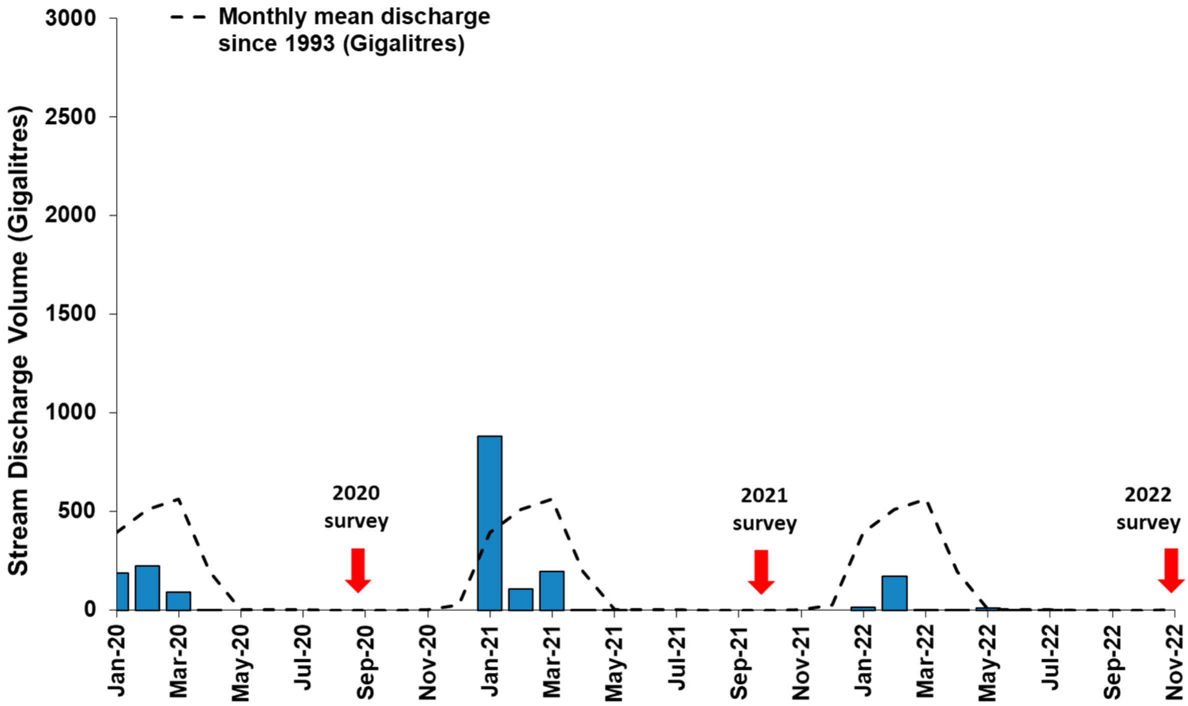


Figure 15. Total Norman River flow (measured as stream discharge volume in Gigalitres) recorded at Glenore Weir, January 2020 - November 2022.

3.6.3 Air Temperature

Air temperature was above-average in the region in 2021/22, with a mean annual daily maximum air temperature of 34.4°C (Figure 16). Monthly average maximum daily temperatures were also above average for most of the 12 months prior to the survey with the exception of November and December in 2021 and July and November 2022 (Figure 17).

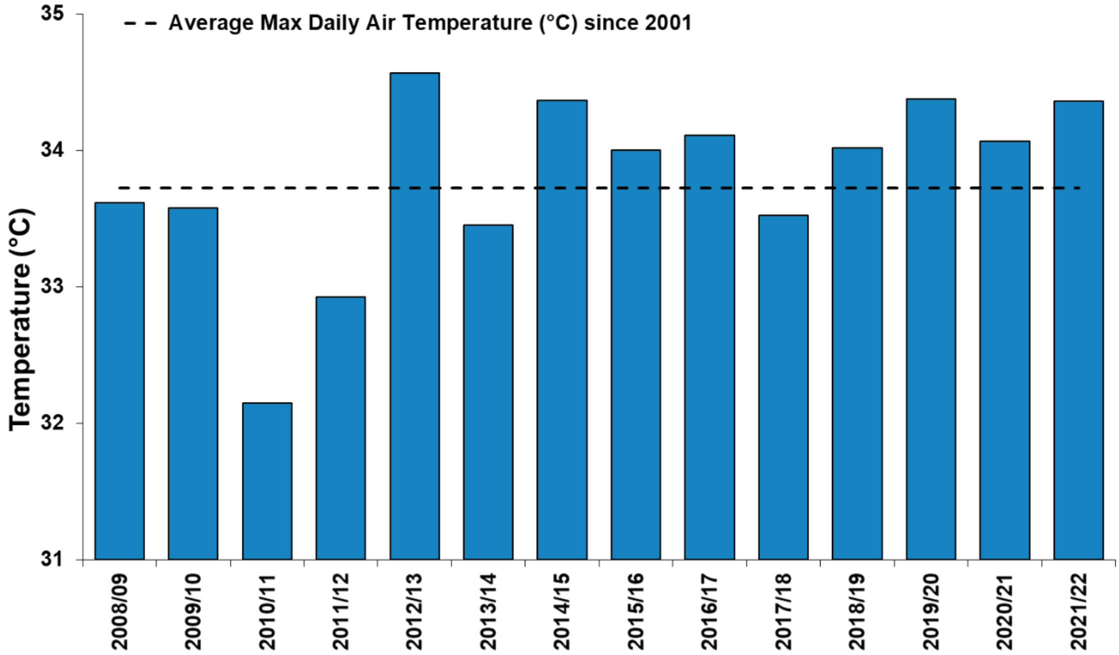


Figure 16. Mean maximum daily air temperature (°C) recorded at Normanton Airport, 2008/09 - 2021/22. Twelve month year (2020/21) is twelve months prior to survey.

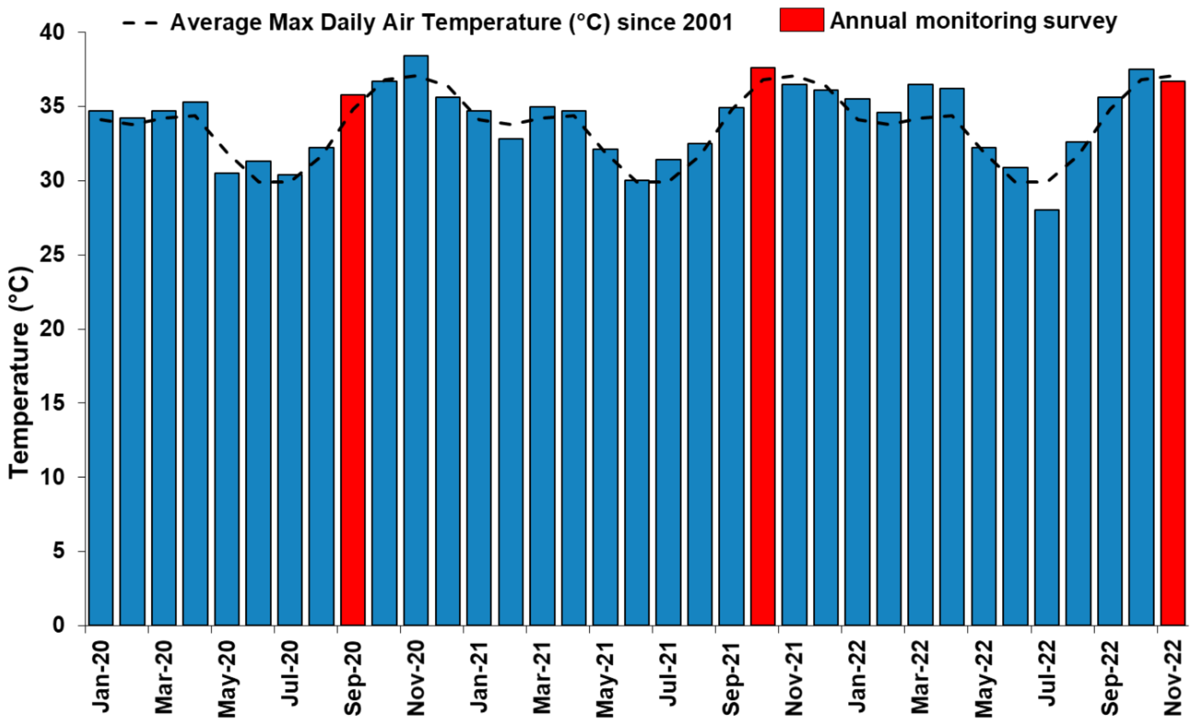


Figure 17. Monthly mean maximum daily air temperature (°C) recorded at Normanton Airport, January 2020 – November 2022.

3.6.4 Daily Global Solar Exposure

Daily global solar exposure is a measure of the total amount of solar energy falling on a horizontal surface in one day. Values are generally highest in clear sun conditions during spring/summer and lowest during winter. Global solar exposure in the Normanton area was slightly below-average in 2021/22 at 22.0 MJ m^{-2} (MegaJoules m^{-2}) (Figure 18), with solar exposure close to or below average for most of the 12 months prior to the survey (Figure 19).

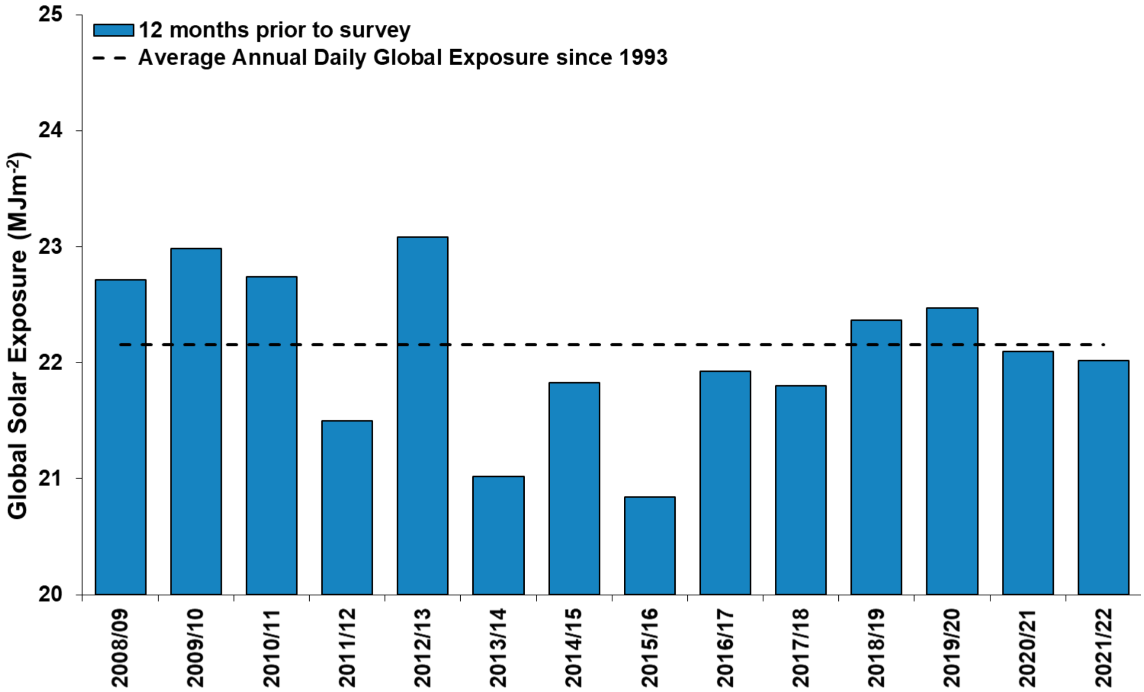


Figure 18. Mean daily global exposure (MegaJoules m^{-2}) recorded at Normanton Airport, 2008/09 – 2021/22. Twelve month year (2020/21) is twelve months prior to survey.

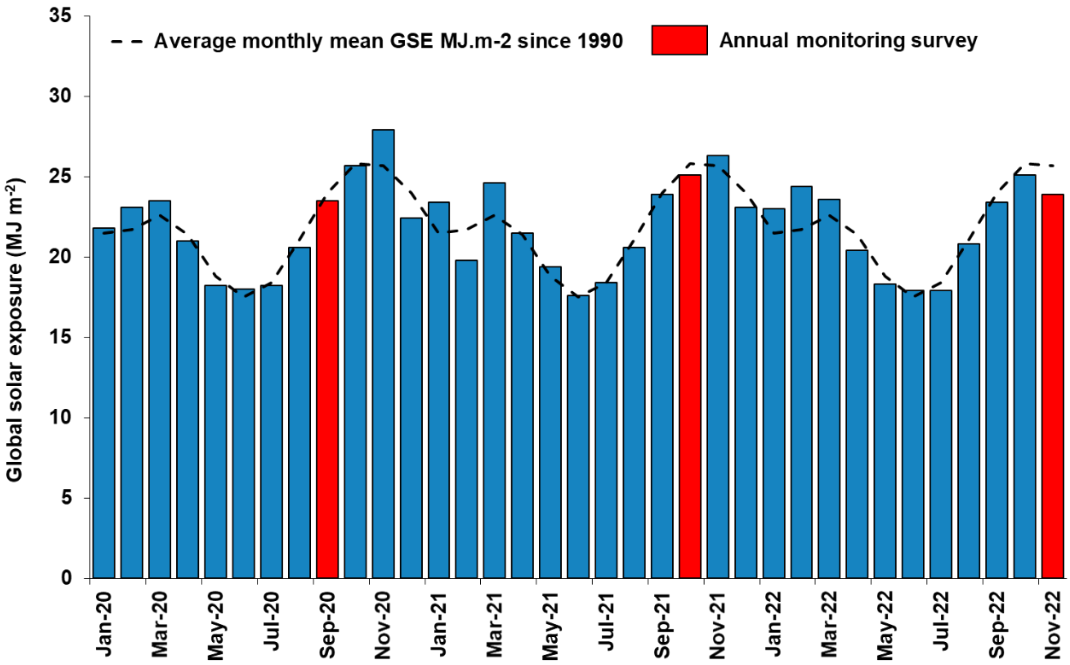


Figure 19. Mean daily global solar exposure (MegaJoules m^{-2}) recorded at Normanton Airport, January 2020-November 2022.

3.6.5 Tidal Exposure of Seagrass Meadows

Annual daytime exposure to air for intertidal seagrass was well below-average in 2022 (Figure 20). Intertidal banks were exposed for a total of 73 daytime hours in the 12 months prior to the survey (Figure 21). Monthly daytime exposure to air was also below-average in the year prior to the survey, with the exception of February 2022 (Figure 21).

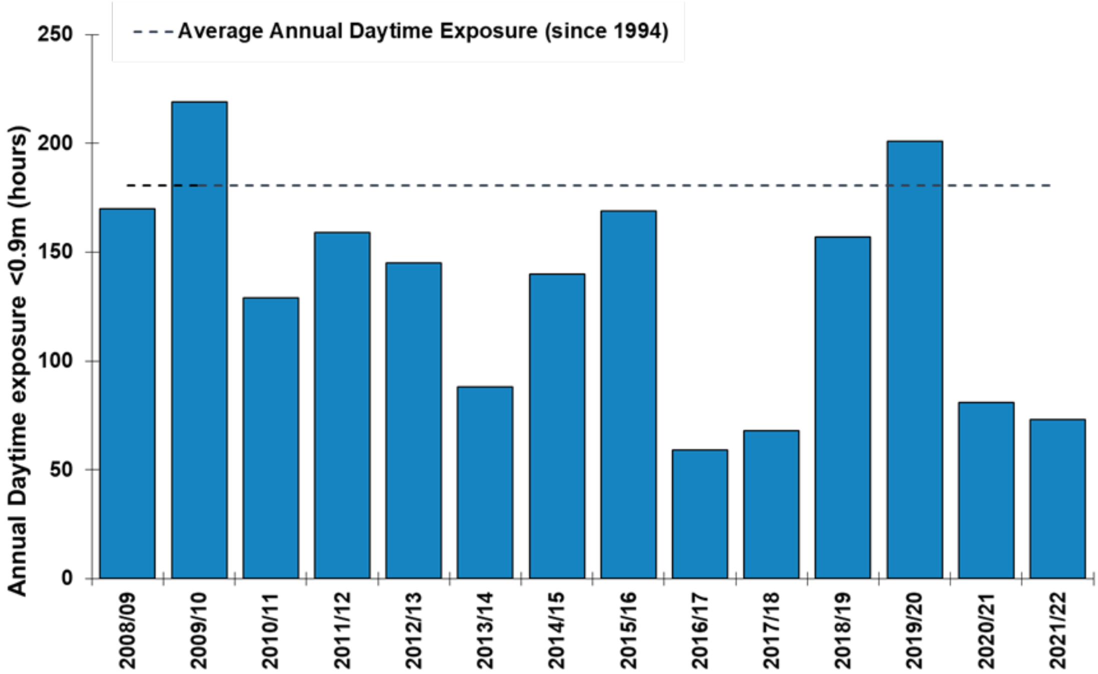


Figure 20. Total hours daytime exposure (annual) of intertidal seagrass in Karumba; 2008/09 – 2021/22. Twelve month year is twelve months prior to survey. *Assumes intertidal banks become exposed at a tide height <0.9m above Lowest Astronomical Tide.

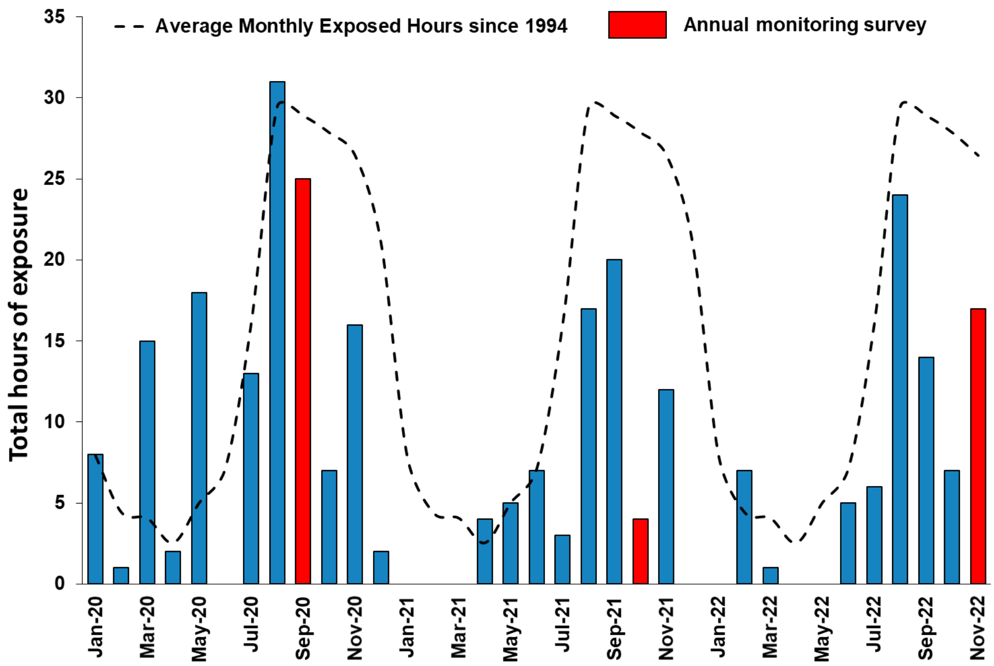


Figure 21. Total hours of daytime exposure (monthly), January 2020 to November 2022. *Assumes intertidal banks become exposed at a tide height <0.9m above Lowest Astronomical Tide.

4 DISCUSSION

In 2022 the Alligator Bank seagrass monitoring meadow continued to improve in condition after the flood related declines in 2019. Environmental conditions were once again favourable for seagrass growth and expansion and have allowed continued improvement of meadow condition. All seagrass condition scores have now equalled or exceeded their pre-flood values with continued improvement in seagrass biomass and species composition. Seagrass biomass was the third highest recorded since monitoring began and these increases were widespread in the meadow, with relatively consistent cover throughout the meadow footprint. There was an improvement in species composition with the meadow dominated by the more stable species *Halodule uninervis.* The Alligator Bank meadow remained in very good condition and the overall meadow score in 2022 was the highest since this scoring methodology was applied in 2015. The seed bank (seeds stored in the below-ground sediments) was above average, giving the meadow some resilience. All of these metrics point to a meadow which has recovered to pre-food levels and is resilient to future disturbances.

The improvement in seagrass condition in Karumba comes after severe weather caused seagrass declines resulting in the poorest condition recorded in over a decade in 2019. Flooding of the Norman River in 2018/19 caused large-scale declines of seagrass biomass and area in Karumba. These flooding and flow events created a persistent turbid plume that reduced light levels and resulted in seagrass loss (Shepherd et al. 2020, Van De Wetering et al. 2019). In 2020, more favourable conditions allowed the meadow to begin to recover achieving a satisfactory condition. In 2021 conditions were once again favourable allowing recovery of the Alligator Bank seagrass meadow to a very good condition and in 2022 this improvement in condition continued.

Environmental conditions were favourable for seagrass growth in 2022. River flow, temperature and long-term tidal exposure cycles have been identified in past research as strongly influencing changes in seagrass biomass and distribution in Karumba (Rasheed and Unsworth 2011) and in 2022 these were all at levels considered to be favourable for seagrass growth. There were no extreme weather events in the region which would have impacted the seagrass meadow, air temperature was the only climatic variable to be above average in the 12 months prior to the survey; rainfall, river flow, solar exposure and tidal exposure were all well below the annual average, with the majority of monthly totals also below average.

Recovery of the seagrass meadow at Karumba to pre-flood levels has taken three years with largely favourable environmental conditions. This meadow has previously recovered from smaller scale losses by the year following the disturbance (McKenna and Rasheed 2013, Taylor et al. 2014), however the cumulative and severe flooding of 2018 and 2019 caused a sudden and dramatic decline in seagrass condition at a scale not previously recorded. Given the scale of the declines in 2019, it is not surprising that recovery of this meadow to pre-flood levels has taken three years with favourable climatic conditions, in Cairns Harbour the seagrass meadows are still recovering a decade after severe weather caused declines (Reason et al. 2022). Maintenance of the very good condition of the seagrass meadow in Karumba was enabled by the very favourable climate conditions in 2022. This recovery means that the meadow is likely to be more resilient in the face of any short-term weather events. The Alligator Bank meadow was in a good or very good condition from 2004 to 2017, maintaining this score even in high rainfall years, showing it can be resilient in years of higher rainfall and river flow if area and biomass are high, as they are in 2022. However, any extreme weather could still have a significant impact on the meadow.

In 2022 there was another improvement in the species composition score in Karumba, continuing the shift towards the more stable species *H. uninervis*, which made up 99% of seagrass biomass. This is a dramatic change from 2020 where the meadow had the highest recorded percentage of the colonising species *Halophila ovalis*, resulting in a satisfactory species score for the first time. In tropical Queensland and elsewhere, *Halophila* species are often the first to return following disturbance events, where they persist at higher densities until the recovery of larger slower growing species occurs (Rasheed 2004). The meadow at Karumba has now completely shifted away from this colonising species and is dominated by the more stable species *H. uninervis*, this is an important feature of a healthy and resilient seagrass meadow (Unsworth et al. 2015).

Seed densities in the Karumba Alligator Bank monitoring meadow were above average in 2022, there was a small decrease from the previous year, however the number of pericarps (seed casings) increased, indicating some of these seeds are germinating. The seed bank is now stable with above average numbers of seeds and germination of seeds taking place to drive continued recovery, a dynamic not seen in this meadow since pre-flood conditions. A similar pattern in seed numbers was observed in Cairns Harbour following seagrass declines caused by climatic conditions, and the seagrass meadows there also recovered over time and a viable seed bank returned (Reason et al. 2020). No *H. uninervis* fruits or flowers were found in the meadow at the time of the survey, consistent with previous surveys since 2016. The reduction in *H. ovalis* fruits and flowers from last year is likely to be due to the low percentage this species contributes to overall biomass.

Seagrasses provide a wide range of important ecosystem services and the improvement of meadow area and biomass in Karumba will likely increase the delivery of a range of services (Nordlund et al. 2016, Scott et al. 2018). For example, Karumba seagrasses are an important nursery ground for prawns and fish (Rasheed et al. 1996) and feeding ground for megaherbivores such as dugong. Seagrass biomass, area and a stable species mix are all important for the delivery of these ecosystem services.

The seagrass at Karumba is the only substantial area of seagrass for dugong feeding between Mornington Island and the Archer River in the southern Gulf of Carpentaria (Rasheed et al. 1996). Observations in 2022 indicate that the higher biomass area of the Alligator Bank meadow remains an important feeding area for dugongs. Megaherbivore feeding activity can maintain the meadow in a lower biomass state, but could also have positive impacts for the meadow such as increasing seagrass productivity and spreading seeds (Scott et al. 2018, Tol et al. 2017).

In 2022 seagrass condition in the Alligator Bank seagrass meadow at Karumba continued to improve, with an improvement in all seagrass metrics for the second year in a row and a stable seed bank. These sustained increases are very encouraging and have resulted in a meadow score of very good with a very high score of 1. Favourable environmental conditions should allow seagrass to be maintained in very good condition. The high biomass across the meadow area and the healthy seed bank recorded in 2022 also means that the meadow is likely to have good levels of resilience, and a capacity to recover from future weather related or anthropogenic impacts during 2023.

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6 APPENDICIES

APPENDIX 1. SEAGRASS SCORE CALCULATION

A1.1 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 (1994-2003) following the methods of Carter et al. (2015) and Bryant et al. (2014). The 1994-2003 period incorporates a range of conditions present in the Port of Karumba, including El Niño and La Niña periods, and multiple extreme rainfall and river flow events (Sozou et al. 2016).

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 Section A1.4 Grade and Score Calculations and Figure A1.1).

A1.2 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 A1.1). Meadow area was classified as either highly stable, stable, variable, or highly variable (Table A1.1). The CV was calculated by dividing the standard deviation of the baseline years by the baseline for each condition indicator.

Table A1.1 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%	-

A1.3 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 A1.2).

TABLE A1.2. 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

A1.4 GRADE AND SCORE CALCULATIONS

A score system (0–1) and score range was applied to each grade to allow numerical comparisons of seagrass condition (see Carter et al. 2015 for a detailed description, and Table A1.3).

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 the current year's 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 A1.3). 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 A1.3. SCORE RANGE AND GRADING COLOURS USED IN THE KARUMBA SEAGRASS REPORT CARD.

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

Where species composition was determined to be anything less than in “perfect” condition (i.e. a score <1), a decision tree was used to determine whether equivalent and/or more persistent species were driving this grade/score (Figure A1.1). 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 A1.1). 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* 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 A1.1).

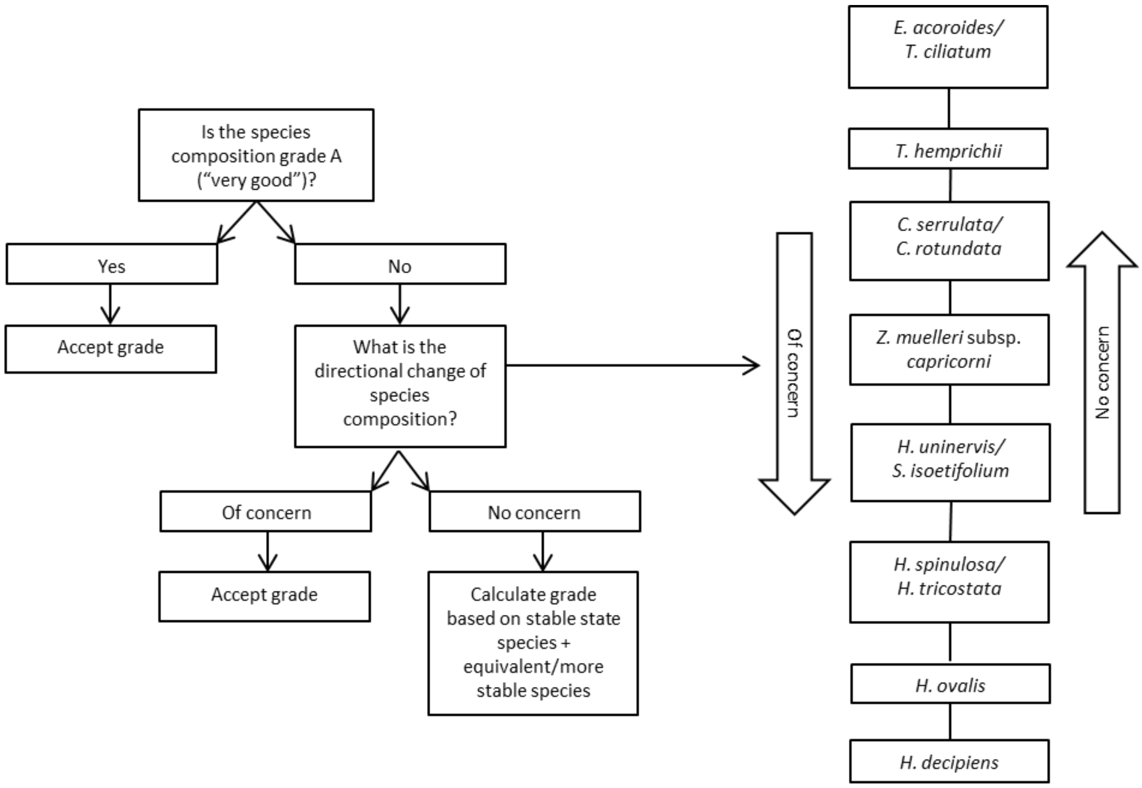

FIGURE A1.1 DECISION TREE AND DIRECTIONAL CHANGE ASSESSMENT FOR GRADING AND SCORING SEAGRASS SPECIES COMPOSITION.

A1.4 SCORE AGGREGATION

Each overall meadow grade/score was defined as the lowest grade/score of the three condition indicators within that meadow. The lowest score, rather than the mean of the three indicator scores, was applied in recognition that a poor grade for any one of the three described a seagrass meadow in poor condition. Maintenance of each of these three fundamental characteristics of a seagrass meadow is required to describe a healthy meadow. This method allowed the most conservative estimate of meadow condition to be made (Bryant et al. 2014). In cases where species composition was the lowest score, an average of both the species composition score and the next lowest score is used to determine the overall meadow score. This is to prevent a case where a meadow may have a spatial footprint and seagrass biomass but a score of zero due to changes in species composition.

Overall 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. BIOMASS SCORE CALCULATION EXAMPLE

An example of calculating a meadow score for biomass in satisfactory condition in 2019.

1. Determine the grade for the 2019 (current) biomass value (i.e. satisfactory).

2. Calculate the difference in biomass (B_{diff}) between the 2019 biomass value (B_{2019}) and the area value of the lower threshold boundary for the satisfactory grade ($B_{satisfactory}$):

$$B_{diff} = B_{2019} - B_{satisfactory}$$

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_{2019} takes up:

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

5. Determine the biomass score for 2019 ($Score_{2019}$) by scaling B_{prop} against the score range (SR) for the satisfactory grade ($SR_{satisfactory}$), i.e. 0.15 units:

$$Score_{2019} = LB_{satisfactory} + (B_{prop} \times SR_{satisfactory})$$

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