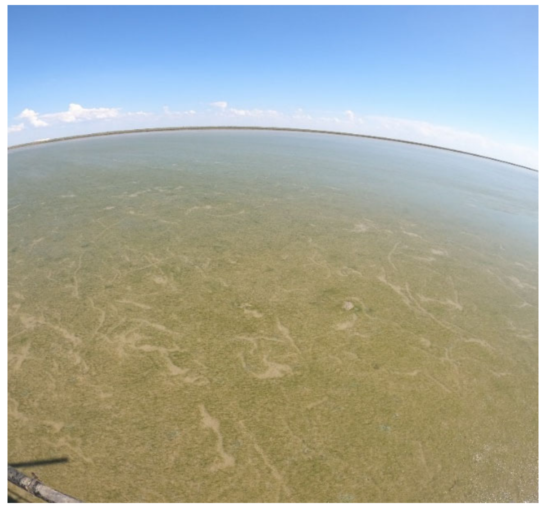

PORT OF KARUMBA LONG-TERM ANNUAL SEAGRASS MONITORING 2021

Scott A, McKenna S and Rasheed M

Report No. 21/70

January 2022

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A Report for Ports North

Report No. 21/70

January 2022

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KEY FINDINGS

Seagrass Condition 2021

VERY GOOD

1. In 2021 there were improvements in all seagrass condition indicators in the Karumba monitoring meadow. Seagrass condition was very good for the first time since 2017.
2. Seagrass condition at the Alligator Bank long term monitoring meadow improved in 2021, continuing the trajectory of recovery from the poorest condition in more than two decades recorded in 2019 following local floods.
3. Above average numbers of *Halodule uninervis* seeds and *Halophila ovalis* fruits were found in the meadow.
4. The seagrass meadow on Elbow Bank was also surveyed in 2021 and area remained high, however biomass was the lowest recorded.
5. The seagrass in Karumba is an important foraging ground for dugong with their feeding trails recorded in both seagrass meadows, particularly concentrated on Alligator Bank.
6. In 2021 environmental conditions were favourable, enabling significant recovery of the Alligator Bank seagrass meadow. The meadow has now fully recovered from the flood related declines recorded in 2019, with area, biomass and seed banks at high levels likely conferring good levels of resilience for the seagrass meadow in 2022.

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).

In 2021 seagrasses in the broader port limits were also surveyed as part of expanded surveys conducted every 3 years in the monitoring program. This included intertidal areas on Elbow Bank (Figure 1).

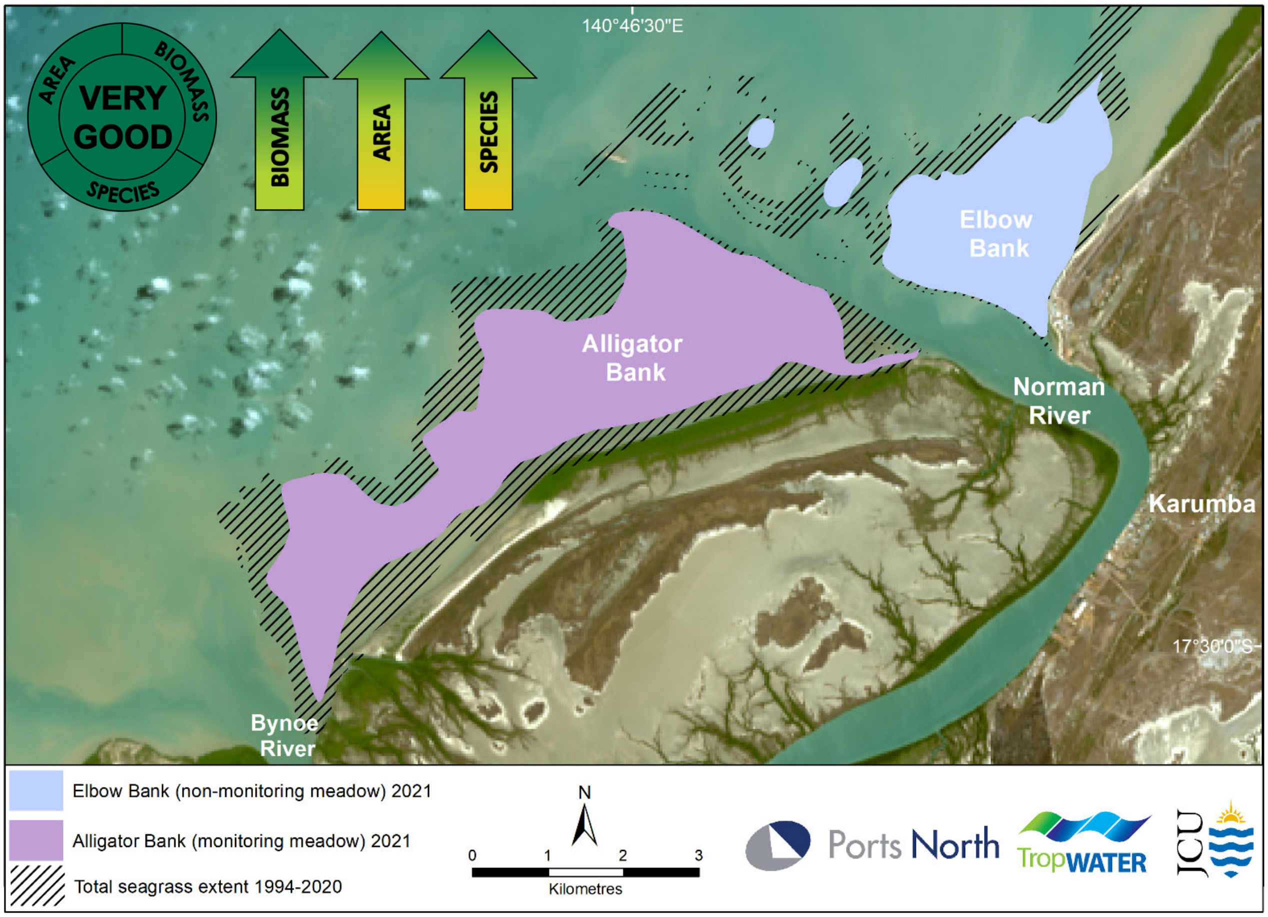

Figure 1. Seagrass condition at Alligator Bank, Karumba, 2021. Non-monitoring meadow at Elbow Bank also shown.

Seagrass in the Alligator Bank monitoring meadow at Karumba had fully recovered in 2021 from flood related declines and was in very good condition. This improvement continues the trajectory of recovery from 2019 after severe weather caused major losses, and the meadow was in the poorest condition recorded in more than two decades. Seagrass biomass, area and species composition all improved in 2021. From 2020 to 2021, the largest improvement was seen in area, with the south western end of the meadow returning for the first time since 2018. Additionally there was a substantial increase of the more stable species *Halodule uninervis* in 2021, displacing the colonising species *Halophia ovalis* that had driven much of the early recovery.

Accompanying the return of seagrass area, biomass and species was the return of above average numbers of *Halodule uninervis* seeds in the below ground seed bank, as well as *Halophila ovalis* fruits in the meadow.

Dugong feeding was recorded in both meadows at Karumba and was concentrated in the Alligator Bank monitoring meadow.

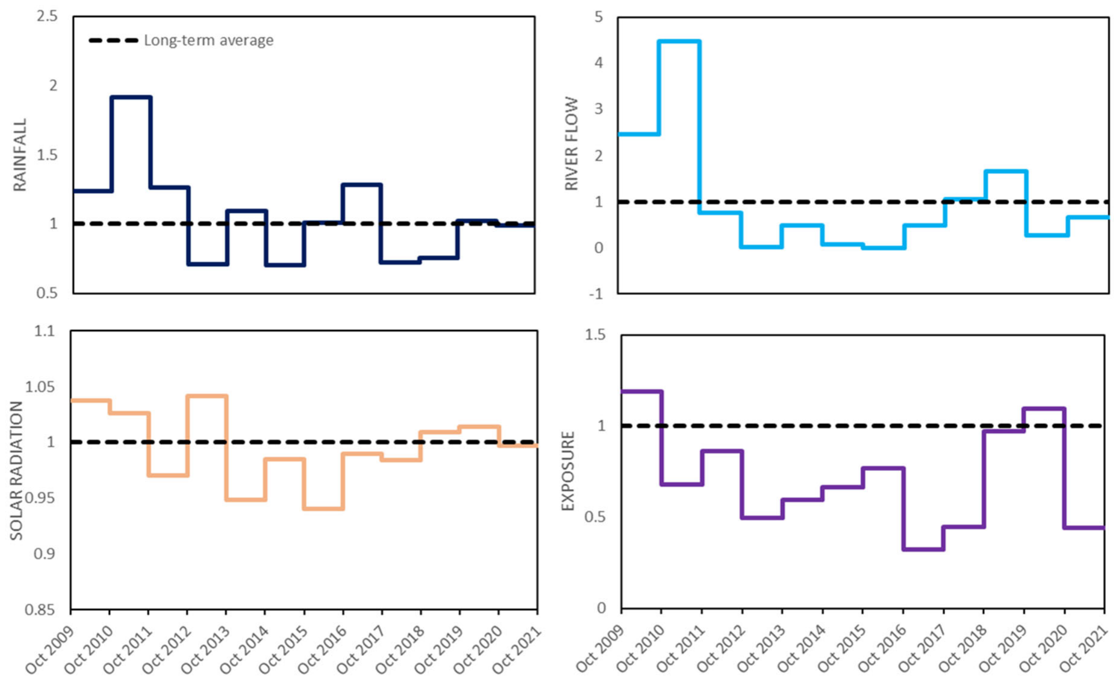

Figure 2. Change in climate variables as a proportion of the long-term average in Karumba. See Section 3.5 for detailed climate data.

The favourable environmental conditions in 2021 have facilitated meadow recovery, with all of the climate variables measured close to or below the long-term average in 2021 (Figure 2). The recovery of the meadow and the below ground seed bank in 2021, means Karumba seagrasses have a high level of resilience leading into 2022 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 2021, 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 the 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 September 2021 monitoring and port limit wide 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. Conduct an expanded survey to include intertidal seagrass on Elbow bank to provide updated information on seagrass distribution and density in the wider port area;
5. Assess seagrass condition in the Alligator Bank monitoring meadow by comparing results with previous monitoring surveys, and compare results with other seagrass monitoring programs throughout Queensland.

2 METHODS

2.1 Sampling Approach

The 2021 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 14-15th September 2021. The survey area covered the intertidal area of Alligator Bank and Elbow 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, and dugong feeding activity 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 monitoring meadow. A Van Veen sediment grab (0.01885m^{-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); dugong feeding trail presence/absence.
- 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 of unvegetated sediment

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) 2019, 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 (2003-2021) 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.

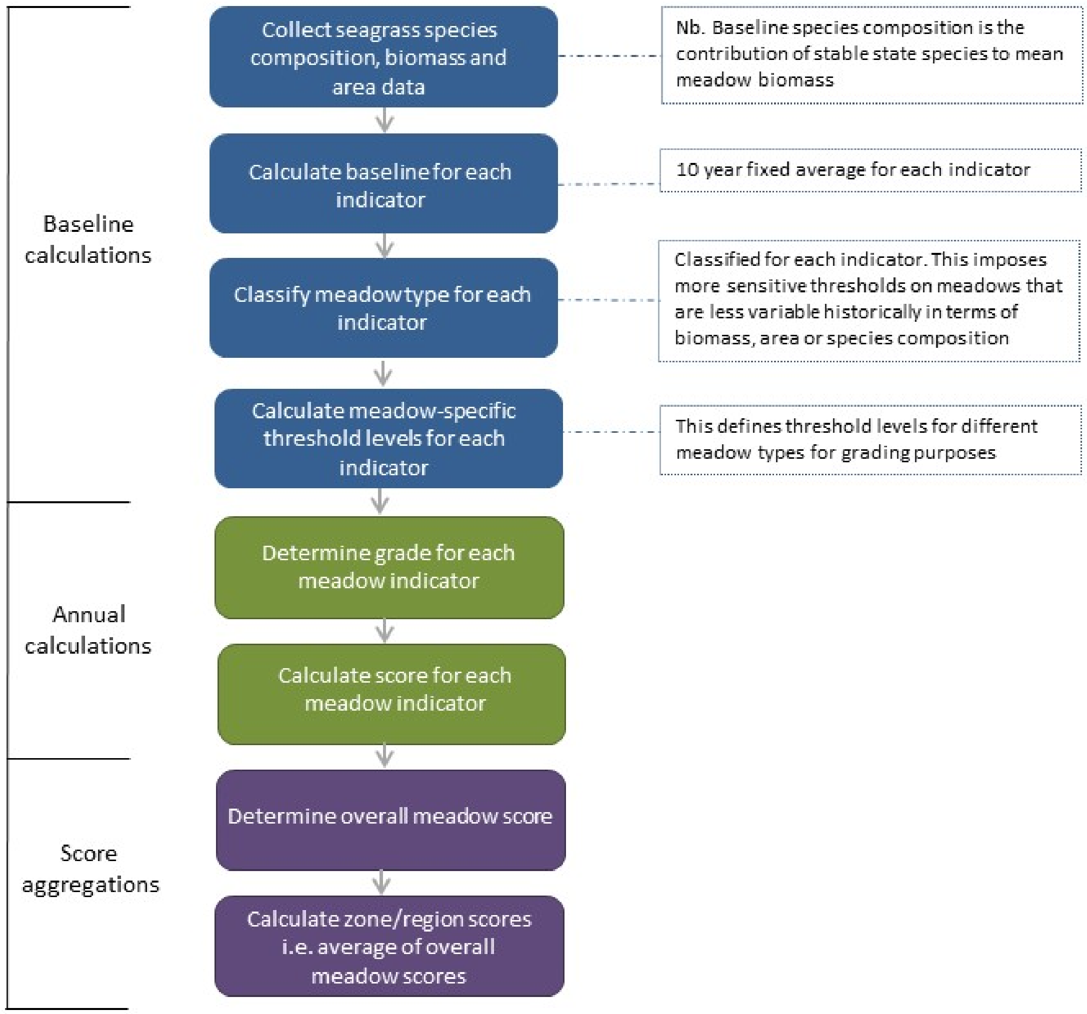

Figure 5. Process used to determine Karumba seagrass monitoring meadow condition grades and scores each year.

3 RESULTS

3.1 Seagrass Species

Seagrass was present at 102 of the 103 sites surveyed in the Alligator bank monitoring meadow in 2021 and at 36 of 41 sites surveyed on Elbow Bank. Two seagrass species were present in Karumba: *Halodule uninervis* (narrow leaf form) was the dominant species recorded and accounted for approximately 94% of above-ground seagrass biomass in the Alligator Bank Monitoring meadow, while *Halophila ovalis* accounted for the remaining 6%, (Figures 6 and 7). The Elbow Bank meadow was also dominated by *H. uninervis*, with this species accounting for approximately 69% of above-ground biomass, and *H. ovalis* accounting for 31%.

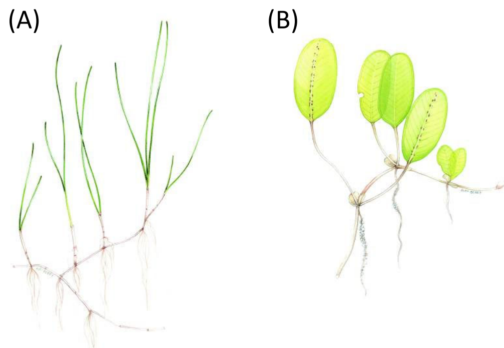

Figure 6. Seagrass species found in Karumba: (A) *Halodule uninervis*, Family Cymodoceaceae (narrow leaf form); (B) *Halophila ovalis*, Family Hydrocharitaceae.

3.2 Seagrass Condition in the Alligator Bank Monitoring Meadow

Seagrass in the Alligator Bank monitoring meadow was in a very good condition in 2021 (Table 3, Figure 7). The Alligator Bank meadow has recovered from the losses in biomass and area documented in the 2019 survey. Above-ground biomass increased from 3.8 $\pm$ 0.3 g DW m^{-2} in 2020 to 6.8 $\pm$ 0.7 g DW m^{-2} in 2021 and condition improved from good to very good (Table 3, Figure 7). Meadow area increased from 933 $\pm$ 9 ha in 2020 to 1324 $\pm$ 13 ha in 2021 and improved from satisfactory to very good condition (Table 3, Figures 7 and 8). Seagrass species composition has recovered from the lowest ever recorded score in 2020, to a very good score, with the meadow dominated by the more stable species *H. uninervis* in 2021.

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	0.93	1	0.93	0.93

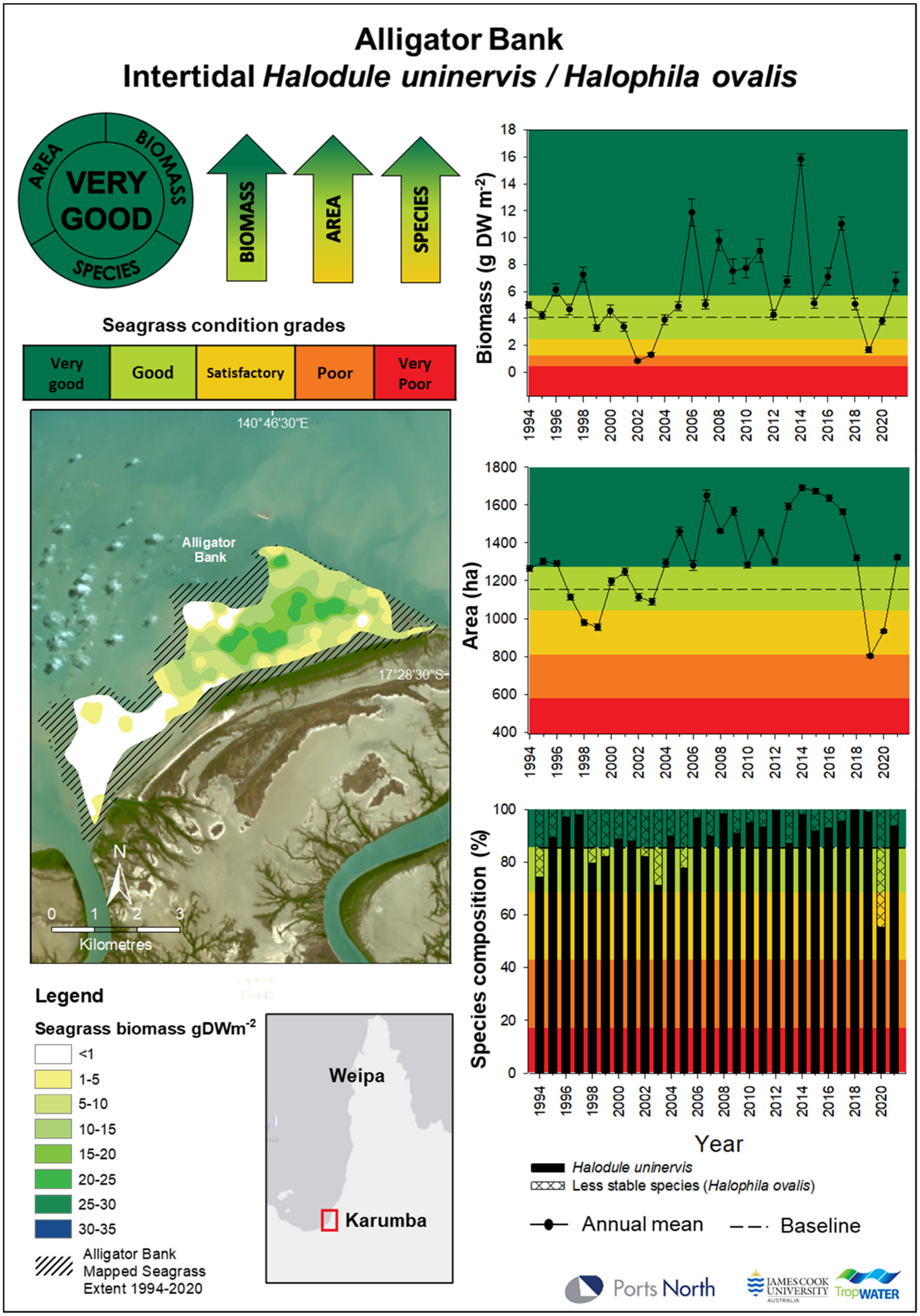

Figure 7. Changes in biomass, area and species composition for the Karumba seagrass monitoring meadow from 1994 to 2021 (biomass error bars = SE; area error bars = "R" reliability estimate).

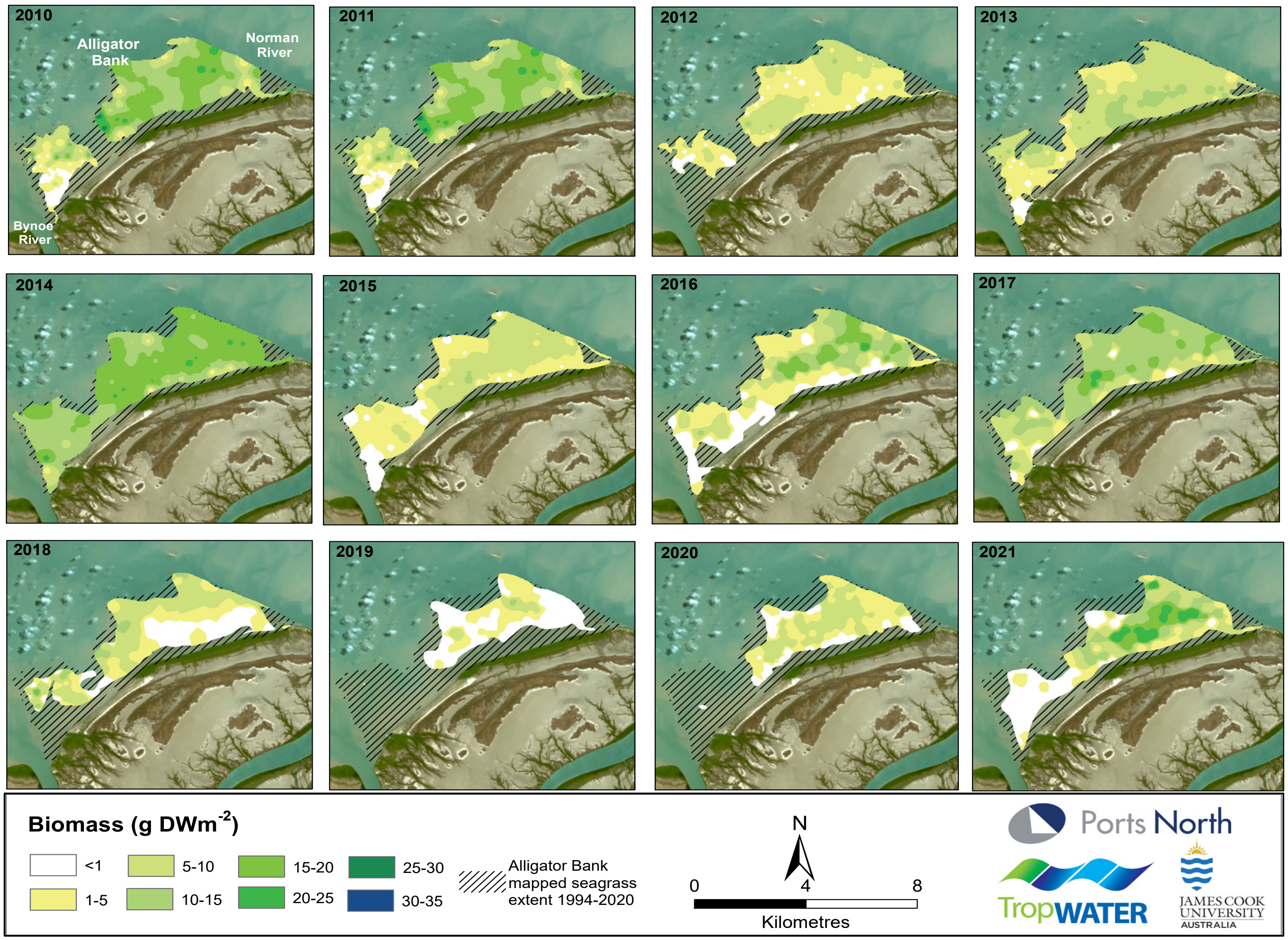

Figure 8. Biomass and area change in the Alligator Bank monitoring meadow, 2010 to 2021.

3.3 Seagrass in the broader Port of Karumba

In 2021 seagrasses in the broader Karumba port limits (beyond the Alligator Bank monitoring meadow) were surveyed. As in previous broader surveys; October 1994, October 1997, September 2015 and November 2018 (see Rasheed et al. 2001a, Sozou et al. 2016, Van de Wetering et al. 2018), large areas of intertidal seagrass were found (Figure 9).

A total of 41 habitat characterisation sites were assessed within the mapped boundary of the Elbow Bank seagrass meadow in 2021. Similar to previous surveys, *Halodule uninervis* and *Halophila ovalis* were the two species present and formed a large area of seagrass in several meadows across the bank, although in 2021 these meadows were less fragmented than in previous years.

Seagrass biomass on Elbow Bank in 2021 was 0.98 $\pm$0.37 g DW m^{-2}, which was lower than previously recorded values (Table 4). The area of seagrass on Elbow Bank in 2021 was the second highest recorded (Table 4).

Dugong feeding trails were recorded at 5% of sites on Elbow Bank (Figure 13) which is lower than the 36.4% recorded in 2018 and 33% recorded in 2015.

Table 4. Table of Area (ha) and Mean Biomass (g DW m^{-2}) of Elbow Bank seagrass monitoring surveys 1994, 1997, 2015, 2018 & 2021.

Area (ha)				
1994	**1997**	**2015**	**2018**	**2021**
152	422	571	543	567
Mean Biomass ± SE (g dw m^{-2})				
3.36 $\pm$ 0.30	6.99 $\pm$ 0.46	2.36 $\pm$ 0.41	1.32 $\pm$ 0.19	0.98 $\pm$ 0.37

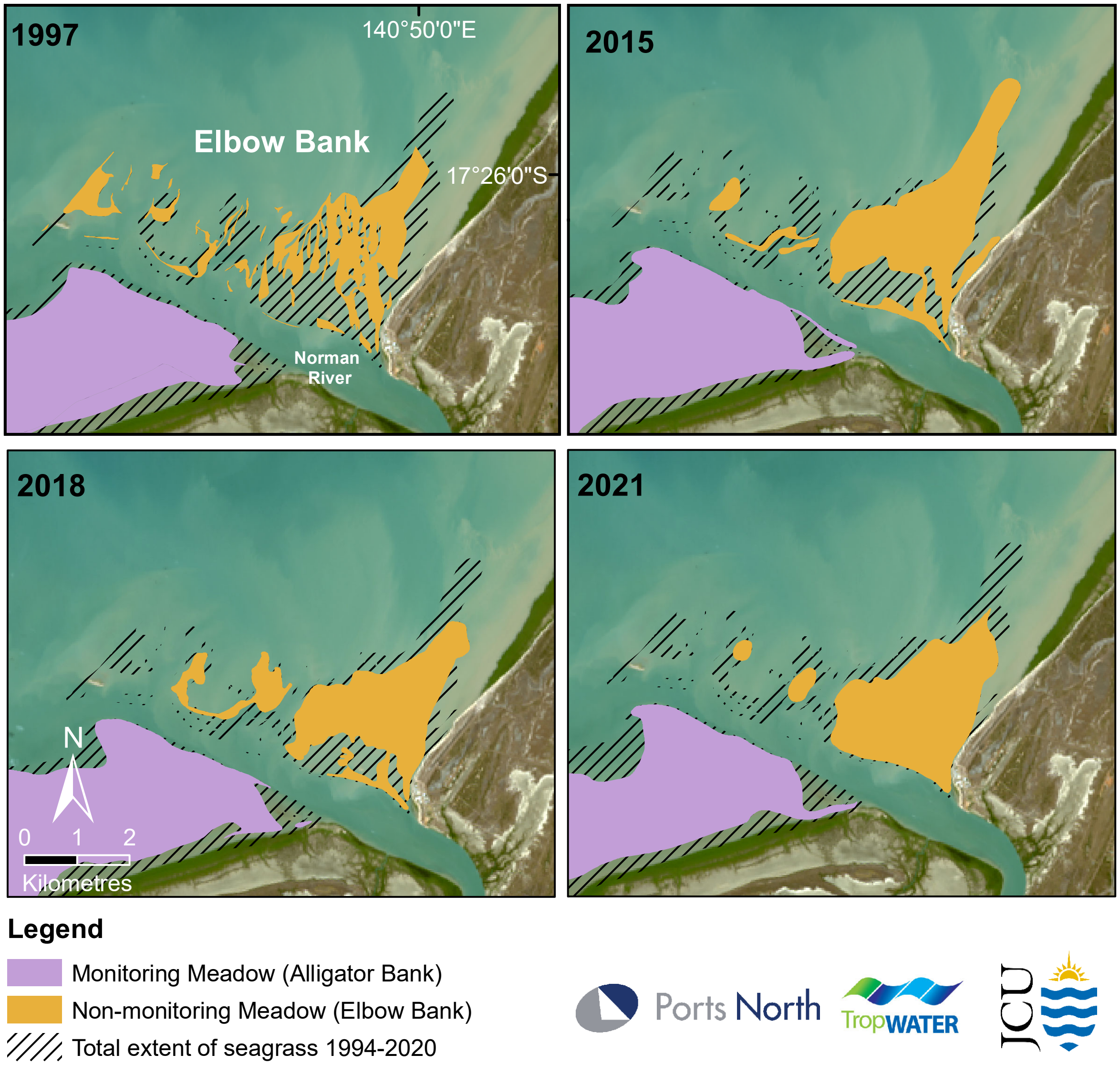

Figure 9. Comparative map of seagrass distribution on Elbow Bank for years 1997, 2015, 2018 and 2021.

3.4 Comparison with Previous Monitoring Surveys

Overall seagrass condition improved to very good in 2021 for the first time since 2017, continuing the trajectory of recovery from poor in 2019 and to satisfactory in 2020 (Table 3, Figure 7). This change in score was driven by improvements in seagrass biomass, area and species composition in the monitoring meadow. Above-ground biomass increased in 2021 and improved from good to very good. Area increased substantially in 2021 and improved from satisfactory to very good. Species composition increased from satisfactory to very good condition in 2021, reversing the condition declines seen in 2020.

Average meadow above-ground biomass increased by 3 g DW m^{-2} from 2020 to 2021 (Figure 7). This trend continues the steady recovery in above-ground biomass also seen in 2020, from the low levels in 2019. Above-ground biomass condition in 2021 has returned to very good for the first time since 2017 (Figure 7). There is now a larger area of high biomass seagrass within the monitoring meadow, and multiple sites where biomass of over 20 g DW m^{-2} was recorded (Figures 7 and 8).

Seagrass meadow area also improved substantially in 2021, with an over 70% increase compared to 2020. This increase resulted in an improvement in condition from satisfactory to very good, similar to above-ground biomass, the last time area at Karumba was very good was in 2017 (Figure 7). The meadow has once again expanded at the south-western end so that the overall footprint is similar to the historical area here, this is the first time the south western end of the meadow has been present since 2018 (Figure 8).

Seagrass species composition also improved to very good in 2021, from the lowest recorded score in 2020. The meadow was once again dominated by the more stable species *H. uninervis*, in 2021 this species made up 94% of biomass in the meadow (Figure 7). The proportion of *H. univervis* in the meadow has doubled since the 2020 survey and the values are now more similar to those recorded in previous years.

3.5 Seagrass Reproductive Capacity

Halodule uninervis seeds and pericarps (outer casings of seeds) were found throughout the monitoring meadow in 2021 (Figure 10), with a mean density of 84 seeds m^{-2} and 3 pericarps m^{-2} across the meadow. As the 2019 survey used a different sampling method, these results cannot be directly compared, however other survey years used a Van Veen grab and can be compared to 2021. *Halodule uninervis* seed density varied significantly among years at the .05 level (Chi square=88, df=17, p=<0.001) when compared against the NULL model, post hoc analysis showed that in 2021 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=152, df=17, p=<0.001) when compared against the NULL model, post hoc analysis showed that pericarp densities in 2021 were significantly lower than all other years apart from 2004-2007 (p=<0.05) (Figure 11A). Similar to previous years, there were no *H. uninervis* fruits or flowers found in the Alligator Bank meadow in 2021 (Figure 11B). There were an above average number of *H. ovalis* fruits in the meadow in 2021, and *H. ovalis* flowers were found here at one site for the first time since 2015 (Figures 10 and 11C).

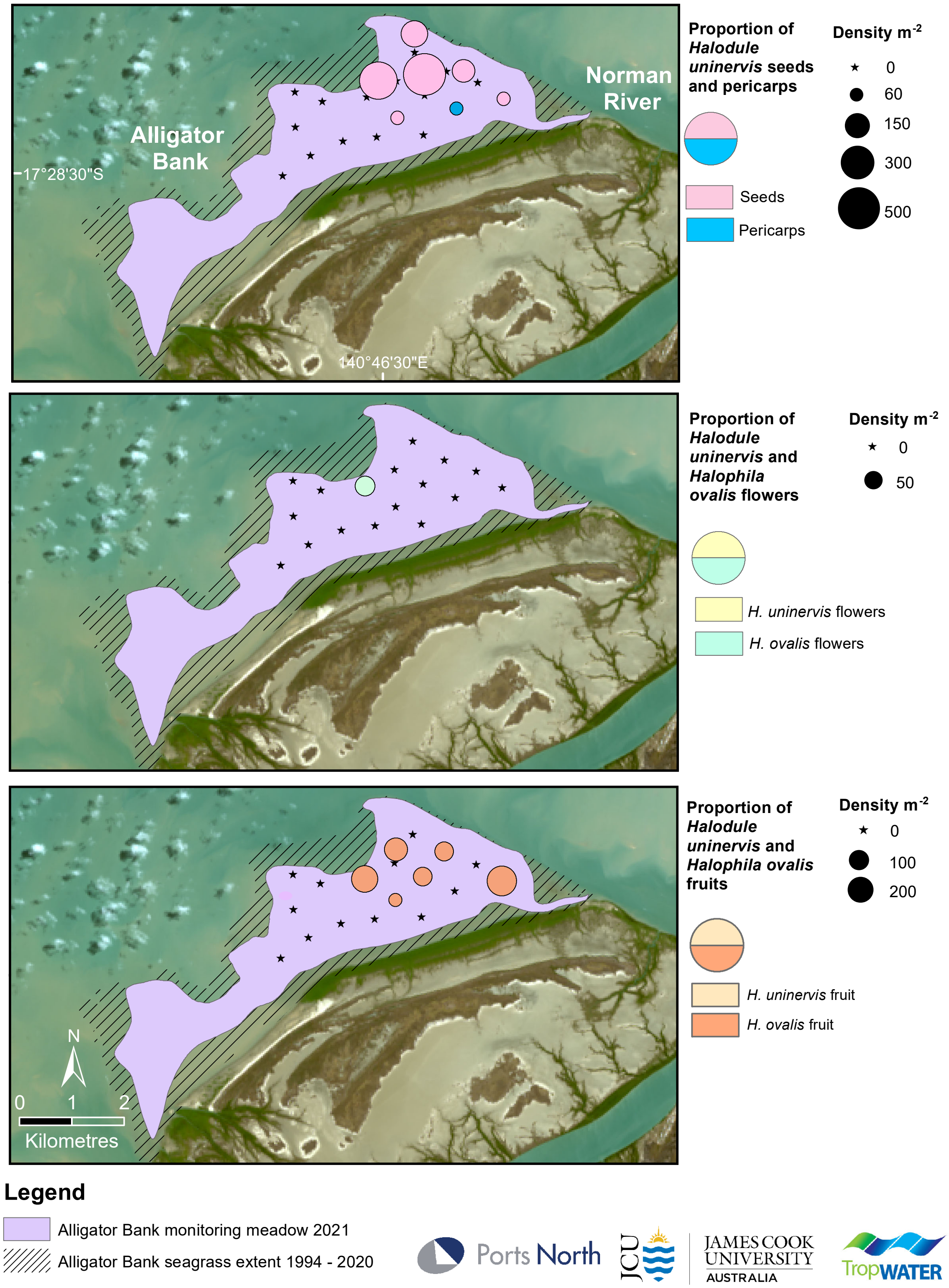

Figure 10. Density of *H. uninervis* seeds and pericarps, and *H. uninervis* and *H. ovalis* flowers and fruits in 2021.

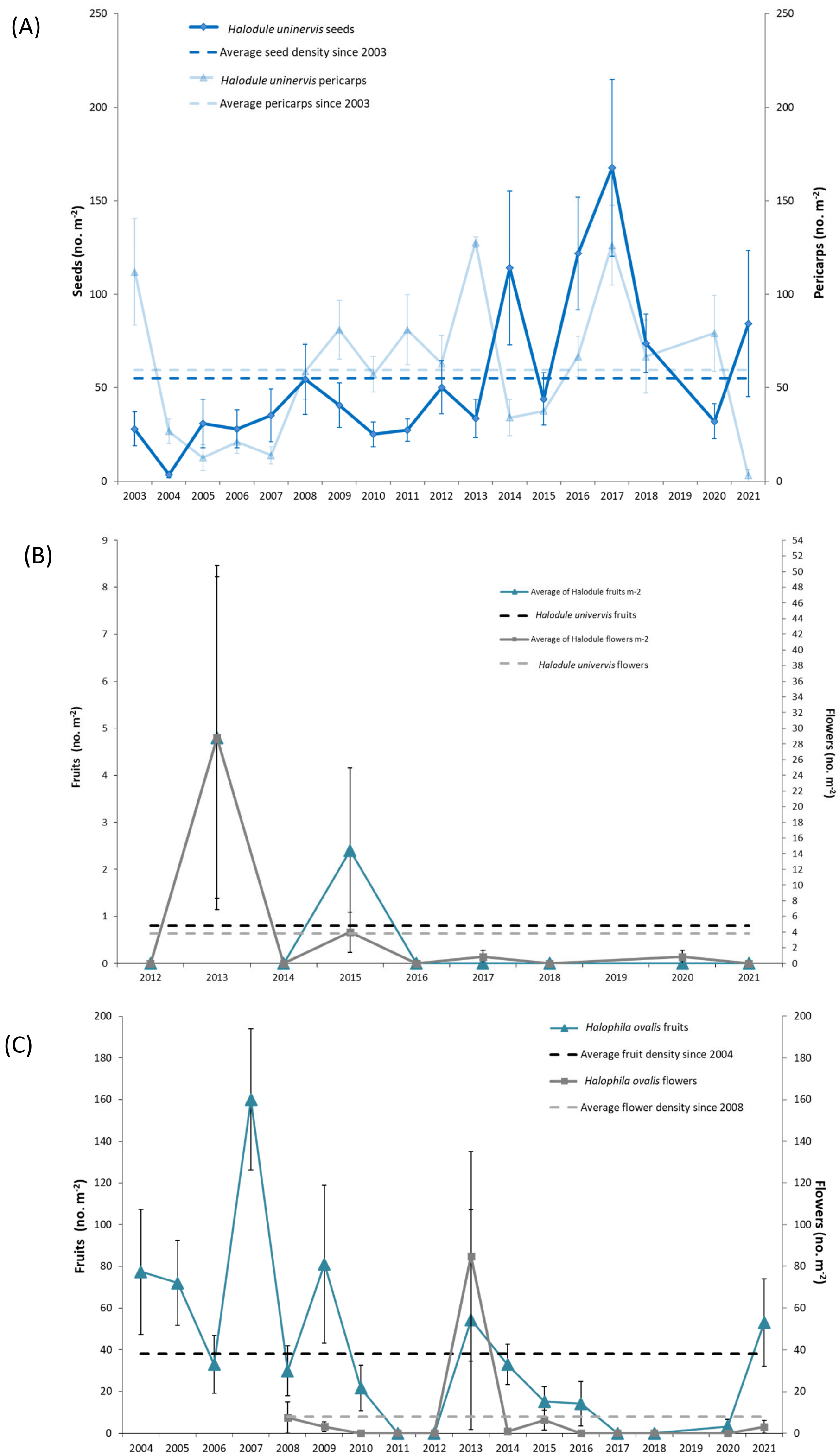

Figure 11. Mean density (± SE) of (A) *Halodule uninervis* seeds and pericarp pieces, (B) *H. uninervis* fruits and flowers, and (C) *Halophila ovalis* fruits sampled within the monitoring meadow. Data from 2019 have been excluded due to a different sampling method used.

3.6 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 at 29% of sites within the Alligator Bank monitoring meadow in 2021, compared to 52% in 2020, 9% in 2019 and 29% in 2018. Although this percentage is lower than previous years, the meadow area has been expanding over time. Feeding trails were particularly abundant on Alligator Bank (Figures 12 and 13).

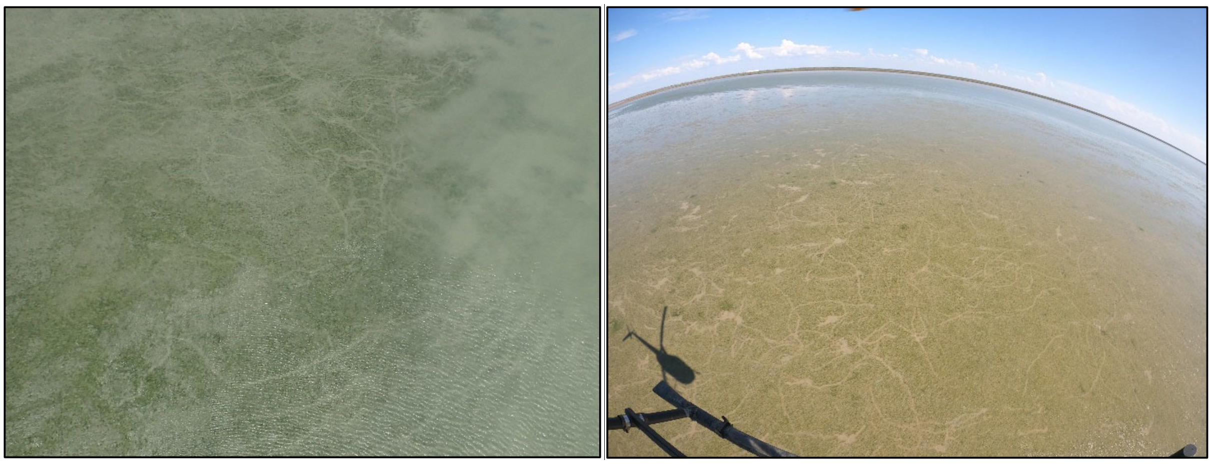

Figure 12. Dugong feeding trails in the Elbow Bank (left) and Alligator Bank (right) seagrass meadow in 2021.

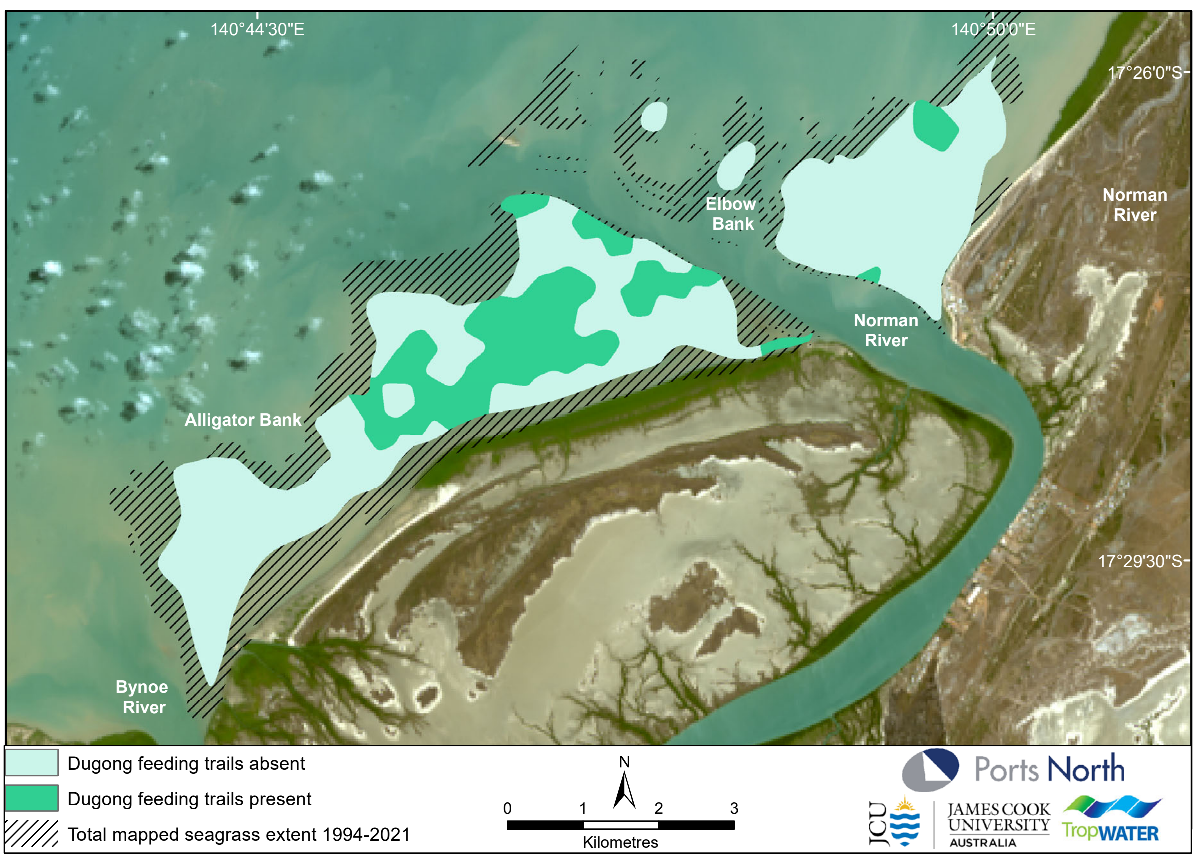

Figure 13. Location of dugong feeding trails within the Alligator Bank and Elbow Bank meadows in October 2021.

3.7 Karumba Environmental Conditions

3.7.1 Rainfall

Total annual rainfall for the Normanton area in the twelve months prior to the September 2021 survey was 785 mm. This was just below the average annual rainfall for the area (Figure 14), however, almost three quarters of this total (558 mm) occurred in January and February 2021 (Figure 15). During the survey month there was 6.2mm of rain, and only 4.2 mm fell in the three months leading up to the survey, all in August 2021 (Figure 15).

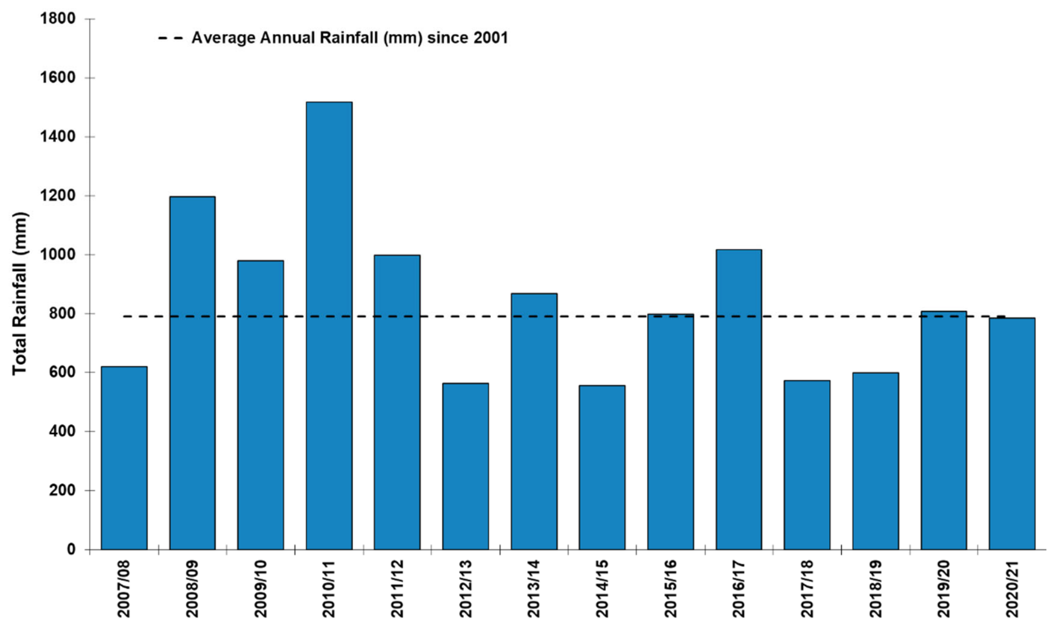

Figure 14. Total annual rainfall (mm) recorded at Normanton Airport, 2007/08 – 2020/21, in each 12 months prior to seagrass survey.

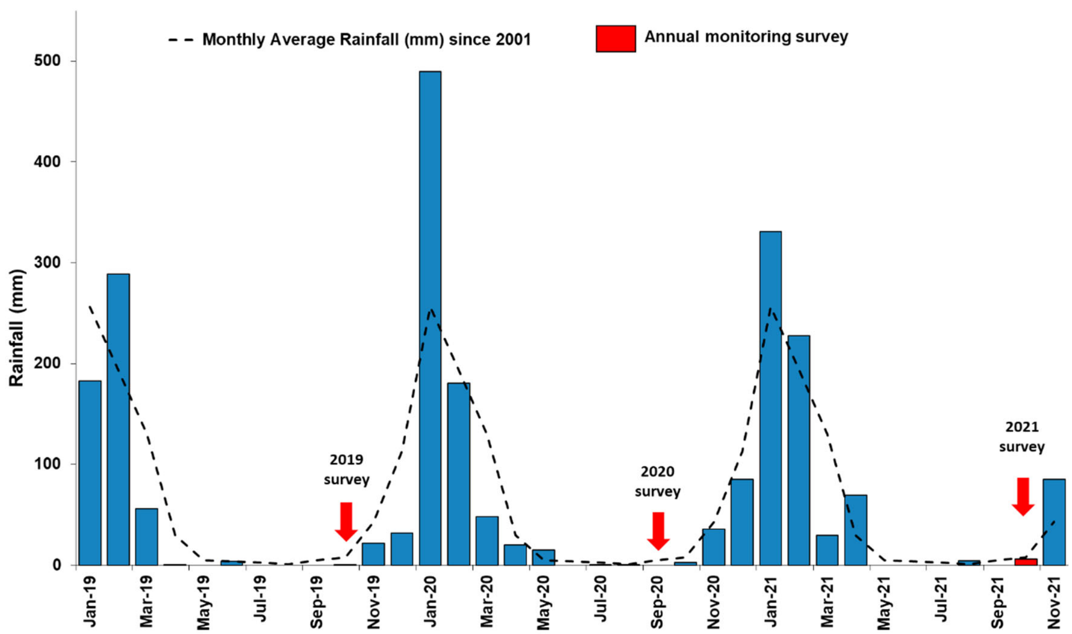

Figure 15. Total monthly rainfall (mm) recorded at Normanton Airport, January 2019 - November 2021.

3.7.2 River flow

Total annual river flow 12 months prior to the seagrass survey was 1181 GL, the majority of this flow (880GL) occurred in January 2021 (Figures 16 and 17). The total annual river flow was higher than 2019/20, but remained below the average (Figure 16).

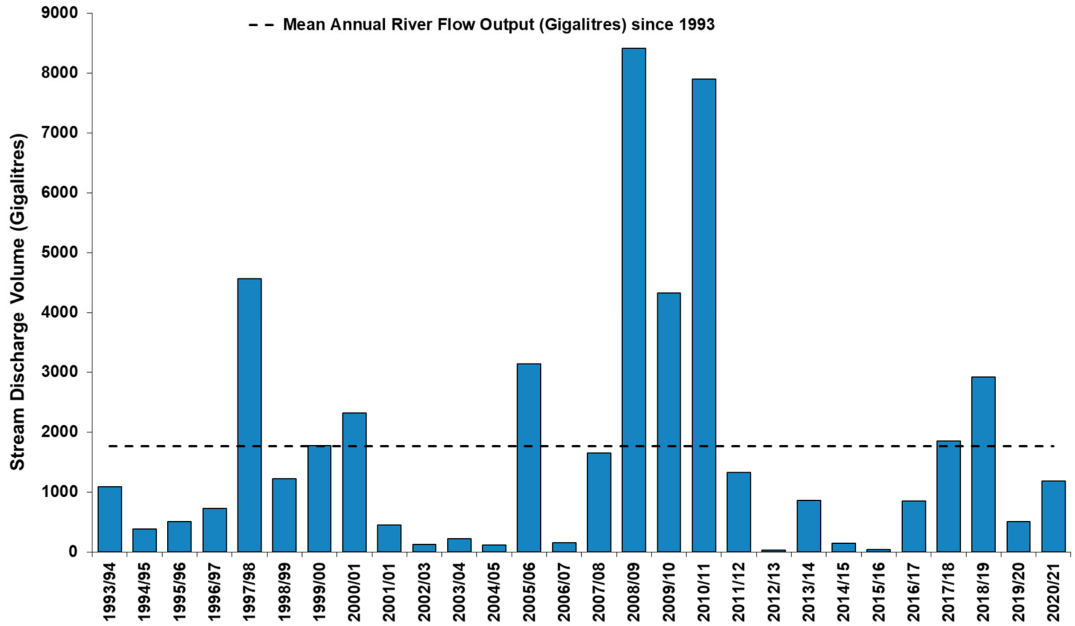

Figure 16. Total Norman River flow (measured as stream discharge volume in Gigalitres, GL) recorded at Glenore Weir, 1993/94 – 2020/21 twelve month year (2020/21) is twelve months prior to survey.

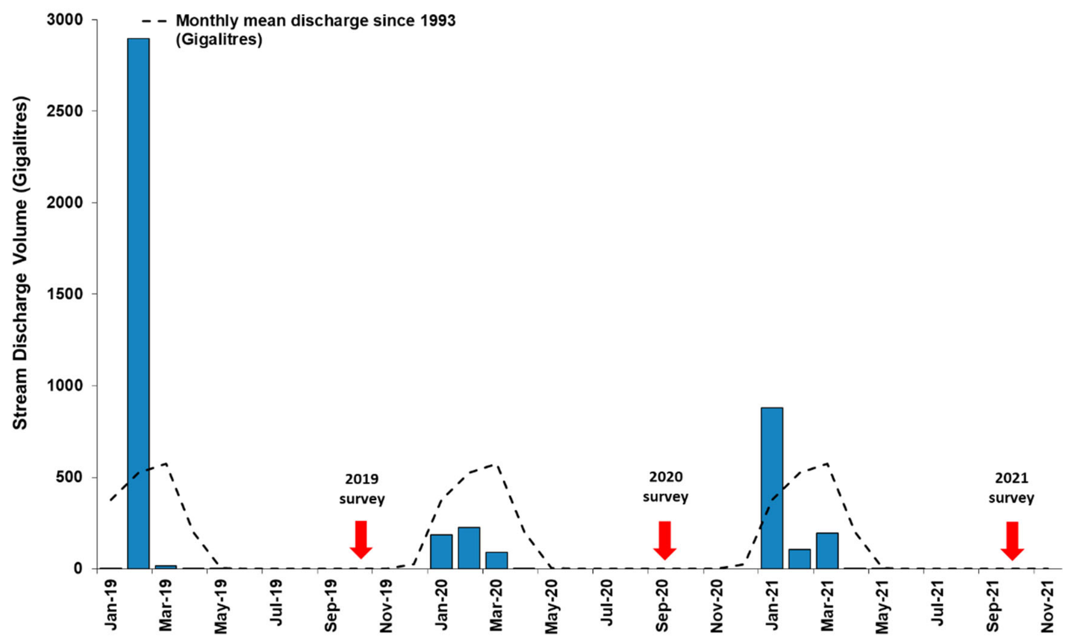

Figure 17. Total Norman River flow (measured as stream discharge volume in Gigalitres) recorded at Glenore Weir, January 2019 - November 2021.

3.7.3 Air Temperature

Air temperature was above-average in the region in 2020/21, with a mean annual daily maximum air temperature of 34.1°C (Figure 18). Monthly average maximum daily temperatures were close to the average for the year prior the survey, but above average in October 2021 (Figure 19).

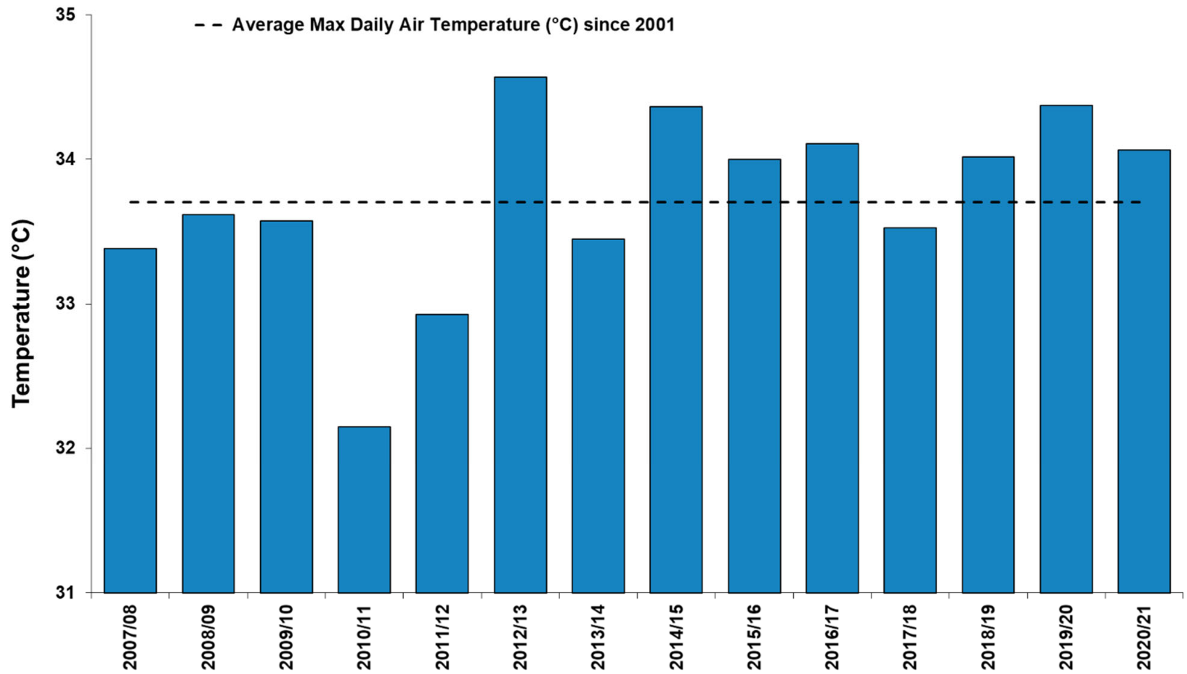

Figure 18. Mean maximum daily air temperature (°C) recorded at Normanton Airport, 2007/08 - 2020/21. Twelve month year (2020/21) is twelve months prior to survey.

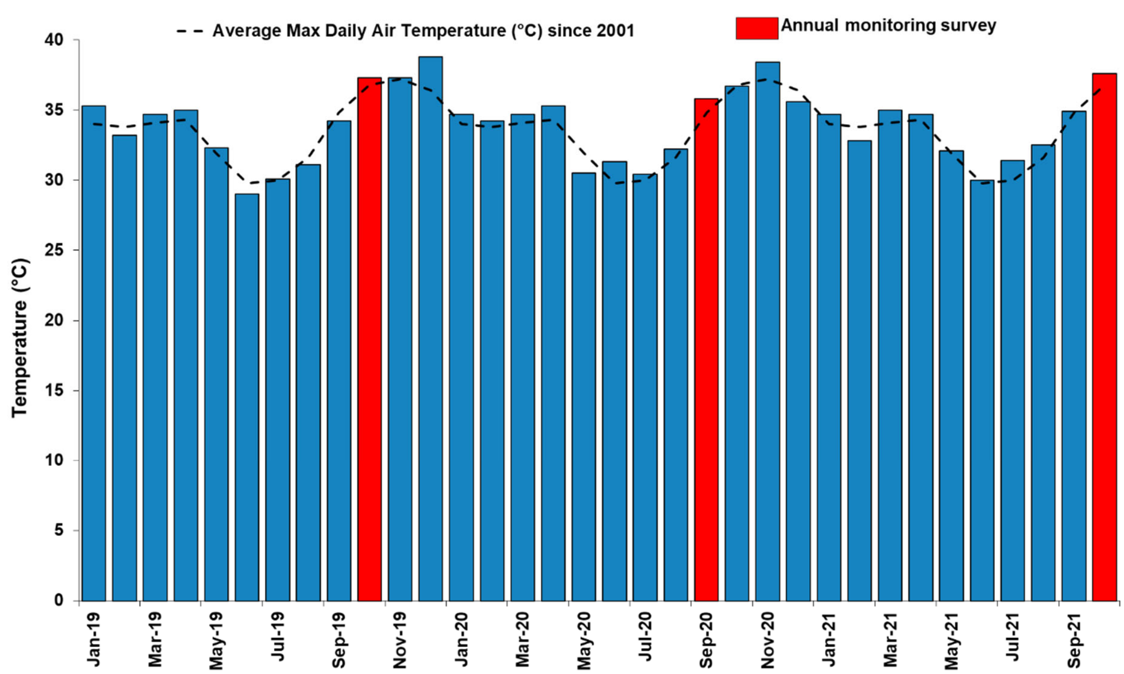

Figure 19. Monthly mean maximum daily air temperature (°C) recorded at Normanton Airport, January 2019 – October 2021.

3.7.4 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 2020/21 at 22.1 MJ m^{-2} (MegaJoules m^{-2}) (Figure 20), with solar exposure well above average in November 2020 and March 2021 (Figure 21).

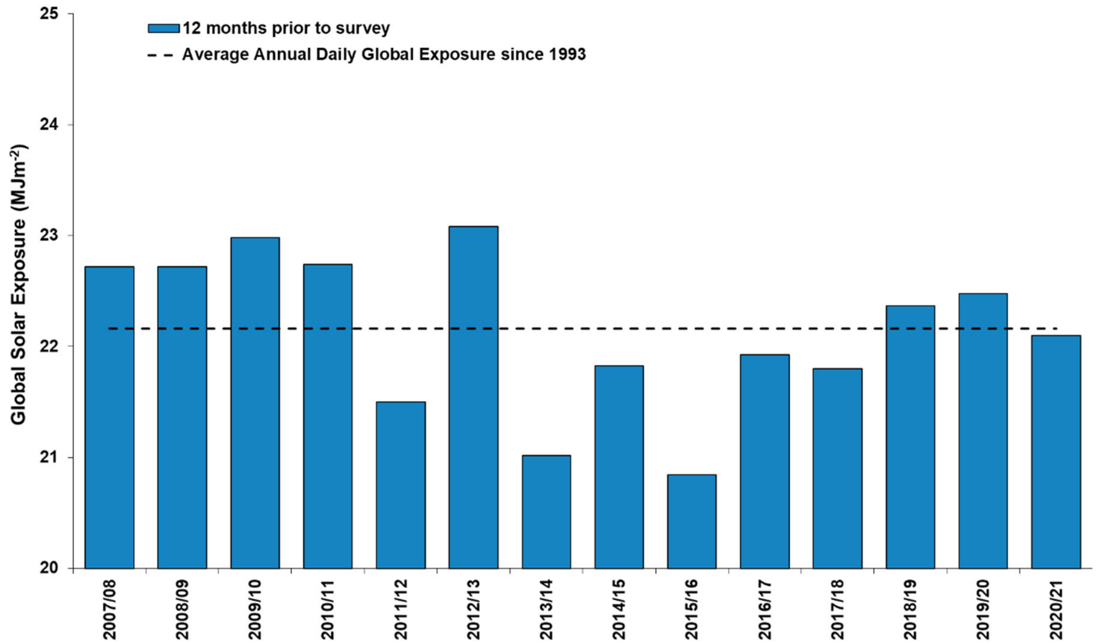

Figure 20. Mean daily global exposure (MegaJoules m^{-2}) recorded at Normanton Airport, 2007/08 – 2020/21. Twelve month year (2020/21) is twelve months prior to survey.

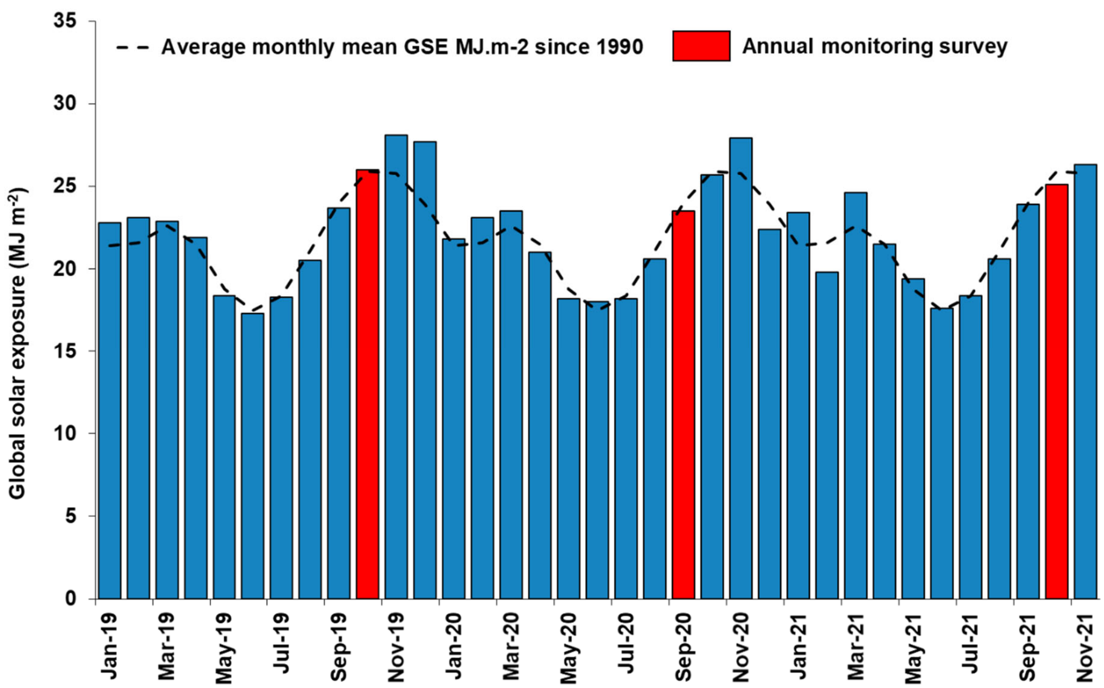

Figure 21. Mean daily global solar exposure (MegaJoules m^{-2}) recorded at Normanton Airport, January 2019-November 2021.

3.7.5 Tidal Exposure of Seagrass Meadows

Annual daytime exposure to air for intertidal seagrass was well below-average in 2021 (Figure 22). Intertidal banks were exposed for a total of 81 hours in the 12 months prior to the survey (Figure 22). Monthly daytime exposure to air was also below-average in the year prior to the survey, with the exception of April 2021 (Figure 23).

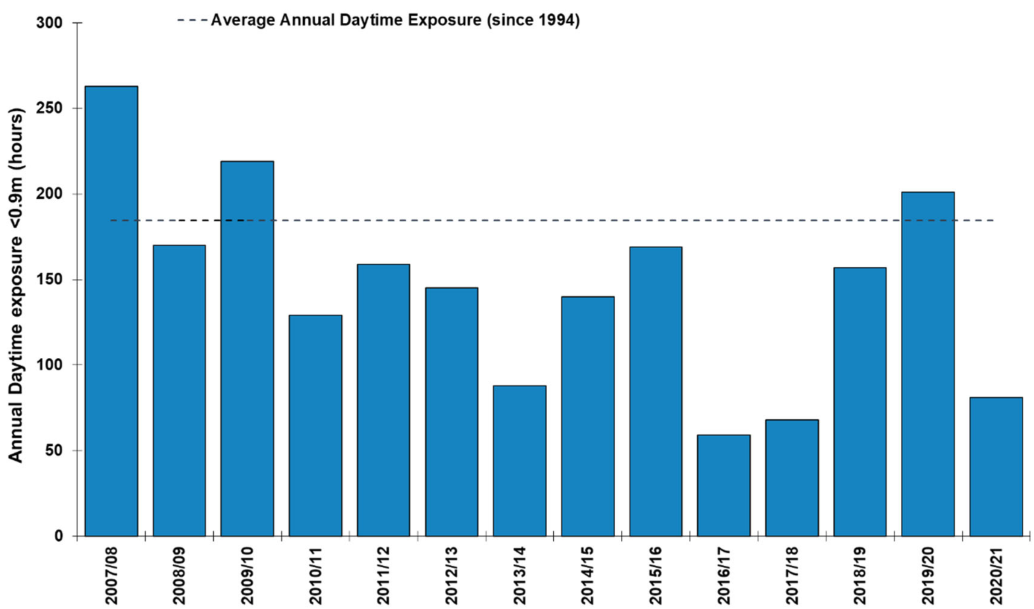

Figure 22. Total hours daytime exposure (annual) of intertidal seagrass in Karumba; 2007/08 – 2020/21. Twelve month year is twelve months prior to survey. *Assumes intertidal banks become exposed at a tide height <0.9m above Lowest Astronomical Tide.

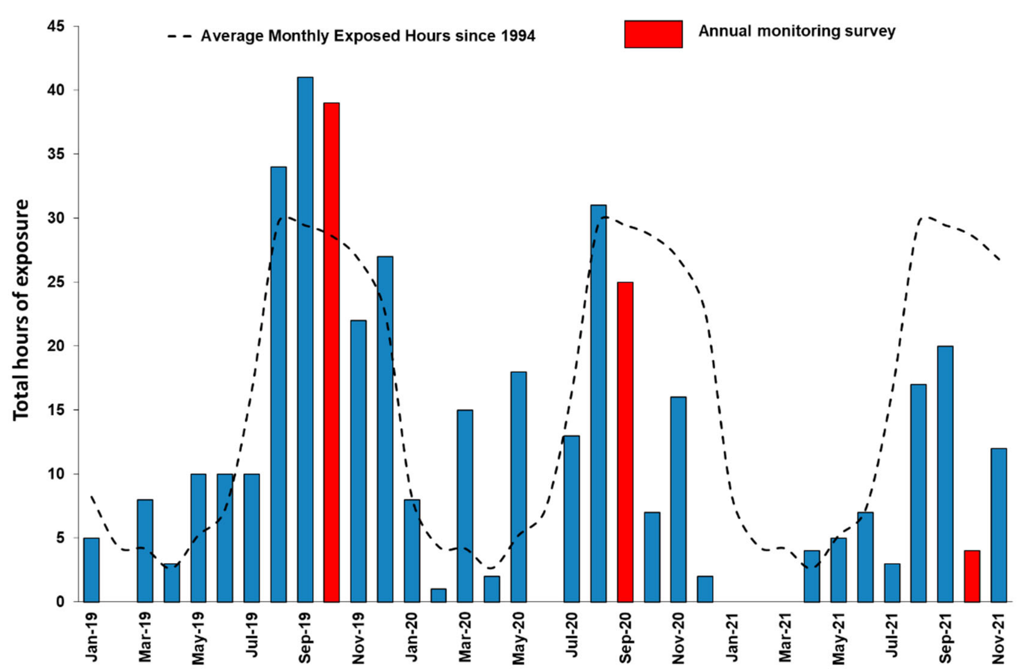

Figure 23. Total hours of daytime exposure (monthly), January 2019 to November 2021. *Assumes intertidal banks become exposed at a tide height <0.9m above Lowest Astronomical Tide.

4 DISCUSSION

In 2021 the Alligator Bank seagrass meadow had fully recovered from the flood related declines recorded in 2019. All seagrass indicators improved to give an overall score of very good, with dramatic improvements in both meadow area and species composition. Environmental conditions were favourable for seagrass growth, allowing significant recovery that was characterised by a high percentage of the usually dominant and more stable species *Halodule uninervis* returning to the meadow. The seed bank (seeds stored in the below ground sediments) was also replenished in 2021 following reductions in seed numbers in 2020, leading to increased meadow resilience.

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.

Environmental conditions were favourable for seagrass growth in 2021. 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 2021 these were all at levels considered to be favourable for seagrass growth. The only extreme weather was on 4th January 2021 when Tropical Cyclone Imogen crossed the coast just north of Karumba, with 263 mm of rain falling in one day causing flooding and high river flow rates for much of January. This resulted in above average rainfall and river flow for January 2021, however this event was less severe than previous years, and did not cause sustained flooding or a persistent turbid plume, so it does not appear to have had a long-term impact on seagrass recovery.

Recovery of the seagrass meadow at Karumba has taken two 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. Maintenance of the very good condition of the seagrass meadow will depend on favourable conditions remaining, but the 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 2021.

In 2021 there was a dramatic improvement in the species composition score in Karumba, with a shift towards the more stable species *H. uninervis*, which made up 94% of seagrass biomass. This is an improvement from 2020, where the colonising species *H. ovalis* made up 45% of seagrass biomass in the meadow, this was the highest proportion in the 27-year history of sampling at Karumba. 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 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).

In 2021 seagrasses in the broader port limits of Karumba were also surveyed, including the meadow on Elbow Bank. This area was last surveyed in 2018 prior to the most serious flooding and flow events which caused declines in the Alligator Bank meadow. It is likely this meadow was also impacted by flooding in 2018, and particularly 2019, and may still be recovering. Although meadow area was the second highest recorded at Elbow Bank in 2021, seagrass biomass was the lowest recorded and there was a high percentage of colonising *H. ovalis* present in the meadow. The Elbow Bank meadow appears to be recovering at a slower rate than the meadow on Alligator Bank, this may be due to its smaller size and often more fragmented nature. Fragmented meadows may be less resilient and can take longer to recover from disturbance (Unsworth et al. 2015), however favourable environmental conditions should allow increases in biomass of *H. uninervis* in this meadow similar to those seen on the Alligator Bank meadow.

Seed densities in the Karumba Alligator Bank monitoring meadow increased in 2021 and were above average, whereas numbers of pericarps were very low. This was a shift from 2020 where there were high numbers of pericarps but low numbers of seeds. This shift suggests that in 2020 seeds in the seed bank were germinating to help drive recovery, whereas in 2021 the seed bank was replenished and fewer seeds were germinating. 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).

Seagrasses provide a wide range of important ecosystem services and the recovery 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). Although dugong feeding activity was observed at fewer sites in 2021 than in 2020, the meadow area was much larger in 2021, and also included some lower biomass areas at the south western end. 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 2021 seagrass condition in the Karumba seagrass meadow had recovered with an improvement in all seagrass metrics, and replenishment of the seed bank. These improvements are very encouraging and have resulted in a meadow score of very good. Favourable environmental conditions should allow seagrass to be maintained in very good condition. The high biomass, area and healthy seed bank recorded in 2021 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 2022.

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6 APPENDICES

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			Decrease below threshold from previous year		

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	≥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 A1.1). 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).

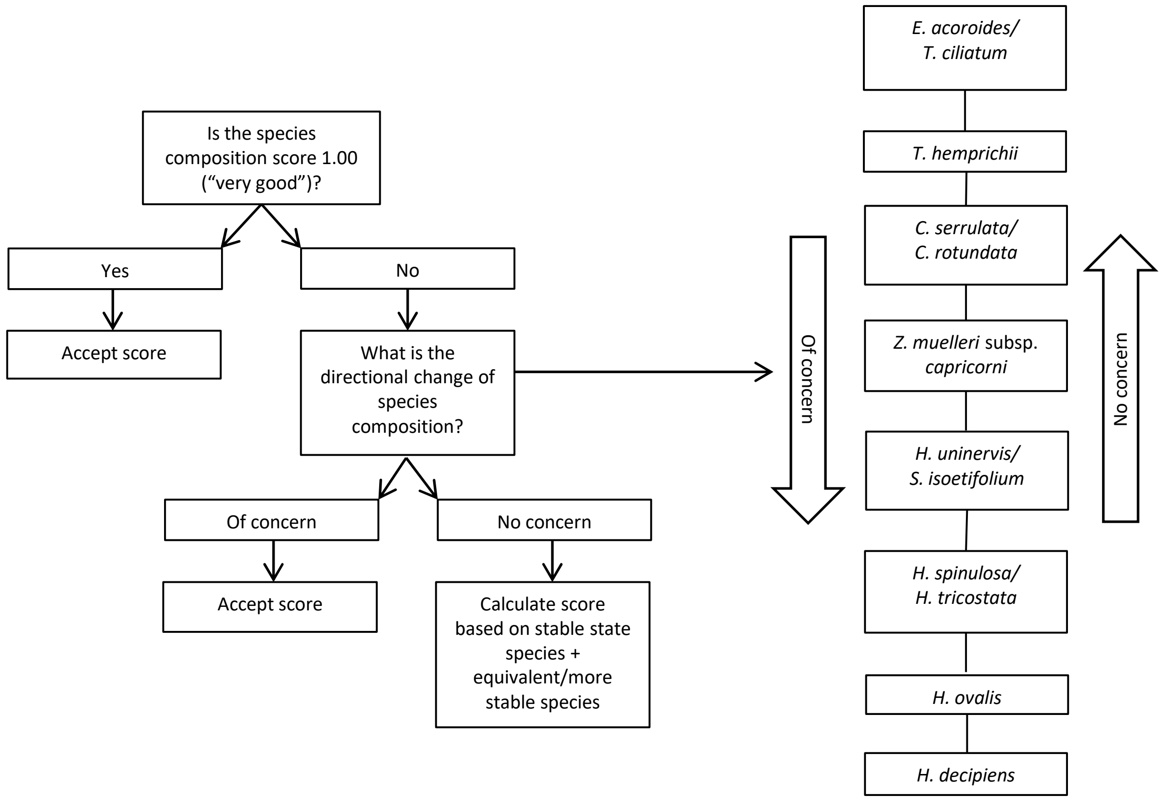

Figure A1.1. (a) Decision tree and (b) directional change assessment for grading and scoring species composition for Karumba seagrass.

A1.5 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.

Appendix 2. Biomass score calculation example

1. Determine the grade for the 2015 (current) biomass value (i.e. good).

2. Calculate the difference in biomass (B_{diff}) between the 2015 biomass value (B_{2015}) and the biomass value of the lower threshold boundary for the "good" grade (B_{good}):

$$B_{diff} = B_{2015} - B_{good}$$

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

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

$$B_{range} = B_{very\ good} - B_{good}$$

Where B_{good} is the upper threshold boundary for the good 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 mean plus the standard error (i.e. the top of the error bar) for the maximum recorded mean annual value for that indicator and meadow.

4. Calculate the proportion of the good grade (B_{prop}) that B_{2015} takes up:

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

5. Determine the biomass score for 2015 ($Score_{2015}$) by scaling B_{prop} against the score range (SR) for the good grade (SR_{good}), i.e. 0.20 units (see Table 6):

$$Score_{2015} = LB_{good} + (B_{prop} \times SR_{good})$$

Where LB_{good} is the defined lower bound (LB) score threshold for the good grade, i.e. 0.65 units.