


Long-term seagrass monitoring in Roebuck Bay, Broome:

Report on the first 10 years.


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June 2017

This report should be cited as:
McKenzie, L.J., Yoshida, R.L., Langlois, L., Rau, J., Weatherall, K., Bishop, F., Bain, D., Ferguson, S. and Lindsay, M. (2017). *Long-term seagrass monitoring in Roebuck Bay, Broome: Report on the first 10 years*. A report for the Broome Community Seagrass Monitoring Project, Environs Kimberley. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) report 17/35. James Cook University, Cairns, Australia. 44 pp.

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This publication has been compiled with support from Environs Kimberley by Seagrass-Watch HQ.

Cover images: photos courtesy Seagrass-Watch HQ (Len McKenzie & Rudi Yoshida) and Broome Community Seagrass Monitoring Project.

Acknowledgments:
The datasets used within this report are the result of many people's efforts over the past 10 years. We thank the past and present participants of the Broome Community Seagrass Monitoring Project for their continued support and giving their valuable time collecting field data. We thank the team from Environs Kimberley and the WA Department of Parks and Wildlife for their support. We also thank our other project partners Nyamba Buru Yawuru and Roebuck Bay Working Group. Funding for the project has been provided by CoastWest, the Kimberley Ports Authority, Normal Wettenhall Foundation, the Shire of Broome, Foundation for Rural and Regional Renewal, Rangelands NRM and Seagrass-Watch HQ. We acknowledge the traditional custodians of the lands on which we conducted this project. We pay our respects to ancestors and elders, past, present and future.

Author Contributions:
Framing hypotheses and experimental design: LM, RY, DB. Field work: LM, RY, JR, KW, FB, DB, SF, ML. Data analysis and interpretation: LM, RY, LL. Manuscript preparation: LM, RY, LL, ML.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

ACRONYMS & ABBREVIATIONS USED IN THIS REPORT

App .... Application software
BCSMP .... Broome Community Seagrass Monitoring Project
CI .... Confidence Interval
GPS .... Global Positioning System
HQ .... Head Quarters
JCU .... James Cook University
km .... kilometre
LAT .... Lowest Astronomical Tide
m .... metre
MDD .... Minimum Detectable Difference
QAQC .... Quality Assurance-Quality Control
SE .... Standard Error
TropWATER ..... Centre for Tropical Water & Aquatic Ecosystem Research

EXECUTIVE SUMMARY

Introduction

This report summarises data from the first ten years (2007 to 2016) of seagrass monitoring in northern Roebuck Bay, in the Kimberley region of Western Australian. The aim of the monitoring program was to assess the status and trends of seagrass meadow condition in Roebuck Bay over time, at replicate sites using standardised assessment measures, to provide an early warning of environmental decline. Field data was collected by trained participants from the Broome Community Seagrass Monitoring Project, coordinated by Environs Kimberley in partnership with Seagrass-Watch HQ.

We report on seagrass community and environment condition, including temporal and spatial trends in seagrass abundance, species composition, canopy height and seed banks, as well as epiphyte, macroalgae and *Lyngbya majuscula* abundances at intertidal sites in northern Roebuck Bay. We identify the key features of the communities and provide some insight into the drivers of change. We also integrated reporting on Roebuck Bay seagrass condition through the production of a pilot report card. The pilot report card used two indicators of seagrass condition, based on their significance to seagrass resilience: abundance, which represents the state of the seagrass to resist stressors; and seed banks, which represents the capacity of the seagrass to recover from loss/disturbance. Finally, we recommended a number of priority actions/activities and research questions to assist with the management of the ecological values of seagrass communities in Roebuck Bay and the Yawuru Nagulagun Marine Park.

Results & key findings:

Two species of seagrass (*Halodule uninervis* and *Halophila ovalis*) with an additional two species (*Halodule pinifolia* and *Halophila minor*) under review for synonymy, were confirmed from Roebuck Bay.

Long-term monitoring of seagrass condition was conducted quarterly (every 3 months) since 2007 at 3 replicate sites in the enduring seagrass meadows of northern Roebuck Bay. Field monitoring was conducted by trained participants from the Broome Community Seagrass Monitoring Project (BCSMP), and the quality of data submitted was moderate to good. An outcome of the QAQC process was that accuracy of data collected by BCSMP increases with training frequency, but requires considerable effort to correct when training frequency decreases. Approximately 15% of data submitted was non-compliant and nearly a third required correction by Seagrass-Watch HQ. Nevertheless, greater than 95% of data was of high quality and sensitive at detecting change in seagrass abundance (MDD <6%, with 80% power); meeting the statistical requirements for monitoring seagrass habitat cover globally.

Over the decade of monitoring, seagrass abundance (% cover) followed a unimodal pattern of growth annually, with higher abundances in late-dry to early-monsoon (October-December) and lower in late-monsoon to dry (April-July) seasons of each year. Seagrass abundance in Roebuck Bay appears to be primarily driven by environmental factors which modify the interactive effect of sea water temperature (over preceding 2 weeks) and light availability. A dominate negative influence on available light appears to be runoff from seasonal rainfall in the preceding 3 months. Although seagrass abundance fluctuated between years, there were no detectable long-term trends at any site. Of particular note is the lower seagrass abundance reported through much of the monitoring period at the site immediately adjacent to the Port of Broome.

The most abundant seagrass was the opportunistic foundational species *Halodule uninervis* which dominated the meadows in abundance and canopy height throughout the decade of monitoring. The colonising species *Halophila ovalis* also occurred throughout the decade of monitoring, but fluctuated seasonally in abundance, declining in the wet season (monsoon and late-monsoon).

Macroalgal abundances fluctuated both within and between years, but remained low at all sites with no long-term trend. Epiphyte abundances were similar across sites, being significantly higher in 2007-2009 and 2013-2014, and generally more abundant in late-dry/early monsoon of each year. No long-term trends were detectable. Epiphyte abundance appears to be driven by increasing light availability and lower mean temperatures.

Lyngbya majuscula occurred episodically across all sites throughout the decade, particularly during the early months of the year. When present, *L. majuscula* abundances remained low to very low and did not appear to significantly impact seagrass abundance. *L. majuscula* abundances increased after prolonged periods of above average rainfall (possibly a consequence of elevated nutrients in runoff) once growth conditions (increasing temperature and light availability) had improved.

A seed bank of the foundation seagrass *Halodule uninervis* persisted at all sites, and although highly variable, densities appeared higher in the wet (December to May), after the main seagrass growing period (August to December). Analysis suggests that meadows may require only a moderate seed bank for recovery capacity, and that greater sized seed banks provide greater probability of recovery (i.e. greater probability of viable seeds) but not necessarily greater abundance.

Climate for the decade was wetter, windier, and warmer than the long-term average (1939-2016). Seagrass abundance declined to its lowest overall abundances since monitoring was established after the fourth consecutive year of above-average rainfall (2011 to 2014). Over the decade, 2016 was the warmest year on average followed by 2010; both years were periods of increased seagrass growth where abundances improved.

A pilot report card was developed using two indicators of seagrass condition, based on their significance to seagrass resilience: abundance, which represents the state of the seagrass to resist stressors; and seed banks, which represents the capacity of the seagrass to recover from loss/disturbance. The pilot report card representing the annual relative health of seagrass in Roebuck Bay, shows that seagrass condition has fluctuated over the 10-years of monitoring. Seagrass condition was in a fair state when monitoring was established in 2007, but improved the following year to a good condition where it remained until 2014 (Figure 1). From 2014 seagrass condition had declined to fair, but improved to good in 2016 (grade A) (Figure 1), driven by improving abundances and seed banks.

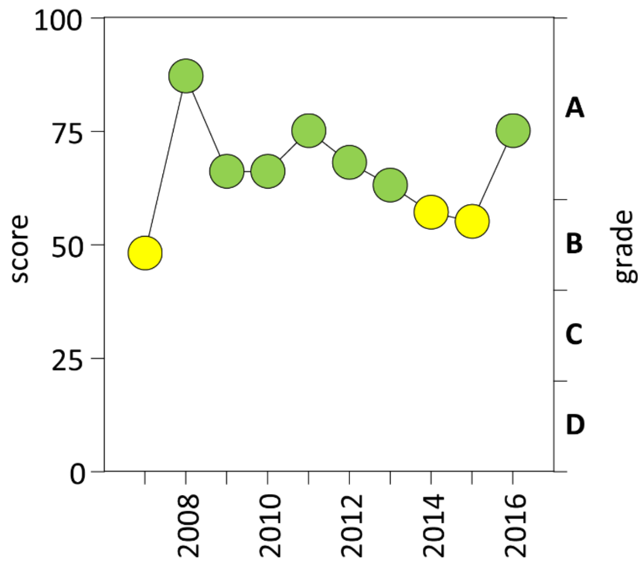

Figure 1. *Report card for Roebuck Bay seagrass condition, 2007 - 2016.Reporting scores are categorised to a four point scale; ■ = good (≥ 60-100), ■ = fair (≥ 40 < 60), ■ = poor (≥ 20 < 40), ■ = very poor (0 - < 20). NB: Scores are unitless.*

Recommendations

- That routine monitoring based on Seagrass-Watch standard protocols at existing long-term monitoring sites be continued and supported,
- That annual refresher workshops and additional training from Seagrass-Watch HQ be supported, or alternatively Seagrass-Watch HQ be supported to conduct post-field assessments on data submitted,
- Continue the collaborative arrangement with Broome Community Seagrass Monitoring Project, Department of Parks and Wildlife and Seagrass-Watch HQ. This is a very effective and beneficial arrangement.
- That monitoring be conducted at least twice yearly: late in the main growing period, September to December; and wet season (January to April),
- Introduce routine *in situ* light and temperature monitoring at representative sites,
- Investigate the factors which influence the growth and formation of epiphytic aggregations on the seagrass, particularly the potential link with catchment nutrients,
- Seed bank monitoring be conducted as part of standard monitoring, but concentrated on wet season (January to April),
- Seed viability studies be conducted to quantify viability of the seed bank,
- Assessment of seagrass flowering and reproductive health be conducted at monitoring sites,
- Assess the nature, extent and level of impact of *L. majuscula* blooms on seagrass communities in and adjacent to the Marine Park,
- Conduct routine water quality assessments to identifying drivers of the *L. majuscula* blooms and possible sources of elevated nutrients,
- That the seagrass report card for Roebuck Bay be adopted by management agencies and stakeholders and produced annually,
- The report card continue to be improved and where possible integrated with a larger report card on the ecological, cultural and social values of Yawuru Nagulagun / Roebuck Bay Marine Park,
- Prioritise assessment to characterise the distribution, diversity, and abundance of intertidal and subtidal seagrass communities in the Marine Park (i.e. mapping),
- Identify representative seagrass communities/meadows and establish additional long-term monitoring sites to report seagrass condition/health in the Marine Park.

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OBJECTIVES:

1. An analysis of 10 years of seagrass data to describe patterns, trends and correlations with external factors, including development of a pilot report card,
2. An evaluation of the project's methods, systems and structure, with recommendations on the project's future in particular reference to the Roebuck Bay Marine Park.

INTRODUCTION & BACKGROUND

Seagrasses are marine flowering plants that are an important component of the coastal marine ecosystem of the Kimberley region. The services provided by seagrass ecosystems makes them a high conservation priority (Cullen-Unsworth and Unsworth, 2013). Seagrass act as substrate stabilisers (Madsen *et al.*, 2001; Gacia *et al.*, 2003), provide habitat and nursery grounds for many marine animals including those of commercial and subsistence fisheries importance (Coles *et al.*, 1993; Cullen-Unsworth and Unsworth, 2013), and are a major food source for grazing animals such as the dugong (*Dugong dugon*) and green turtle (*Chelonia mydas*) (Marsh *et al.*, 2011). Seagrass also produce natural biocides and improve water quality by controlling pathogenic bacteria to the benefit of humans, fishes, and marine invertebrates such as coral (Lamb *et al.*, 2017). Nutrient cycling in seagrass meadows makes them one of the most economically valuable ecosystems in the world (Costanza *et al.*, 1997) and the retention of carbon within their sediments contributes significantly to Blue Carbon sequestration (Fourqurean *et al.*, 2012; Unsworth *et al.*, 2012). However, despite their economic value (Costanza *et al.*, 1997; Costanza *et al.*, 2014), seagrasses have declined dramatically in the last five decades, with widespread and substantial losses in global seagrass extent. These losses are often on par or greater than that of rainforests and coral (Waycott *et al.*, 2009) and are frequently the result of anthropogenic activities such as coastal change, land-use (Yaakub *et al.*, 2014), poor land management, physical destruction (Cullen-Unsworth and Unsworth, 2013) and declining water quality (Orth *et al.*, 2006a).

Western Australia has the highest diversity of seagrasses in the world, with 25 species represented (Walker and Prince, 1987; Kirkman, 1997; Walker, 2003). These are generally divided into temperate and tropical distributions, with Shark Bay representing the biogeographical overlap. 12 species are represented in the tropics (*Thalassia hemprichii, Thalassodendron ciliatum, Enhalus acoroides, Halophila ovalis, Halodule uninervis, Halophila minor, Cymodocea angustata, Syringodium isoetifolium, Cymodocea serrulata, Halophila spinulosa, Halodule pinifolia* and *Halophila decipiens*), one of which is endemic (*Cymodocea angustata*) (Kirkman, 1997; Walker, 2003; Huisman and Sampey, 2014).

The Kimberley region of extends from the border with the Northern Territory in the north to Sandy Point (Roebuck Bay) in the south. Seagrass distribution throughout the region is most likely influenced by shelter, sediment characteristics, water turbidity and tidal sheer (McKenzie and Yoshida, 2014; Kendrick *et al.*, 2017). Seagrass meadows are mostly found in the sheltered bays along the southern mainland coast. Extensive terracing of these expanses in the intertidal zone often result in seagrass high in the intertidal (Walker, 2003). The majority of the meadows are low to moderate in abundance, dominated by *Halophila* and *Halodule* species (Walker, 2003), however in some coral reef and shallow environments, meadows of *Thalassia hemprichii* and *Enhalus acoroides* can attain high biomasses where water is ponded during the falling tide (Kendrick *et al.*, 2017). In these environments seagrass must also tolerate extremes of high light, high temperature, low oxygen and low *p*H water to survive (Pedersen *et al.*, 2016; Kendrick *et al.*, 2017; Vanderklift and Kendrick, 2017). Subtidal populations of seagrasses are poorly known, with the exception of the ephemeral *Halophila decipiens* in the deeper waters off James Price Point (Hovey *et al.*, 2015).

Seagrass communities are a critical component of the Roebuck Bay marine system, forming extensive meadows in the lower intertidal areas, particularly in the northern Bay (Walker and Prince, 1987; McKenzie and Yoshida, 2014). Dugongs and green turtles use the bay as a feeding and migration transit area. Aerial surveys in 2009 from Lagrange Bay in the south to Cape Leveque in the north, estimated the dugong population of Roebuck Bay to be 542 (SE: ±216) individuals in the late wet season (March), 709 (95% CI: 455 – 952) in the dry season (July) and 531 (95% CI: 274 – 811) in September (RPS, 2010). These were significantly higher than the 50-100 individuals previously reported in 1984 (Holley and Prince, 2008). The 2009 surveys also reported that Roebuck Bay supported the greatest number of calves in the region and in all survey periods (RPS, 2010).

Roebuck Bay is also a major nursery for fishes and crustaceans, supporting an exceptionally high biomass and diversity of benthic invertebrates (approximately 300 – 500 species), placing it among the most diverse mudflats known in the world (de Goeij *et al.*, 2003). As a Ramsar site, Roebuck Bay is one of the most important sites for shorebird conservation in the East Asian-Australasian Flyway in Australia and globally.

For the Yawuru traditional owners of Roebuck Bay, the Bay is of immense cultural importance due to the important food and ceremonial species it contains many which rely on seagrass (e.g., dugong), as well as the many connections to dreaming stories, law and other spiritual and cultural practices (Yawuru Registered Native Title Body Corporate, 2013).

Seagrass meadows are considered “sentinels” of coastal degradation because they integrate environmental pressures (Orth *et al.*, 2006a), and therefore they are frequently incorporated into assessments of coastal integrity (e.g., Romero *et al.*, 2007; Borja *et al.*, 2008). Monitoring of seagrass condition and trend can provide insight into the condition of the surrounding environment and is often a key priority in many coastal monitoring programs (Dennison *et al.*, 1997; Fourqurean *et al.*, 2003; McKenzie *et al.*, 2016). Monitoring of key indicators, can also provide insight into the resilience of the system.

Ecological resilience is “the capacity of an ecosystem to absorb repeated disturbances or shocks and adapt to change without fundamentally switching to an alternative stable state” (Holling, 1973), and therefore it relates to the ability of a system to both resist and recover from disturbances (Unsworth *et al.*, 2015). Changes in resilience indicators show if the ecosystem is in transition (i.e. has already, or may undergo a state-change). Abundance of plants/population reflects the cumulative effects of past environmental conditions and can indicate the capacity of the population to resist disturbance / impacts. Persistence of a seedbank is an important feature of recovery (and therefore, of resilience) in tropical seagrass meadows, as it is well recognized that coastal seagrasses are prone to disturbances that cause local losses (Collier and Waycott, 2009). Community structure (species composition) is also an important feature conferring resilience, both resistance (as some species are more resistant to stress than others), and recovery (as some species may rapidly recover and pave the way for meadow development).

Environs Kimberley recognised that seagrasses are an important and sensitive component of the marine ecosystem within Roebuck Bay and in partnership with the Kimberley Ports Authority, the Shire of Broome, Nyamba Buru Yawuru, the Roebuck Bay Working Group and the Department of Parks and Wildlife are committed to maintaining the health of these habitats. In 2007 the Broome Community Seagrass Monitoring Project was initiated and seagrass monitoring commenced with the additional support of CoastWest, Norman Wettenhall Foundation, and Seagrass-Watch HQ.

This report presents data from the first 10 years of monitoring seagrass ecosystems in Roebuck Bay (undertaken from April 2007 to August 2016). The key aims of this report were to:

- Examine the quality of data collected by trained participants of the Broome Community Seagrass Monitoring Project and assess the sensitivity of the data to detect change,
- Report on the temporal and spatial trends in seagrass abundance, species composition and canopy height at intertidal sites in northern Roebuck Bay,
- Report on the temporal and spatial trends in seagrass seed banks at intertidal sites in northern Roebuck Bay,
- Report on the temporal and spatial trends in epiphyte, macroalgae and *Lyngbya majascula* abundances at intertidal sites in northern Roebuck Bay,
- Report on seagrass community and environment condition and trends,
- Integrate reporting on Roebuck Bay seagrass condition including production of a pilot report card, and
- Recommend priority actions/activities and research questions to assist with the management of the ecological values of seagrass communities in Roebuck Bay and the Yawuru Nagulagun Marine Park.

METHODOLOGY

Site description

Roebuck Bay is a tropical marine embayment with extensive, highly biologically diverse, intertidal mudflats. The bay has very large tidal ranges which exposes around 160 km^2 of mudflat, approximately 45% of the total bay area, with tides travelling at up to 20cm.sec^{-1} mid cycle (Hickey *et al.*, 1998; Piersma *et al.*, 2002). Most of the mudflat area is inundated by high tide and at times, spring tides and/or cyclones may cause the adjoining coastal flats to become inundated. The tidal system is semi-diurnal with an average tidal amplitude of 5.7m. Tidal range varies from c. 1 m on neap tides to 10.5 m on the highest spring tides. These factors dominate the intertidal ecology.

Roebuck Bay is characterised by a hot and humid climate. The average air temperature is 27°C, with relative humidity in the range of 50-57% (Bureau of Meteorological, 2017). The average annual rainfall is 613.3 mm, with 75% falling during the tropical monsoon (January to March) (Bureau of Meteorological, 2017). Roebuck Bay is also within the most cyclone prone part of Australia's coastline. Tropical cyclones primarily occur between December and April, with 2.2 cyclone crossings per year; one of which is severe on average (www.bom.gov.au/cyclone/faq/).

Extensive seagrass meadows occur in the northern regions of Roebuck Bay, particularly in the Port of Broome area, and are dominated by *Halophila ovalis* and *Halodule uninervis* (www.seagrasswatch.org). The most vigorous stands of seagrass grow in areas that are exposed for less than two hours at low tide (Prince, 1986).

The subtidal waters of the Roebuck Bay were declared within the Yawuru Nagulagun / Roebuck Bay Marine Park on October 7, 2016, and the marine park will be extended to the high water mark once indigenous Land Use Agreements are registered with the traditional owners representative body, the Yawuru Registered Native Title Body Corporate (WA Department of Parks and Wildlife, 2016). The park covers an area of approximately 78,800ha from Gantheaume Point in the north to Cape Villaret in the south. The Class A Marine Reserve has seven management programs with prioritised strategies. One of the Parks key requirements is high water quality, healthy biological communities and functioning ecosystems, including seagrass and algae communities (WA Department of Parks and Wildlife, 2016).

Long-term monitoring

Long-term monitoring of seagrass meadows on the northern shores of Roebuck Bay commenced from April 2007, at sites within the Port of Broome boundary (outside the Marine Park). The Broome Community Seagrass Monitoring Project (Environs Kimberley), established sites at Town Beach, Demco and Port (Table 1) to monitor the condition and status of Roebuck Bay's seagrass meadows within the Kimberley Ports Authority waters.

Table 1. *Description of long-term monitoring sites in Broome, WA, 2007-2016.*

Location	Monitoring sites	Description	Height when exposed (metres above LAT)
Town Beach	**RO1** S17.97671 E122.23855 (heading 160 degrees)	Intertidal sand/mud flat. Approximately 640m from Town Beach boat ramp	3.28
Demco	**RO2** S17.98062 E122.23173 (heading 150 degrees)	Intertidal sand/mud flat. Approximately 715m from Demco Beach. Located between Town Beach and Port sites	3.71
Port	**RO3** S17.99672 E122.21418 (heading 120 degrees)	Intertidal sand/mud flat, located 785m from Broome Port	3.24

The 50 × 50 m sites, are not permanently marked, due to high use of the mudflats (e.g., recreational vessels and commercial hovercraft operations). However, positions are marked at 0 m and 50 m points for all three transects at each site using GPS (accuracy ±3 m). This ensures that the same site is monitored at each sampling event. At each site, observers used a 50cm x 50cm quadrat (not anchored to the substrate) to record estimates of seagrass percent cover (only shoots that originated in the quadrat were included), species composition, presence of reproductive structures (e.g., flowers, seeds/fruits), evidence of herbivory (e.g., turtle grazing/cropping or dugong feeding burrows) and visual/tactile estimation of sediment grain size composition (0–2 cm below the sediment/water surface). Epiphyte and macroalgae cover were also measured. Detailed descriptions of the Seagrass-Watch monitoring protocols can be found in McKenzie et al. (2003; 2000). From January 2012, seed data collection commenced at regular intervals every 3 months.

Figure 2. *Map of Roebuck Bay showing the location of the 3 seagrass long-term monitoring sites: RO1, Town Beach; RO2, Demco; and RO3, Port.*

At the request of Environs Kimberley, the abundance data of the marine cyanobacterium, *Lyngbya majuscula*, collected concurrently with seagrass data was also examined. *Lyngbya* blooms have been reported to affect benthic invertebrate abundance (García and Johnstone 2006) and diversity in affected areas of Roebuck Bay (de Goeij *et al.*, 2008; Estrella *et al.*, 2011), and possibly cover and smother the seagrass meadows resulting in significant declines, as reported in other locations such as Moreton Bay (Queensland) and the Indian River Lagoon (Florida) (Watkinson *et al.*, 2005; Tiling and Proffitt, 2017). *Lyngbya* abundance measures are additional quadrat measures (not globally standard Seagrass-Watch measures) and followed the rapid assessment protocols by Estrella (2013) where observers visually estimated *Lyngbya* biomass (g DM m^{-2}) against a set of reference images and assigned biomass into density categories (Table 2). On occasion, field observers alternatively recorded *Lyngbya* abundances as % cover. To facilitate the inclusion of all available data, *Lyngbya* field densities were scored to equivalent % cover for analysis (Table 2).

Table 2. *Table indicating the relationship between Lyngbya density and biomass. Modified from (Estrella, 2013). Equivalent scores and % cover categories used for analysis in this report are also shown.*

Score	g DM m^{-2}	% cover	Density
0	0	0	No presence
1	<10	<5	Very low
2	10-50	5-30	Low
3	50-150	31-60	Medium
4	150-300	61-80	High
5	>300	>80	Very high

Data quality and sensitivity

All monitoring data submitted to Seagrass-Watch HQ underwent standardised and accepted Quality Assurance-Quality Control (QAQC) procedures (McKenzie and Yoshida, 2012) to ensure data was of high quality and acceptable for reporting. Data was first checked for compliancy (e.g., collected by qualified scientist or trained/competent participant; collected and recorded in accordance with protocol requirements), and then accuracy of seagrass visual % cover estimates validated. Field observations were checked by an experienced member of Seagrass-Watch HQ against submitted quadrat photographs (blinded assessment to eliminate bias) to ensure consistency and conformity to global estimates. Field estimates within maximum acceptable difference were accepted, otherwise estimates were reviewed by second scientist and revised estimate (i.e. corrected) accepted.

To examine sensitivity of the abundance (% cover) data, the Minimum Detectable Difference (MDD) was calculated at each site. The MDD is the minimum difference between the largest and smallest means, and is based upon differences in precision of the mean Standard Error for each sample number. From the method of Bros and Cowell, (1987), using the degrees of freedom at a particular sample number, critical t-values were selected from t-value tables for both 0.05 (α set at 5%) and 0.20 (β set at 80% power), using 2-tailed tests. These t-values were entered into the following formula (eq. 1) in order to determine the minimum detectable difference:

$$MDD=\sqrt{2}\, S_{\overline{Y}}\, (t_{(0.05),\nu} + t_{(0.2),\nu}) \qquad \text{(equation 1)}$$

where $S_{\overline{Y}}$ = SE for sample size, ν =2 (number of replicates -1) and all t-values are 2-tailed.

Climate and environmental data

Climate data were accessed courtesy of the Australian Bureau of Meteorology (BOM). Tidal height data from the Port of Broome was provided courtesy National Tidal Centre (BOM), however, as 9% of days had no measurements, missing data was substituted with predicted heights from SeaFarer Tides and AusTides (courtesy Australian Hydrographic Service). The duration of daylight exposure (total hours between sunrise and sunset) was determined for each site based on the meadows height relative to the chart datum (Table 1).

For each site, a mean value for all environmental factors for the previous 15, 30, and 90 days prior to each seagrass monitoring event was determined. These three different durations represent biologically meaningful changes in seagrass growth and environmental conditions (e.g., lunar) within these meadows.

Table 3. *Climate and environmental factors together with their averaging times used in regression analysis of seagrass meadow abundance (2007 to 2016).*

Factor	Averaging time used in regression
total rainfall (mm)	previous 15, 30, and 90 days
total global solar radiation ($MJ.m^{-2}$)	previous 15, 30, and 90 days
average daily temperature (°C)	previous 15, 30, and 90 days
maximum daily temperature (°C)	previous 15, 30, and 90 days
daylight tidal exposure (hours)	previous 15, 30, and 90 days

Data analysis

Prior to all analysis, data exploration protocols including checks for collinearity, zero inflation (of percent cover data), normality (Shapiro-Wilk test) and homogeneity of variances (Cochrans Test), were conducted and data transformed (e.g. ArcSine) if required. Once data exploration was complete, results were modelled with a linear regression using a distribution selected appropriate for the characteristics of the data.

In this report, results are presented to reveal temporal changes in seagrass community attributes and key environmental variables. Generalised additive mixed effects models (GAMMs) were fitted to seagrass cover to identify the presence and consistency of trends, using the "mgcv" (Wood, 2006;Wood, 2014) package in R 3.2.1 (R Core Team, 2014) (see also Appendix). GAMMs (Wood, 2006) were used to decompose the irregularly spaced time series into its trend cycles (long-term) and periodic (seasonal) components. Percent cover data models were fitted using a quasibinomial distribution due to the proportional (bound between 0 and 1) nature of the data. These models include random effects to the quadrat level to provide the maximum resolution for modelling. Two separate models were produced. Firstly, an overall model with the 3 sites pooled and secondly a model including 3 different smoothers for the individual sites (RO1, RO2, and RO3). The results of these analyses are graphically presented in a consistent format: predicted values from the model were plotted as bold black lines, the 95% confidence intervals of these trends delimited by shading or dashed lines. Please note: some care should be taken when dealing with the confidence intervals produced by the models as there is small zero inflation and heterogeneity variance in the residuals.

To detect significant differences in seagrass abundance between years we used Bayesian General Linear Mixed Models (GLMM) using Integrated Nested Laplace Approximations (INLA) technique (see Appendix). The Bayesian output consists of posterior distributions with 95% credible intervals. As analysis was conducted using Bayesian statistics, hypothesis testing of the type used in traditional (frequentist) power analysis was not possible.

Trend analysis was conducted to determine if there was a significant trend (reduction or increase) in seagrass cover at a particular site (averaged by sampling event) over all time periods. A Mann-Kendall test was performed using the "fume" package in R 3.2.1 (R Core Team, 2014). Mann-Kendall is a common non-parametric test used to detect overall trends over time. As the test assumes independence between observations, a *p*-value adjustment is required if autocorrelation is significant. The adjustment consists of running the test on the un-correlated observations only.

Within and between year differences in each abiotic variable were also examined, using the seasonal averages. Analysis of variance (ANOVA) and regression analyses were performed using XLSTAT v. 2014.5.03 (Addinsoft SARL.) and Tukey's *post hoc* test was used to identify significant differences. Relationships between seagrass abundance, seed banks, epiphyte abundance, *Lyngbya* abundance and abiotic factors were tested using backward stepwise removal multiple regression in XLSTAT v. 2014.5.03 (Addinsoft SARL.). After preliminary analysis, cloud and wind data were removed from analysis due to the high correlation with solar radiation.

Report card

Long-term monitoring provides valuable information on temporal trends in the health status of seagrass meadows and a pilot report card was developed to represent the relative health of seagrass in Roebuck Bay and provide a tool for decision-makers in adopting protective measures. It encourages local communities to become involved in seagrass management and protection. Working with both scientists and local stakeholders, this approach is designed to draw attention to the many local anthropogenic impacts on seagrass meadows which degrade coastal ecosystems and decrease their yield of natural resources. The pilot report card uses two indicators of seagrass condition, based on their significance to seagrass resilience: abundance, which represents the state of the seagrass to resist stressors; and seed banks, which represents the capacity of the seagrass to recover from loss/disturbance. The selection of threshold levels for grading each indicator was determined using the seagrass abundance guidelines developed by McKenzie (2009), and deviation from the long-term baseline.

Abundance (% cover)

Seagrass abundance guidelines (threshold levels) were developed for individual sites based on average % cover data per monitoring event (McKenzie, 2009). Guidelines for individual sites were only applied if the site had been subject to minimal/limited disturbance for 3-5 years. The duration of 3-5 years is based on recovery from impact times (Campbell and McKenzie, 2004)., Seagrass state was determined at each site for each monitoring event using the median against the seagrass guidelines to allocate a grade: good, median abundance at or above 50th percentile; fair, median abundance below 50th percentile and at or above 20th percentile; poor, median abundance below 20th percentile, and above 0; and very poor, median abundance = 0 (Table 4). A grade score was further assigned to enable integration with other indicators. Please note that the scores are unitless and should not be interpreted as a proportion or ratio.

Table 4. *Seagrass abundance guidelines, scores and grades based on percentiles.*

median % cover	Score	Grade	Grade score
≥ 50th percentile	100	good	≥ 60
≥ 20th percentile, < 50th percentile	66	fair	≥ 40 < 60
> 0 < 20th percentile	33	poor	≥ 20 < 40
0	0	very poor	0 - < 20

Seed banks

It is well recognized that tropical coastal seagrasses are prone to disturbances that cause local losses, and the need for a local seed source is critical to support recover in relatively short periods of time (Collier and Waycott, 2009). Seagrass seed banks provide an indication of the capacity of seagrass to recover from loss (following large scale impacts) through the recruitment of new plants, i.e. the resilience of the population (Collier and Waycott, 2009). Due to the large natural variation (within and between sites), it was decided to describe seed bank state using the deviation from the baseline (long-term mean 2012-2016) and the lower 95% confidence interval (Table 5). The 95% confidence interval was chosen as the lower threshold because abundances below this have a 0.05 probability of containing the population mean. Please note that the scores are unitless and should not be interpreted as a proportion or ratio.

Table 5. *Seagrass seed bank thresholds, scores and grades based on seed bank (seed m^{-2}) per site per sampling event.*

Seeds m^{-2}	Score	Grade	Grade score
≥ long-term mean	100	good	≥ 60
< -95%CI from long-term mean	66	fair	≥ 40 < 60
>-95%CI from long-term mean and > 0	33	poor	≥ 20 < 40
0	0	very poor	0 - < 20

Seagrass state

Annual seagrass state was calculate using the average grade score of the two seagrass resilience indicators: abundance, and seed banks. Each indicator was equally weighted and the integrated scores represent grades from A to D (Figure 3).

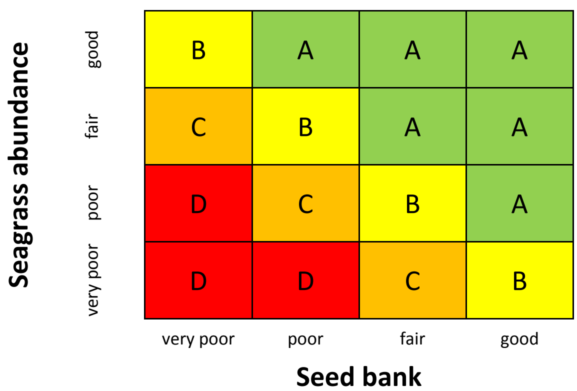

Figure 3. *Matrix of integrated seagrass condition and indicator grades; A (good), B (fair), C (poor), and D (very poor).*

RESULTS & DISCUSSION

Two species of seagrass (*Halodule uninervis* and *Halophila ovalis*) were reported from Roebuck Bay, with a further two species (*Halodule pinifolia* and *Halophila minor*) under review for synonymy.

Family **HYDROCHARITACEAE** Jussieu

Halophila ovalis (R. Br.) Hook. *f.*

Halophila minor (Zoll.) den Hartog

Family **CYMODOCEACEAE** N. Taylor

Halodule uninervis (Forsskål) Ascherson

Halodule pinifolia (Miki) den Hartog

H. uninervis and *H. ovalis* are opportunistic and colonising species (Kilminster *et al.*, 2015), respectively, and occurred in an extensive enduring meadow across the intertidal banks of Roebuck Bay in which three replicate monitoring sites were located. It is unknown if seagrass occurs in the subtidal waters seaward of the banks, as no investigations have been conducted to date.

The taxonomic authenticity of *Halodule pinifolia* and *Halophila minor*, remains under review. Waycott (2004) suggested that *H. pinifolia* and *H. uninervis* were conspecific, recognising that the plasticity of blade size is attributed to local conditions, however, recent rbcL gene sequencing has suggested the species may be separate (Wagey and Calumpong, 2013). Similarly, *H. minor*, originally reported as *Halophila ovata* (Kuo, 2000), is considered synonymous with *Halophila ovalis* (Waycott *et al.*, 2004), despite preliminary genetic evidence suggesting the species may be distinct (Waycott *et al.*, 2002). Until these are resolved, we currently only recognise *H. uninervis* and *H. ovalis* as per Waycott (2004).

Long-term monitoring at the replicate sites was established in April 2007 and was conducted quarterly (every 3 months) where possible.

Data quality and sensitivity to detect change

At completion of each monitoring event, all data was submitted to Seagrass-Watch HQ to undergo checks to ensure compliancy with global standards and data quality. When necessary, Seagrass-Watch HQ corrected data (if possible) to ensure consistency across the program (e.g., compliant quadrat images enabled post field visual assessments). Although >95% of data submitted (per transect) by the Broome Community Seagrass Monitoring Project passed QAQC, approximately 15% was non-compliant and nearly a third was corrected by Seagrass-Watch HQ (Figure 4). Assessment of the data submitted demonstrates that annual training improves data compliancy to standardised procedures and generally improves data quality (Figure 4). However, only 45% of training workshop participants completed all components of the training and were able to demonstrate competency in field sampling (e.g., submit compliant data, accurately estimate percent cover, correctly identify all seagrass species present, accurately estimate seagrass species composition, correctly describe sediment, measure seagrass canopy height, estimate macroalgae cover, estimate epiphyte cover, correctly take a quadrat photo and accurately record data). The low level of training completion was to some extent the result of high participant turnover; where individuals departed the region or were unable to volunteer their time due to competing commitments. Nevertheless, the QAQC assessments indicate that the level of data correction by Seagrass-Watch HQ increases with reduced training. For example, in 2015 and 2016, the majority of data required corrections by Seagrass-Watch HQ (Figure 4).

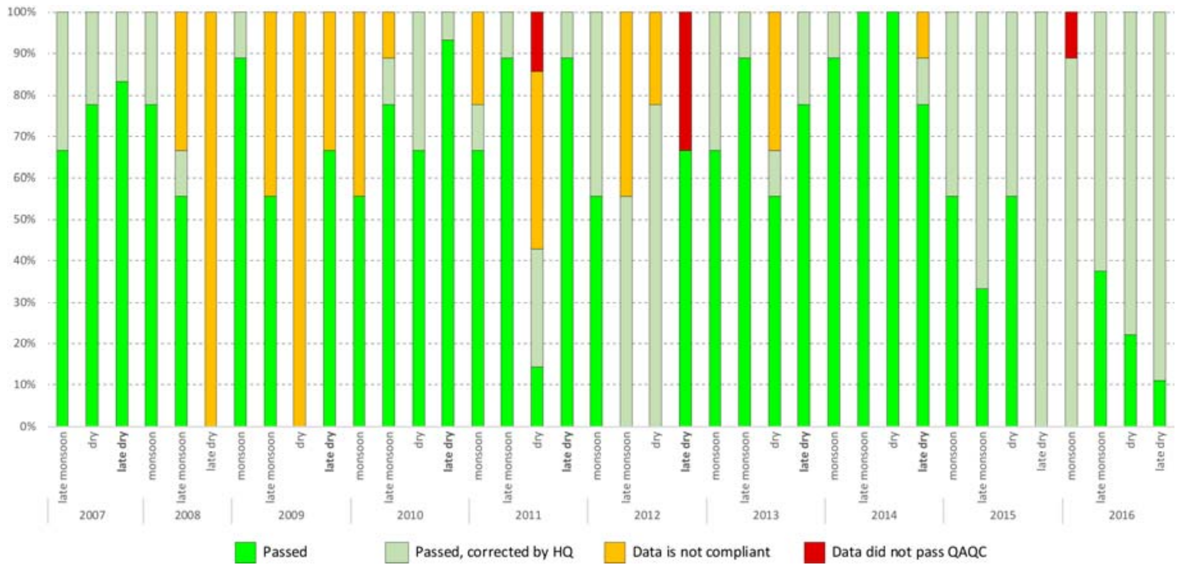

Figure 4. *Frequency of QAQC assessment on data submitted to Seagrass-Watch HQ by Broome Community Seagrass Monitoring Project, 2007 to 2016. Seasons in bold indicate periods when training occurred.*

The corrections made by Seagrass-Watch HQ were predominately visual estimates of percentage cover and seagrass species composition. These corrections were possible as every quadrat assessed in the field is photographed and the images submitted as part of the data. As only two distinctly morphology different seagrass species occur in Roebuck Bay (strap vs oval), composition of species to the total cover was also estimated post-field. These findings indicate that volunteer observers have moderate accuracy conducting seagrass % cover estimates and an option if training is reduced, or not possible, is that all cover estimates be conducted post-field by Seagrass-Watch HQ. This would, however, increase the necessity for accuracy in the field taking compliant quadrat photos (e.g., high resolution images of entire quadrat free of shadows, sun glint, pre- and post-removal of obscuring macroalgae, *etc*.) and would require additional funds for Seagrass-Watch HQ to conduct the assessments. Field observers would still be required to conduct all other standard assessments (e.g., sediment grain size, faunal observations, canopy height measures, epiphytes, *etc*.).

All data submitted which passed all QAQC requirements, was used for analysis and reporting in the following report. The sensitivity of the data to detect change between sampling events was calculated using equation 1. The Minimal Detectable Difference (MDD) for monitoring sites ranged from 4.4 to 5.7%, which supports the sites suitability for monitoring, i.e., monitoring can detect a statistically significant change of <6% with a 5% chance of reporting a change when none actually exists and a 20% chance of reporting no change when actually there was one. The ability to perceive a small change/loss is crucial for any early warning system, and these findings meet the statistical properties of standard methods for monitoring of seagrass habitat cover worldwide (Schultz *et al.*, 2015). The findings also address the critical management priority recommended by Duarte (2002), that long-term seagrass assessment programs use monitoring methods with statistical power sufficient to detect a loss of 10%.

Species abundance (% cover)

Over the decade of monitoring, seagrass abundance (% cover) has varied within and between years (Figure 5), with all sites reporting Coefficients of Variation (CV) above >0.8 (highest CV = 1.23 at RO3). Seagrass abundance appears seasonal within years, with higher % cover in late-dry to early-monsoon (October-December) and lower in late-monsoon to dry (April-July).

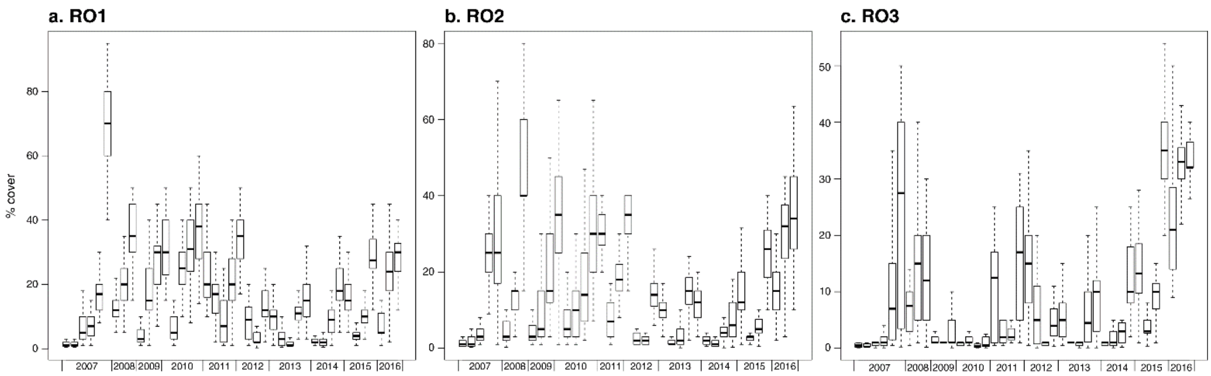

Figure 5. *Boxplot of seagrass abundance (% cover) per quadrat from sites monitored from April 2007 to August 2016 (sites pooled). The box represents the interquartile range of values, where the boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles.*

When seagrass monitoring was established in 2007, seagrass percentage cover was very low (<5% cover) across all sites, but increased over the following 12 months. In 2009 seagrass abundance declined across all sites, recovering slightly for a short period at both RO1 and RO2 before subsequently declining from late-2011 to mid-2014 (Figure 6). Seagrass cover was lower and recovery slower at RO3 between 2007 and late-2011, however since late-2014, seagrass cover has improved at all sites (Figure 6).

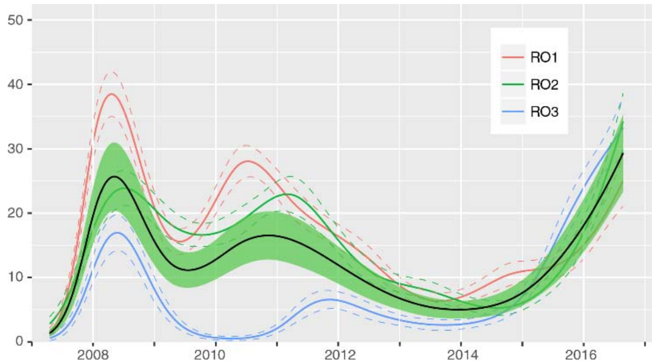

Figure 6. *Trends in seagrass abundance (% cover) for each site represented by a GAMM plot. Trends are solid lines with shaded areas and dashed lines defining 95% confidence intervals of those trends.*

Seagrass cover was significantly higher (95% credible intervals did not overlap) in 2011 and 2016 than the remaining years at RO1 and RO2 (Figure 7). Seagrass cover at RO3 remained low and did not increase significantly until 2016. Seagrass cover was significantly higher at all sites in late 2016 than when monitoring was established in early 2007 (Figure 7).

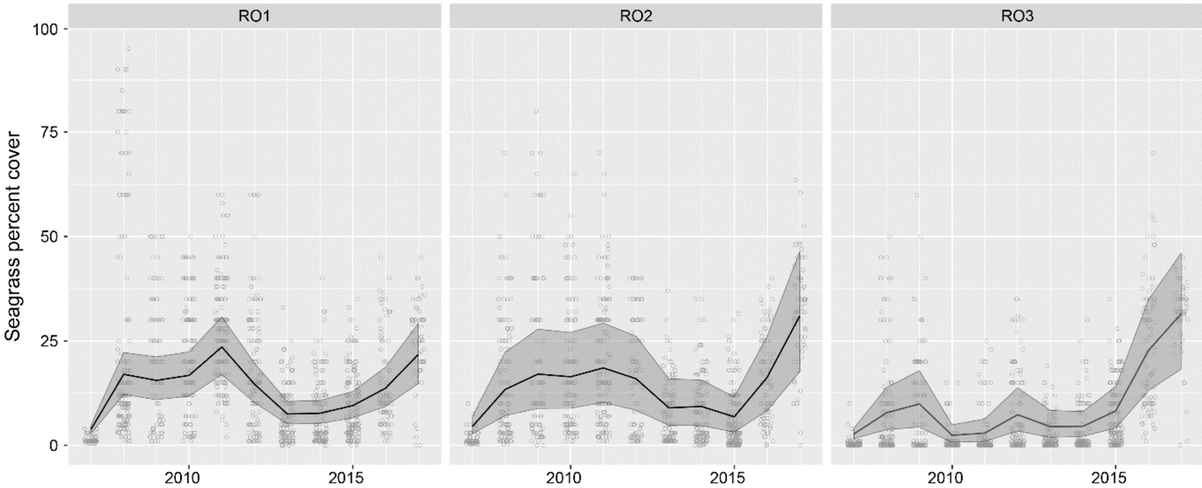

Figure 7. *Total seagrass precent cover posterior mean values and 95% credible intervals per year and site obtained by a Zero-altered beta model (combination of a Bernouilli and Beta GLMM models).*

Seagrass abundance was not significantly different between RO1 and RO2 over the 10 years of monitoring (Figure 8a), however RO3 was significantly lower than both RO1 and RO2 from 2010 to 2012 as the credible intervals did not cross zero (Figure 8b, 8c). Abundance was also higher at RO1 than RO3 during 2008 (Figure 8b).

Figure 8. *Posterior mean differences between fitted values at each site calculated by Bayesian analysis using Integrated Nested Laplace Approximations (INLA). Shaded area is credible interval.*

The cause of the lower abundances at RO3 for much of the monitoring period, and the slower recovery between 2007 and late-2011, is unclear. The site is immediately adjacent to the Port of Broome (Kimberley Ports Authority), which is the largest deep-water access port servicing the Kimberley region (kimberleyports.wa.gov.au). The port supports livestock export, offshore oil and gas operations, pearling, fishing, charter boats, cruise liners, private vessels and Navy and Customs patrol vessels (around 1,200 berthings per annum). The port is the main fuel and container hub port for the Kimberley region, and in recent years its principal exports have been livestock and offshore drilling rig equipment and materials (kimberleyports.wa.gov.au). The presence of any chronic or acute impacts from the Port or associated activities (e.g., major works) during the 2007-2011 period are unknown. Kimberley Ports Authority (KPA) recognises the importance of environmental protection and is committed to acting in an environmentally responsible and sustainable manner. To that end, KPA has had an accepted Environmental Management Plan since 2004 to reduce risks to the natural environment. The most recent plan includes risks to environmental values such as seagrass health. In 2016, KPA completed a marine baseline assessment, which reported the marine environments of the

Port of Broome to be in a good condition, and will be implementing an ongoing marine monitoring program (Kimberley Ports Authority, 2016).

Although seagrass abundance (% cover) at all sites fluctuated within (seasonally) and between years, there were no detectable long-term trend at any site (Table 6).

Table 6. *Results of Mann-Kendall analysis to assess if there was a significant trend (decline or increase) over time in seagrass cover. The reported output of the tests performed are Kendall's tau statistic, the two-sided p-value, the Sen's slope (showing the sign and strength of the trend) and the corrected p-value for autocorrelation.*

Site	***p*** (2-sided)	***Tau***	**Sen's slope**	**autocorrelation**	***corrected p*** (2-sided)	**overall trend**
RO1	0.8135	-0.0268	-0.00115	No		No trend
RO2	0.9412	0.0095	-0.00044	No		No trend
RO3	0.0054**	0.3077	0.0016	Yes	0.11	No trend

Seagrass over the decade of monitoring appears similar to when first reported in 1986 (Figures 8 & 9).

Figure 9. *Mixed Halodule uninervis and Halophila ovalis meadow adjacent to Mangrove Point inner anchorage area, Roebuck Bay: left, 01 August 1984 (Prince, 1986); right, October 2012.*

Figure 10. *Halophila ovalis meadow adjacent to Mangrove Point, northern Roebuck Bay: left, 01 August 1984 (from Prince 1986); right, 7 November 2006 (courtesy Danielle Bain, EK).*

Over the decade of monitoring, evidence of continual dugong grazing (excavating) was observed during each monitoring event. This suggests a resident population of dugong inhabit the bay, and as the level of grazing appears similar to reports from the early 1980's, it is possible the population has changed little (Prince, 1986).

Figure 11. *Dugong feeding trails in mixed Halodule uninervis and Halophila ovalis meadow in the north area of Roebuck Bay, adjacent to Town Beach: left, 01 August 1984 (from Prince 1986); right, 30 September 2012.*

Species composition

The most abundant seagrass species was *Halodule uninervis* which dominated the meadows throughout the monitoring period (Figure 12).

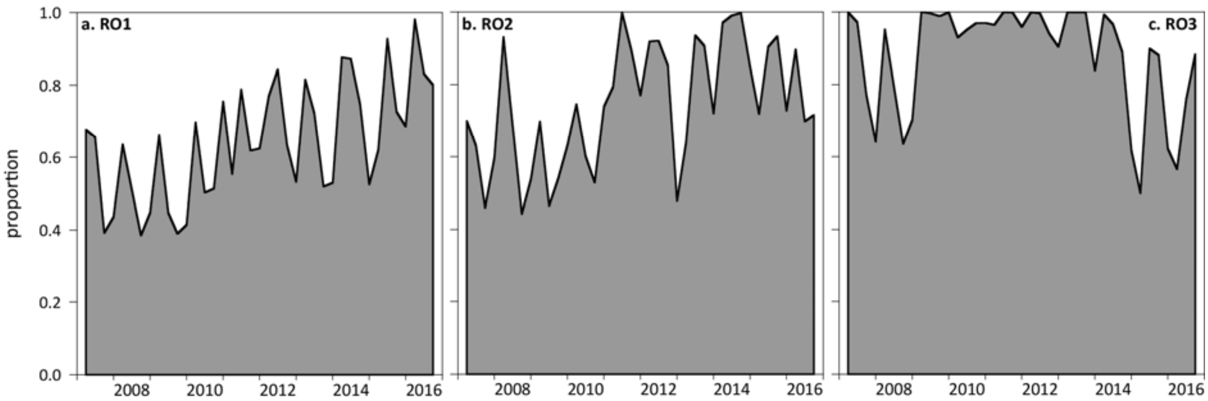

Figure 12. *Proportion of Halodule uninervis to seagrass abundance at each long-term monitoring site in Roebuck Bay, 2007-2016.*

The contribution of *Halodule uninervis* to the total seagrass cover at RO1 and RO2 fluctuated seasonally (Figure 13) and was greater in the late monsoon and dry periods (March to August) (Figure 14). At site RO3, the contribution of *H. uninervis* did not differ significantly between seasons (Figure 13) as the meadow was essentially monospecific from 2009 to 2014 (Figure 12).

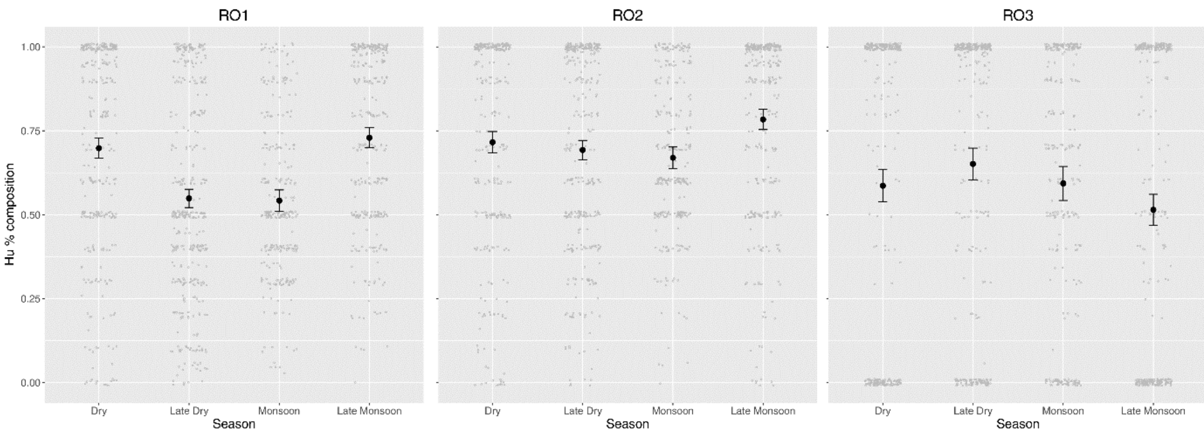

Figure 13. *Seasonal proportion of Halodule uninervis to total percentage cover (years pooled)*

The early (March - August) and late (September-February) periods of the year generally correspond to the slow-growth and main growing periods (respectively) for seagrass in the tropics. During the early periods of the year, conditions are generally less conducive for growth (e.g., lower light, declining temperatures) and the non-leaf replacing species *Halophila ovalis* are less abundant (leaves senesce) (Figure 12). It is during the early period of the year that the foundational species *Halodule uninervis* would be expected to dominate (Figure 14) as it would be able to draw on its below ground non-structural carbohydrates (sugars and starch) reserves (Burke *et al.*, 1996; Touchette and Burkholder, 2000; Alcoverro *et al.*, 2001; Unsworth *et al.*, 2015), while senescence of *H. ovalis* would be greater as its reserves are much lower with smaller rhizomes and therefore little capacity to store carbohydrates (Longstaff *et al.*, 1999). Also, the decline in the quantity of photosynthetic leaf tissue in relation to non-photosynthetic rhizome tissue in *H. ovalis* may lead to anoxia in the roots due to the reduced availability of O_2 (Smith *et al.*, 1988), and increased utilisation of storage carbohydrates (Zimmerman *et al.*, 1989).

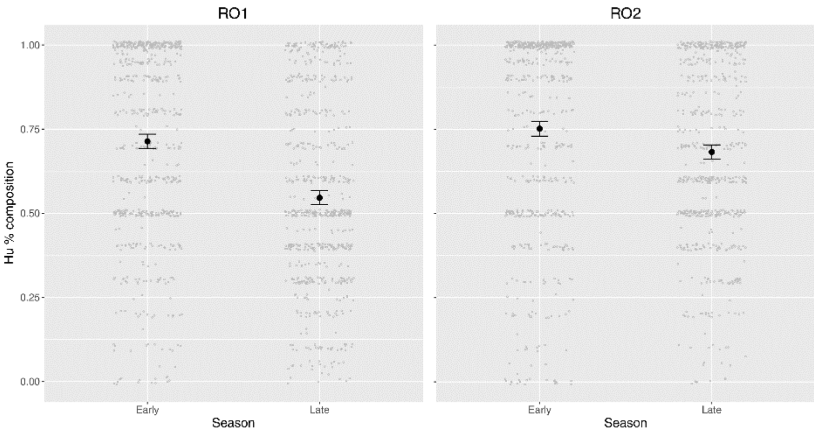

Figure 14. *Contribution of Halodule uninervis to the total seagrass abundance (% cover) in the meadows of Roebuck Bay (2007 to 2016).*

Seagrass canopy height

Canopy height was only recorded for *Halodule uninervis*, as it is a di-meristematic strap leafed species where leaf length/height is correlated with vertical growth rate (Short and Duarte, 2001). *Halophila ovalis* is a mono-meristematic, non-leaf replacing species with no vertical growth rate. Canopy height differed within and between years (Figure 15). Although canopy heights were overall lower at RO3 (*p*<0.001), canopy heights at all sites were significantly higher in the early monsoon and lower in the dry season ($F_{3,104}$=23.53, *p*<0.001) (Table 10).

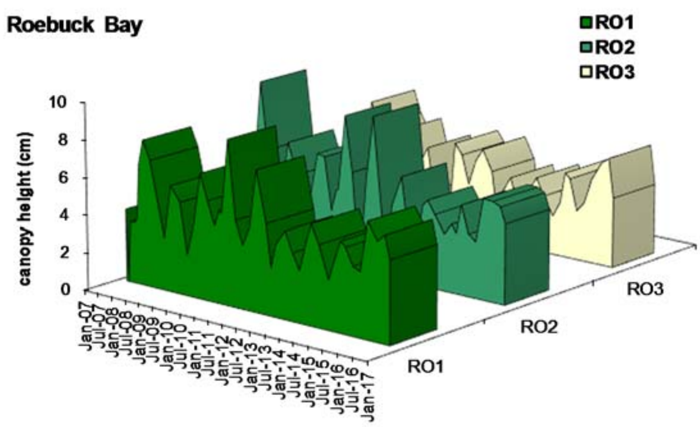

Figure 15. *Average Halodule uninervis canopy heights at each site over the monitoring period.*

Canopy height provides an indication of available habitat for associated fauna and flora. As canopy heights increase in the later part of the year, it provides greater leaf surface area and above-ground seagrass biomass. By coupling % cover and canopy height measures, above-ground seagrass biomass (grams per unit area) can be calculated, which in future may provide critical information on the available food resource for mega herbivores in the bay, including dugong and green sea turtle.

Epiphyte and macroalgae abundance

Macroalgal abundances fluctuated both within and between years since monitoring was established (Figure 16). Macroalgae generally consisted of *Halimeda* species (e.g. *Halimeda opuntia*). The long-term annual mean macroalgal abundance was low at all sites and not significantly different (RO1 = 1.1 ±0.5, RO2 = 2.5 ±0.8, RO3 = 2.2 ±1.0; p=0.18). Epiphyte abundances were generally similar across the sites (Figure 16), however there was a statistically significant interaction between the effects of season and year on epiphyte abundance ($F_{25,77}$ = 4.296, p<0.001) (Table 11). Epiphytes abundances were significantly higher in 2007-2009 and 2013-2014 (Tukey's post hoc, p<0.001), and generally more abundant in late dry/early monsoon of each year (p<0.001).

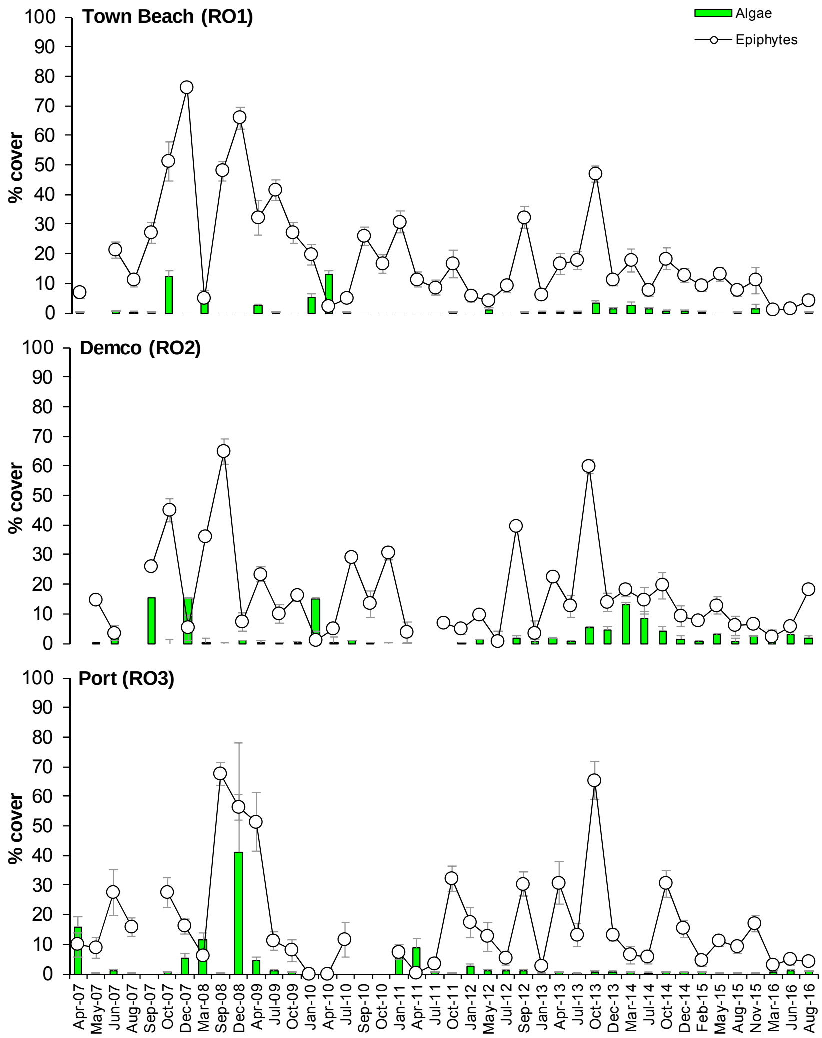

Figure 16. *Macro-algae and epiphyte abundance (% cover) at each site over the monitoring period.*

Macroalgal abundance at RO3 declined over time, however, no other trends were detected at the other sites or for epiphyte abundance (Table 7).

Table 7. *Results of Mann-Kendall analysis to assess if there was a significant trend (decline or increase) over time in macroalgae and epiphyte cover. The reported output of the tests performed are Kendall's tau statistic, the two-sided p-value and the Sen's slope (showing the sign and strength of the trend).*

Site		*p* (2-sided)	*Tau*	Sen's slope	overall trend
RO1	macroalgae	0.4454	-0.02	-0.05208	*no trend*
	epiphytes	0.3587	-0.2364	-0.0020	*no trend*
RO2	macroalgae	0.7612	0.09	0.1213	*no trend*
	epiphytes	0.6481	-0.1273	-0.0006	*no trend*
RO3	macroalgae	0.0031	-0.6727	-0.4108	negative
	epiphytes	0.3587	-0.2364	-0.0041	*no trend*

Lyngbya abundance

Blooms of the cyanobacterium (blue-green algae) *Lyngbya majuscula* first appeared in Roebuck Bay during the 2005 wet season, prior to the onset of seagrass monitoring, and were reported to be increasing in extent each wet season since then (de Goeij *et al.*, 2008; Pearson, 2008). These blooms were believed to be the result of elevated nutrient levels in water originating from Broome township and moving into the bay (Vogwill, 2003). *Lyngbya* was present episodically at seagrass sites throughout the monitoring period, and site had no significant influence on abundance (Kruskal-Wallis H_2=5.992, *p*=0.87) (Figure 17). When present, *Lyngbya* occurred in low to very low abundance during the early months of the year (Figure 17), and did not appear to have any significant impact on seagrass abundance (*p*=0.149). The reported *Lyngbya* "bloom" of early 2010 (Bishop, 2010) did not flag as exceptionally high abundances in the long-term dataset (Figure 17). Although the presence of *Lyngbya* was more persistent in 2015 and 2016 across all sites, its occurrence during the periods of seagrass slow-growth possibly limited any impacts to seagrass abundance.

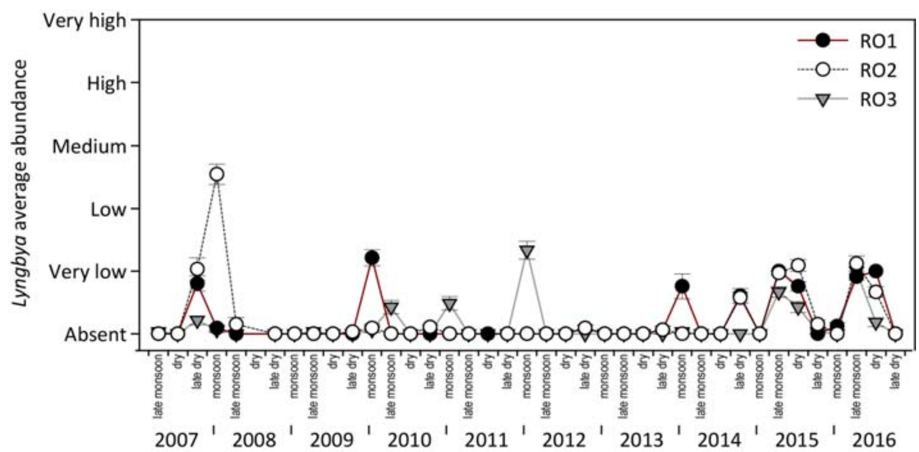

Figure 17. *Average Lyngbya abundance at long-term monitoring sites in Roebuck Bay, 2007-2016.*

Seed abundance

Halodule uninervis seed banks were routinely assessed from 2012 to 2016. Sampling did not include *Halophila ovalis* seed banks due to the size of seeds (<1mm diameter) and level of sampling required (e.g., collection of sediment cores and microscopic examination). *Halodule uninervis* flowering in tropical Australia tends to occur during the main growing season in the late dry (September-November) (Waycott *et al.*, 2004; Seagrass-Watch, unpublished data); peaking in November (Inglis, 2000). Single seeded fruits (approximately 2mm diameter) develop at the sediment surface and seeds are released (i.e. seed set) at or just below the sediment surface from December to May (Waycott *et* *al.*, 2004). *H. uninervis* seeds have a stony pericarp, are negatively buoyant and can persist in the sediment for 2 to 4 years (Orth *et al.*, 2000).

Seeds were found at all sites during the monitoring period, with seeds banks rarely absent at a site (Figure 18). Seeds were absent from RO3 on three separate sampling events (Jul12, Apr14 and Aug15). Seed bank densities within all sites were highly variable (CV>1.6), and the maximum seed bank recorded was at RO1 on 30 September 2012 with 9,677 seeds m^{-2}. This is not surprising as significant heterogeneity in *Halodule uninervis* seed banks has been reported at multiple spatial scales, indicating seed production does not occur in consistent patches or storage (Inglis, 2000). The Roebuck Bay meadow seeds banks varied over the monitoring period (all sites pooled), and there was no significant interaction between season and year ($F_{4,20}$=0.233, *p*=0.916). Although the number of seeds appeared higher in the wet, it was not significant ($F_{1,20}$=1.616, *p*=0.218) (Table 12).

Halodule uninervis seed bank abundance (including advancing by 3, 6 and 9 months) was not significantly correlated with *H. uninervis* abundance (% cover) at RO1 or RO2, suggesting that the size of the bank does not influence abundance amplitude in the immediate future. The correlation between seed banks and *H. uninervis* cover at RO3 however, was significantly higher than average (only time matched) (Pearson's *r* = 0.5352, *p* = 0.0398). This suggests that the meadows may require only a moderate seed bank for recovery capacity, and that greater sized seed banks provide greater probability of recovery (i.e. greater probability of viable seeds) but not necessarily greater abundance.

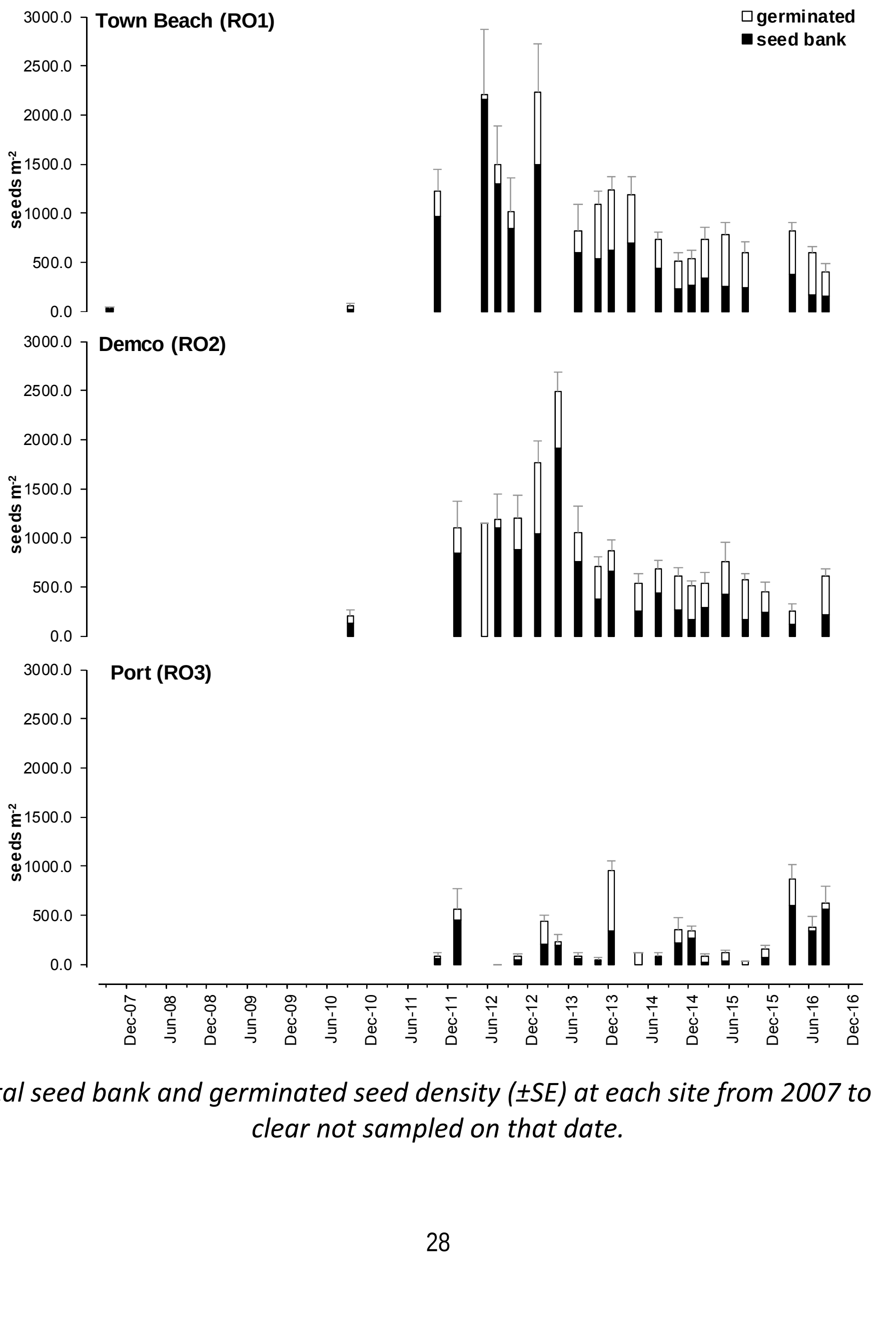

Figure 18. *Total seed bank and germinated seed density (±SE) at each site from 2007 to 2016.x-axis is clear not sampled on that date.*

The potential for seagrass meadows to recover from the sediment seed bank is dependent upon not only the presence of seeds, but the availability of viable seeds and favourable growing conditions. *H. uninervis* seeds that are incorporated into the seed bank remain until they germinate or are functionally removed due to a loss of viability. It is estimated that only 2% of *Halodule* seeds germinate and that seedling survival is <2% (Orth *et al.*, 2006b). Seed persistence in the sediments of Roebuck Bay can be determined by measuring seed viability; an embryo which maintains the physiological capability to germinate given the appropriate cues (Murdoch and Ellis, 2000). Seed viability can be affected by biotic (e.g., predation) and abiotic (e.g., sediment type, temperature, salinity) factors in the surrounding environment (Moore *et al.*, 1993; Baskin and Baskin, 1998; Murdoch and Ellis, 2000). The findings from the 5 years of monitoring demonstrate the value in continuing seed bank assessments and suggest additional investigations to quantify seed viability and germination success would add substantially to understanding seagrass resilience.

Report card:

Prior to 2012, the only indicator used to determine seagrass condition was abundance. Threshold values (percentile guidelines) for the abundance indicator were calculated using the mean abundance for each sampling event at the site level (Table 13). With the exception of RO3, variance for the 50th and 20th percentiles was found to level off at around 15–20 samples (i.e. sampling events), suggesting this number of samples was sufficient to provide a reasonable estimate of the true percentile value. This sample size is reasonably close to the ANZECC Guidelines recommendation of 24 data values (ANZECC, 2000). At RO3 however, site specific guidelines could not be calculated as abundances were highly variable (CV > 1.0) and included the lowest recorded across Roebuck Bay over the monitoring period. Therefore, RO2 guidelines were applied to RO3. As the foundational seagrass species in Roebuck Bay *(Halodule uninervis)* dominated the meadow throughout the monitoring period (including during the periods of lowest abundances), it was decided that species composition as an additional indicator of condition was superfluous.

The introduction of routine (quarterly) seed bank monitoring from the late monsoon of 2012, provided an indicator for the capacity of the foundational seagrass (*Halodule uninervis*) to recover from loss/disturbance. It was decided to only include seed bank densities immediately after seed set (the period of seed bank replenishment) and three months just prior to the onset of the growing season (McFarland and Shafer, 2011). Seasonal (December to May) seed bank density long-term average (2012-16) was 611 ±157 seeds m^{-2}. It was decided to use this as the baseline indicator for seagrass seed bank state in the report card (Table 5).

Seagrass condition has fluctuated over the 10-years of monitoring. Seagrass condition was in a fair state when monitoring was established at the long-term sites in 2007, but improved the following year to a good condition where it remained until 2014 (Figure 19b). From 2014 seagrass condition was fair, but improved in 2016 to good. In the 1-2 years following improved abundance state (2011 and 2015), seed banks were in fair-good state (Figure 19a).

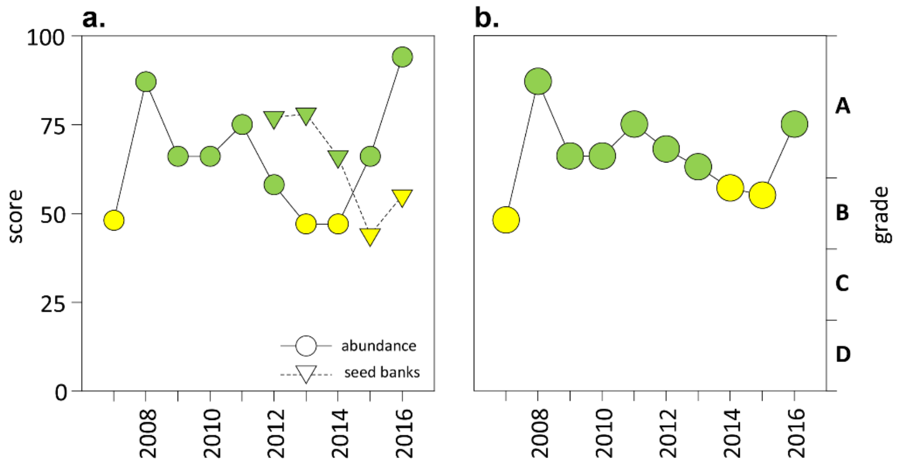

Figure 19. *Report card for Roebuck Bay seagrass condition: a, individual indicators; b, combined index.Reporting scores are categorised to a four point scale; ■ = good (≥ 60-100), ■ = fair (≥ 40 < 60), ■ = poor (≥ 20 < 40), ■ = very poor (0 - < 20). NB: Scores are unitless.*

It is envisioned that as more data becomes available, the report card will be improved. Seagrass are only a component of the Roebuck Bay marine ecosystem, and it is recommended that future report cards be developed to include seagrass stressors and additional ecosystem health indicators, e.g., water quality, sediment quality, shore birds, associated fauna, *etc*.

Relationships between seagrass abundance and environment.

Over the long-term monitoring period (2007-2016), rainfall seasonality was pronounced: increasing in December, peaking during the monsoon period (January) (224.4 ±39.8mm); with drier conditions during the late dry period (August - October) (Figure 20). Seven of the 10 years of monitoring recorded above average rainfall, including the consecutive years 2011 to 2014. The wettest year was 2013 (832mm) and the highest daily rainfall during the monitoring period was 171mm on 22 January 2014. Average daily air temperatures ranged between 15.1°C and 36.2°C and were variable among years. The highest daily air temperature recorded over the monitoring period was 43°C on 09 December 2012 and the coldest was 5.9°C on 15 June 2011. The annual pattern in temperature shows November and December as the warmest months of the year, with temperatures decreasing slightly during the peak rains in January and February, before increasing temporary and then declining during the cooler months (Figure 20). Over the 10 years of seagrass monitoring, 2016 was the warmest year on average followed by 2010 (28.4°C and 28.0°C, respectively).

Cloud cover was higher during the monsoon, and generally follows the rainfall (Figure 20). Surface wind speeds were also higher during monsoon months, and there was also a slight increase during the dry period (Figure 20). Hours of bright sunshine did not range greatly across the year, however solar radiation was lowest in June and highest from September to December of each year (Figure 20).

Seagrasses at all monitoring sites were at or near exposure during daylight hours for at least 45 hours each month of the year (Figure 20). Although hereafter referred to as exposure, in reality, most seagrass at the monitoring sites persisted within shallow pools or depressions which retained some water even during the lowest of spring tides (Personal Observation). Daytime exposure followed a strong 'seasonal type' pattern, with an annual peak reached regularly in August-September and minima in June. Daytime exposure was higher at RO2 than the other sites (Figure 20) and yearly exposure was highest in 2015 (1003 hours). The "deeper" site was RO3 where the lowest daytime exposure occurred during 2013 (683 hours).

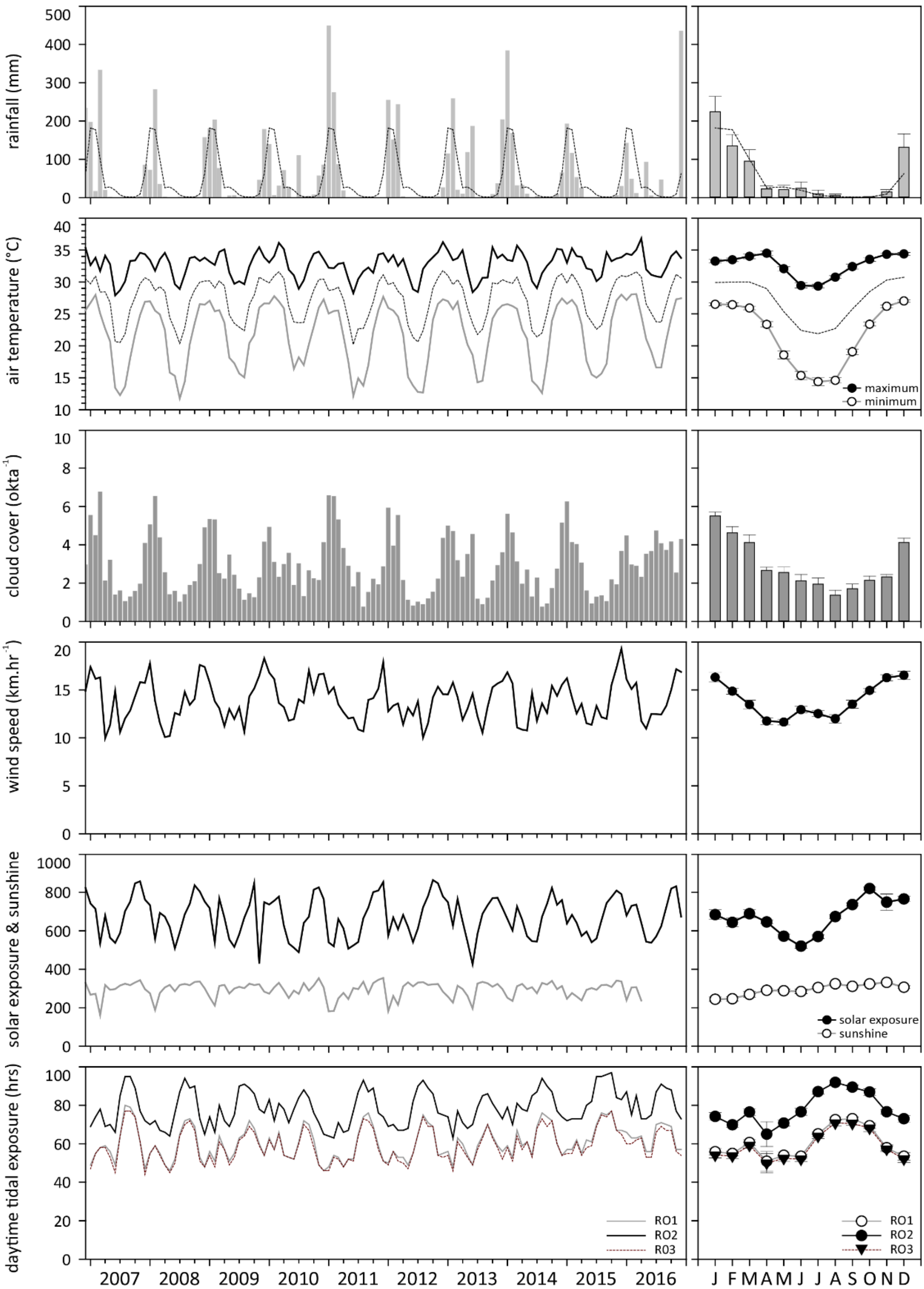

Figure 20. *Environmental parameters during each month 2007–2016 and average across all years at Roebuck Bay: A, total monthly rainfall (dashed line is long-term (78 years) monthly average); B, mean daily maximum, minimum and average air temperature; C, cloud cover; D, mean wind speed (km/h at 3pm); E, total monthly global solar exposure (derived from satellite data in MJ.m^{-2}); and number of hours of bright sunshine. All data recorded at Broome Airport (station 003003) (source www.bom.gov.au).*

The prevailing climate conditions over the course of monitoring provide an important context for understanding changes in seagrass condition and indicator grades. The stepwise regression analysis revealed some significant relationships between variations in environmental variables and seagrass abundance (Table 8). There appears to be a good link between seagrass condition in Roebuck Bay and climate as 23.3% of the variance in total seagrass percentage cover (species pooled) may be explained by the mean air temperature (positively) over the preceding 2 weeks and total rainfall (negatively) during the preceding 3 months (Table 8). These factors with the addition of elevated (maximum) air temperature in the preceding month explain 23.7% of the variance in *Halodule uninervis* abundance. Seagrass abundance at individual sites is similarly explained to various degrees (e.g., 18.4 to 37.1%) by a combination of air temperature (positive) and rainfall (negative) in preceding months (Table 8).

The relationship of seagrass abundance with environmental factors indicates that the growth function in tropical seagrass meadows is complex. Seagrass abundance in Roebuck Bay appears to be primarily driven by environmental factors that influence sea water temperature and light availability. Light is essential for seagrass growth as it drives photosynthetic carbon uptake; increasing light increases photosynthetic carbon uptake, and therefore more carbon is available for investment into biomass production and reserve formation (Fourqurean and Zieman, 1991; Zimmerman *et al.*, 1995). However, light limitation can arise when water quality is reduced (e.g., suspended sediments in turbid freshwater runoff from monsoonal rainfall), or epiphytes/macroalgal blooms over grow seagrass leaves. Light limitation causes seagrass growth rates to slow, and after critical light thresholds have been exceeded for a prolonged period (1-14 weeks, depending on species), leaves and shoots are senesced, causing reductions in abundance (see Ralph *et al.*, 2007).

The positive relationship with mean air temperature is not surprising as temperature exerts a strong control over seagrass photosynthesis and growth, and therefore seasonally varying temperatures affects abundance (Lee *et al.*, 2007). Temperature extremes can however, impair photosystems (Campbell *et al.*, 2006), reducing overall photosynthetic carbon incorporation and abundance (Adams *et al.*, 2017). Increasing temperatures can also enhance the effects of light deprivation (Collier *et al.*, 2016) and herbicide exposure (Wilkinson *et al.*, 2017), and chronic increases in temperature can drive seagrass mortality (Marba and Duarte, 2010).

Climatic factors also had significant relationships with epiphyte and *Lyngbya* abundances in Roebuck Bay. Epiphytes on seagrass leaves appear to be positively influenced by solar radiation, but negatively influenced by mean air temperature over the preceding 90 days; explaining 23.6% of the variance in abundance (Table 8). *Lyngbya* appears positively influenced by air temperature in the preceding 3 months, explaining between 19.6 and 25.7% of the variance in abundance at RO3 and RO1, respectively.

Table 8. *Regression analysis (final models following stepwise removal analysis) of total seagrass abundance (% cover), epiphyte abundance (% cover) and Lyngbya abundance relative to climate and environmental data (average or sum of 15, 30 or 90 days prior to abundance measure) at each site in Roebuck Bay (2007-2016). Seagrass abundance represented as total (all species pooled), Halodule uninervis and Halophila ovalis. Climate and environmental data: total rainfall (mm); temperature = average daily air temperature (°C); max temperature = average daily maximum air temperature (°C); tidal exposure = total daytime hours seagrass meadow exposed during low tide (hrs); solar radiation = rate of total incoming solar energy on a horizontal plane at the Earth's surface (J.m^{-2}). ANOVA statistics (significance level of 0.05) and R^2 value for each regression model shown, including individual regression coefficients of the specific abundance predictors (environmental variables). n.s. = not significant, $p \geq 0.05$.*

site	metric	ANOVA			Model	Predictor Regression Coefficient										
		p	F	DoF	r^2	Air temp 15	Air temp 30	Air temp 90	Max air 30	Max air 90	Solar 15	Solar 30	Solar 90	Rain 90	Exp 15	Exp 90
Pooled	Total cvr	<0.001	17.8	2,117	23.3	0.405								-0.377		
	H. uninervis	<0.001	12.02	3,116	23.7	0.715			-0.344					-0.339		
	H. ovalis	<0.001	13.2	2,117	18.4		0.347							-0.385		
	Epiphyte	<0.001	18.04	2,117	23.6			-0.492					0.545			
	Lyngbya	<0.001	8.15	2,117	12.2			0.413						-0.253		
RO1	Total cvr	0.002	7.09	2,38	27.2		0.473							-0.439		
	H. uninervis	0.002	5.74	3,37	31.8		0.736				-0.365			-0.536		
	H. ovalis	0.007	5.76	2,38	23.3		0.410							-0.435		
	Epiphyte	0.046	4.27	1,39	9.9									-0.314		
	Lyngbya	0.004	6.58	2,38	25.7					0.421						0.392
RO2	Total cvr	<0.001	8.80	2,36	32.9		0.492							-0.476		
	H. uninervis	<0.001	8.12	2,36	31.1	0.500								-0.385		
	H. ovalis	0.011	5.14	2,36	22.2			0.374						-0.545		
	Epiphyte	0.02	5.87	1.37	13.7							0.370				
	Lyngbya	n.s.														
RO3	Total cvr	<0.001	7.09	3,36	37.1			0.726						-0.589	0.415	
	H. uninervis	0.006	4.93	3,36	29.1			0.560						-0.387	0.346	
	H. ovalis	<0.001	7.73	3,36	39.2			0.761						-0.579	0.448	
	Epiphyte	0.002	7.31	2,37	28.3			-0.571					0.571			
	Lyngbya	0.004	9.25	1,38	19.6			0.443								

GENERAL CONCLUSIONS & RECOMMENDATIONS

The findings from the decade of monitoring by the Broome Community Seagrass Monitoring Project provide critical information on the condition of seagrass and insight into the drivers of change in coastal marine habitats in the Kimberley region of Australia. The project has demonstrated the value of building capacity within local communities to monitor local coastal resources, and verifies that trained participants have the competency to collect critical data in partnership with scientists, that meets the statistical requirements for monitoring seagrass habitat cover worldwide.

Recommendations

- That routine monitoring based on Seagrass-Watch standard protocols at existing long-term monitoring sites be continued and supported.
- That annual refresher workshops and additional training from Seagrass-Watch HQ be supported, or alternatively Seagrass-Watch HQ be supported to conduct post-field assessments on data submitted.
- Continue the collaborative arrangement with Broome Community Seagrass Monitoring Project (Environs Kimberley), Department of Parks and Wildlife and Seagrass-Watch HQ. This is a very effective and beneficial arrangement.

Seagrass abundance and species composition was seasonal in Roebuck Bay meadows, with higher abundances in late-dry to early-monsoon (October-December) and lower in late-monsoon to dry (April-July) each year. Seagrass abundance appears to be primarily driven by environmental factors that influence sea water temperature (over preceding 2 weeks) and light availability. Key factors which may impact light availability includes suspended sediments in turbid freshwater runoff from monsoonal rainfall and epiphyte/macroalgal abundance stimulated by elevated dissolved nutrients. The inclusion of routine *in situ* light (Photosynthetically Active Radiation) and temperature monitoring will assist with the identification of seagrass stressors and interpretation of trends.

Recommendations

- That monitoring be conducted at least twice yearly: late in the main growing period, September to December; and wet season (January to April)
- Introducing routine *in situ* light and temperature monitoring at representative sites
- Investigate the factors which influence the growth and formation of microalgal epiphytic aggregations on the seagrass, particularly the potential link with catchment nutrients.

Recovery of seagrass meadows is facilitated by reproductive output, seed banks and seagrass species composition. A persistent seed bank of the foundation seagrass *Halodule uninervis* exists throughout the meadows of northern Roebuck Bay, and although highly variable, densities appeared higher in the wet (December to May), after the main seagrass growth period (September to December). Analysis suggests that meadows may require only a moderate seed bank for recovery capacity, and that greater sized seed banks provide greater probability of recovery (i.e. greater probability of viable seeds) but not necessarily greater abundance. It is estimated in the literature that only 2% of *Halodule* seeds germinate and that seedling survival is <2%. Additional investigations to quantify reproductive output, seed viability and germination success in Roebuck Bay would add substantially to understanding seagrass resilience. This is a knowledge gap that warrants further investigation

Recommendations

- Seed bank monitoring be conducted as part of standard monitoring, but concentrated on wet season (January to April),
- Seed viability studies be conducted to quality viability of the seed bank,
- Assessment of seagrass flowering and reproductive health be conducted at monitoring sites.

Lyngbya majuscula occurred episodically across all the northern Roebuck Bay meadows throughout the decade of monitoring, particularly during the early months of the year. However, when present, *L. majuscula* abundances did not appear to significantly impact seagrass abundance, possibly because *L. majuscula* abundances remained low to very low. Should *L. majuscula* increase in abundance and frequency in future, seagrass may be significantly impacted as reported at other locations globally. Routine water quality monitoring coupled with *L. majuscula* assessments would assist in identifying drivers of the blooms and possible sources of elevated nutrients.

Recommendations

- Assess the nature, extent and level of impact of *L. majuscula* blooms on seagrass communities in and adjacent to the Marine Park
- Conduct routine water quality assessments to identifying drivers of the blooms and possible sources of elevated nutrients

A pilot report card representing the relative health of seagrass in Roebuck Bay was developed, which shows that seagrass condition has fluctuated over the 10-years of monitoring, but no long-term trend is apparent. The pilot report card uses two indicators of seagrass condition, based on their significance to seagrass resilience: abundance, which represents the state of the seagrass to resist stressors; and seed banks, which represents the capacity of the seagrass to recover from loss/disturbance. Current (2016) state shows seagrass communities of northern Roebuck Bay to be in a good condition (grade A) with improving abundances and seed banks. The seagrass report card is an efficient tool for integrating key indicators into simple scores that can be communicated to decision-makers and the general public. The indicators used are meaningful and the grades that represent the level of ecosystem health are based on transparent and statistically defensible indices. The data and collection methods underlying the report card are also standardised and of high quality. However, the report card only represents one component of the ecosystem in the northern region of Roebuck Bay. Ecological report cards should ideally represent more than one component of the ecosystem; include abiotic (e.g., water quality) and social (human) indicators; and use a more geographically detailed approach. It is anticipated that the seagrass report card will be adopted for the region and released annually, based on recent data that summarises ecological conditions from the previous year. It is also suggested the report card be improved each year and expanded to include biotic and abiotic stressors.

Recommendations

- That the seagrass report card for Roebuck Bay be adopted by management agencies and stakeholders and produced annually
- The report card continue to be improved and where possible integrated with a larger report card on the ecological, cultural and social values of Yawuru Nagulagun / Roebuck Bay Marine Park

Roebuck Bay is a large tropical marine embayment and seagrass monitoring only occurs at 3 sites in the northern area, within Kimberley Ports Authority (KPA) port waters (outside the Marine Park). A critical information gap is the distribution, diversity and abundance of seagrass resources in Roebuck Bay. In 2016, KPA completed a marine baseline assessment of the ports waters, however, no assessment has been conducted of the intertidal or subtidal areas of the Marine Park. A high - key management strategy for the Marine Park is to undertake and support research to characterise the diversity, density, abundance and distribution of seagrass and algae; this should be prioritised. Once completed, representative seagrass communities/meadows can be recognised for monitoring to inform management of the Park's ecological value status and identify any significant impacts occurring from human activities.

Recommendations

- Prioritise assessment to characterise the distribution, diversity, and abundance of intertidal and subtidal seagrass communities in the Marine Park (i.e. mapping)
- Identify representative seagrass communities/meadows and establish additional long-term monitoring sites to report seagrass condition/health

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APPENDIX

General Additive Mixed Models (GAMM)

Data was analysed using general additive mixed models in R (mgcv package) to show the variation of seagrass cover over time. The analysis was performed on the % cover data converted to a 0-1 range using the quasibinomial data distribution option of the mgcv package. Two separate model were produced. Firstly, an overall model with the 3 sites pooled (M1). And secondly a model including 3 different smoothers (M2) for the 3 different sites (RO1, RO2, RO3). These models include random effects to the site and quadrat levels. They provide a good picture of the trends of cover over time. However, some care should be taken when dealing with the confidence intervals produced by the models because there is small zero inflation and heterogeneity variance in the residuals.

Table 9. *Summary of GAMM for average cover vs time analysis for 2007-16. n = number of data points analysed, EDF = array of estimated degrees of freedom for the model terms.*

MODELS	n	EDF	F	*P*-VALUE	R-SQ (ADJ)
% cover = s(date) + random	3,898	8.901	125.1	<2e-16	0.201
% cover = s(date) + Site + random	3,898				0.366
RO1		8.875	62.64	<2e-16	
RO2		8.545	54.78	<2e-16	
RO3		8.711	85.19	<2e-16	

Bayesian GLMM using INLA

A similar model to M2 was produced in INLA, this time using a generalized linear mixed model (GLMM) technique. The Bayesian output consists of posterior distributions with 95% credible intervals, one for each site. We are therefore able to directly compare them overtime by just subtracting them. If 0 is not included in the interval produced then it means that there is an important difference between the 2 sites, also referred as "significant" in the frequentist language.

Due to the specific nature of the data (percentage, between 0 and 1), the size of the data set (more than 50000 data points) and the complex structure of the random effect, traditional methods (frequentist) failed to provide the tools to correctly analyse it. Therefore, Bayesian statistic techniques such as Markov chain Monte Carlo (MCMC) or Integrated Nested Laplace Approximations (INLA) had to be used. Contrary to Frequentist statistics, Bayesian statistics are based on probability and the output is presented as a posterior distribution of the estimated parameters (where the mean and 95% credible interval can be calculated). INLA was preferred instead of MCMC as this technique can take several day of computing time for large data sets.

Model choice: Percentage should be analysed by a model following a beta distribution (0<x<1). This issue with percentage of seagrass cover is that the values 0 and 1 can occur. The 1's can be easily deal with by approximating to 0.99999 because of the very few numbers of these values in the dataset. The same cannot be done with the 0's as the dataset is heavily zero-inflated (>30%). Unfortunately, a zero-inflated beta distribution is not yet available to be used in INLA. The only other option is to use a zero-altered beta model (ZABE) similar to the one presented in Zuur and Ieno (2016, Chapter 16). It consists of two components, a Bernoulli part analysing the data as 0 (presence of seagrass) and 1 (absence of seagrass), and a beta part analysing only the data without 0. The ZABE model can be written as:

$$Y_i \sim ZABE\ (\mu, \pi, \phi)$$

$$E(Y) = (1 - \pi_i)\ \times\ \mu_i$$

where E(Y), μ_i and π_i are the mean of the ZABE model, the beta component and the Bernoulli component respectively.

Both components are modelled as a function of covariates such as site and year (fixed terms) and include random effects for transect and quadrat (random terms). Specifically for INLA, diffuse priors were used for the fixed terms and informative priors were used for the random terms.

Analysis of variance (ANOVA)

Table 10. *Results of 2-way ANOVA examining the effect of site and season on seagrass canopy height.*

Source	DF	Sum of squares	Mean squares	F	P
Model	11	216.5452	19.6859	10.9652	< 0.001
Site	2	79.9485	39.9742	22.2660	< 0.001
Season	3	126.7545	42.2515	23.5344	< 0.001
Site*Season	6	7.5143	1.2524	0.6976	0.6521
Error	104	186.7116	1.7953		
Corrected Total	115	403.2568			

Table 11. *Results of 2-way ANOVA examining the effect of season and year on epiphyte abundance.*

Source	DF	Sum of squares	Mean squares	F	P
Model	38	3.9704	0.1045	7.0205	< 0.0001
Season	3	1.0782	0.3594	24.1486	< 0.0001
Year	10	1.2605	0.1261	8.4696	< 0.0001
Season*Year	25	1.5983	0.0639	4.2959	< 0.0001
Error	77	1.1460	0.0149		
Corrected Total	115	5.1163			

Table 12. *Results of 2-way ANOVA examining the effect of season and year on seed bank abundance.*

Source	DF	Sum of squares	Mean squares	F	P
Model	9	2289085.028	254342.781	1.168	0.366
Year	4	1733763.651	433440.913	1.990	0.135
Season	1	351952.708	351952.708	1.616	0.218
Year*Season	4	203368.669	50842.167	0.233	0.916
Error	20	4355710.969	217785.548		
Corrected Total	29	6644795.997			

Seagrass abundance guidelines

Table 13. *Seagrass percentage cover guidelines ("the seagrass guidelines") for each site in Roebuck Bay. ^ from nearest site.*

site	percentile guideline	
	20th	50th
RO1	6.7 %	16.6 %
RO2	4 %	11.4 %
RO3^	4 %	11.4 %