Great Barrier Reef
MARINE MONITORING PROGRAM

Annual Report
INSHORE SEAGRASS MONITORING
2019-20

Australian Government
Great Barrier Reef Marine Park Authority

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TropWATER

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Front cover image: School of small fish above a shallow seagrass meadow (mainly *Halodule uninvervis*), taken near the Green Island jetty © Dieter Tracey.

The Great Barrier Reef Marine Park Authority acknowledges the continuing Sea Country management and custodianship of the Great Barrier Reef by Aboriginal and Torres Strait Island Traditional Owners whose rich cultures, heritage values, enduring connections and shared efforts protect the Reef for future generations.

Comments and questions regarding this document are welcome and should be addressed to:

TropWATER- Centre for Tropical Water and Aquatic Ecosystem Research

James Cook University

Townsville, Qld 4811

Tropwater@jcu.edu.au

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Acronyms, abbreviations and units

Authority	Great Barrier Reef Marine Park Authority
BoM	Bureau of Meteorology
CV	coefficient of variation
DES	Department of Environment and Science, Queensland
JCU	James Cook University
km	kilometre
m	metre
MMP	Great Barrier Reef Marine Monitoring Program
MTSRF	Marine and Tropical Sciences Research Facility
NRM	Natural Resource Management
Paddock to Reef program	Paddock to Reef Integrated Monitoring, Modelling and Reporting Program
PAR	Photosynthetically available radiation
QPWS	Queensland Park and Wildlife Service
Reef	Great Barrier Reef
Reef 2050 WQIP	Reef 2050 Water Quality Improvement Plan
Reef 2050 Plan	Reef 2050 Long-Term Sustainability Plan
RIMReP	Reef 2050 Integrated Monitoring and Reporting Program
RJFMP	Reef Joint Field Management Program
SE	Standard Error
SW	Seagrass-Watch
The Reef	Great Barrier Reef
TropWATER	Centre for Tropical Water & Aquatic Ecosystem Research

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River discharge data provided by the State of Queensland (Department of Natural Resources, Mines and Energy) 2020. The conceptual diagram symbols are courtesy of the Integration and Application Network (ian.umces.edu/symbols/), University of Maryland Center for Environmental Science. Climate data courtesy of the Australian Bureau of Meteorology, and tide data courtesy Maritime Safety Queensland, Department of Transport and Main Roads.

Executive summary

This document reports on the long-term health of inshore seagrass meadows in the Great Barrier Reef. Results are presented in the context of the pressures faced by the ecosystem.

Trends in key inshore seagrass indicators

Inshore seagrass meadows across the Great Barrier Reef (the Reef) remained unchanged in overall condition in 2019–20, with the condition grade remaining **poor**. All regions this year have an overall seagrass condition grade of poor. Within the grade, the score declined in Cape York and the Wet Tropics, and increased in the Burdekin and Mackay–Whitsunday regions.

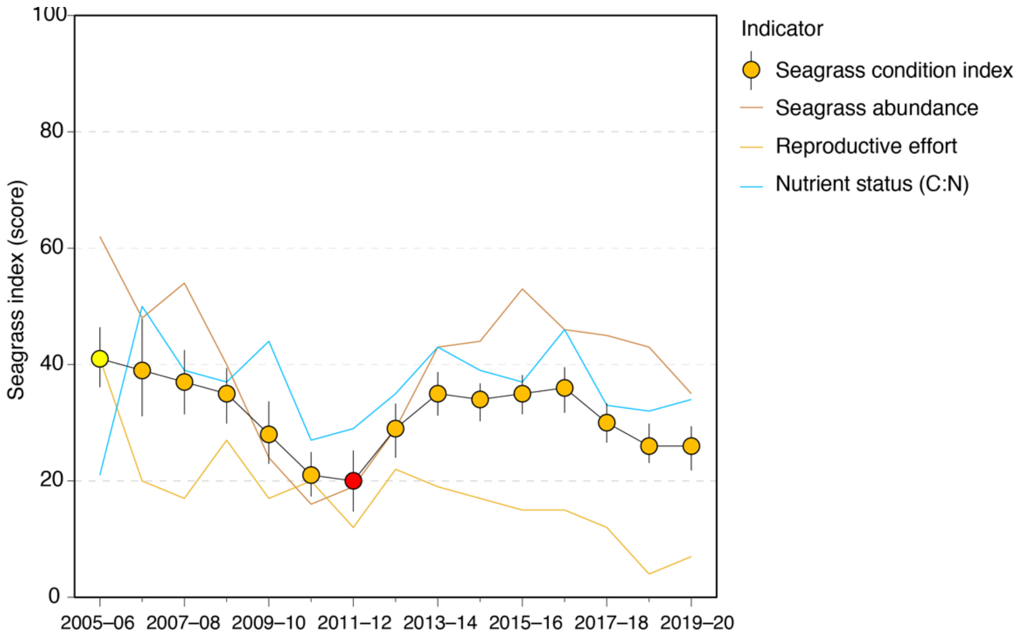


Figure 1. Overall inshore Reef seagrass condition index (±SE) with contributing indicator scores over the life of the MMP. The index is derived from the aggregate of metric scores for indicators of seagrass community health. Index scores scaled from 0–100 and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

Seagrass abundance had been increasing on average since 2010–11, but declined in the past three reporting years including in 2019–20. The decline was driven mostly by seagrass loss in the Burdekin region, with smaller declines also occurring on average in Cape York and the Wet Tropics. There is a legacy effect of heavy rainfall and above-average discharge from rivers in these regions in early 2019. There were, however, increasing or stable abundances at more than half of inshore Reef sites with greatest improvements in the Mackay–Whitsunday region.

Reproductive effort is a measure of resilience and although improved slightly in 2019–20, remained very poor for the inshore Reef overall. It was very poor in northern and southern regions, and poor in the central regions of southern Wet Tropics, Burdekin and Mackay–Whitsunday. Reproductive effort declined or remained stable (and low) at the majority of sites, but there were also increases in reproductive effort at some sites in all regions.

Seagrass tissue nutrients (C:N) indicate the availability of nitrogen relative to growth demand (i.e. carbon fixation). The leaf tissue nutrient indicator improved slightly in 2019–20 and was similar to the long-term average for the inshore Reef.

There are signs of recovery based on additional indicators, including:

- decreasing or stable proportion of colonising species and lower than the inshore Reef long-term average at the majority of sites, which is a sign of recovery towards species that are foundational to the meadows.
- increasing or stable meadow extent of most sites, although estuarine habitats in the Burnett–Mary region, reef habitat in the Fitzroy region and subtidal reef habitat in the Burdekin region remain vulnerable to large disturbances.
- increasing seed banks at a third of coastal and estuarine sites across all regions, but an absence of seed banks at almost half of overall sites, in particular those in reef intertidal and reef subtidal habitats.

Influencing pressures

Pressure affecting inshore Reef seagrass habitats were moderate in 2019–20. There were no cyclones, and rainfall and river discharge were below average. Inshore seagrass sites were none-the-less exposed to ‘brown’ or ‘green’ waters during most weeks of the wet season (November–April).

Benthic light availability was higher than the long-term average for inshore Reef seagrass meadows. Furthermore, benthic light was higher than the long-term average and higher than long-term growth requirements at the majority of the meadows monitored.

Within canopy water temperature of inshore Reef seagrass meadows was around the long-term average.

There is a history of cumulative pressures facing Reef inshore seagrass meadows since program inception and in most years some or all regions have been affected by cyclones, floods, thermal anomalies or periods of very low light availability. Particularly severe and widespread pressures occurred in the period from 2009–10 to 2011–12, when there was above-average river discharge and localised cyclone damage leading to the very poor seagrass condition index. Other regionally-significant impacts were caused by cyclone Debbie in 2016–17 affecting the Mackay–Whitsunday region, and floods in the Burdekin region in 2018–19. Legacy effects of these past pressures are evident in current seagrass condition and the ongoing need for recovery to reach a higher seagrass index.

Conclusions

The findings suggest that seagrass meadows in all regions remain vulnerable to severe disturbances in the near future, but there are signs of recovery in some indicators. Almost half of the sites decreased in abundance, but most meadows were stable or improved in extent, and the proportion of colonising species declined. Reproductive effort increased slightly though remained very poor overall, but there are seed banks present in estuarine and coastal meadows though reef habitats remain largely depleted of seeds.

Climate change is the most significant threat to the Reef’s long-term outlook and is likely to intensify pressures and increase the need for meadow resilience. Water quality improvements to catchment run-off are expected to provide some relief from these impacts and improve meadow condition and resilience, but further options for improving resilience need to be explored.

1 Introduction

Approximately 3,464 km^2 of inshore seagrass meadows has been mapped in Great Barrier Reef World Heritage Area (the World Heritage Area) in waters shallower than 15 m (McKenzie *et al.* 2014c; Saunders *et al.* 2015; Carter *et al.* 2016; McKenzie *et al.* 2016; C. Howley, Unpublished data). The remaining modelled extent (90 per cent or 32,335 km^2) of seagrass in the World Heritage Area is located in the deeper waters (>15 m) of the lagoon (Coles *et al.* 2009; Carter *et al.* 2016), however, these meadows are relatively sparse, structurally smaller, highly dynamic, composed of colonising species, and not as productive as inshore seagrass meadows for fisheries resources (McKenzie *et al.* 2010b; Derbyshire *et al.* 1995). Overall, the total estimated area of seagrass (34,841 km^2) within the World Heritage Area represents nearly 48 per cent of the total recorded area of seagrass in Australia and between 13 per cent and 22 per cent globally (McKenzie *et al.* 2020), making the Reef's seagrass resources globally significant.

Tropical seagrass ecosystems of the Reef are a complex mosaic of different habitat types comprised of multiple seagrass species (Carruthers *et al.* 2002). There are 15 species of seagrass in the Reef (Waycott *et al.* 2007) and a high diversity of seagrass habitat types is provided by extensive bays, estuaries, rivers and the 2,300 km length of the Reef with its inshore lagoon and reef platforms. They can be found on sand or muddy beaches, on reef platforms and in reef lagoons, and on sandy and muddy bottoms down to 60 m or more below Mean Sea Level (MSL).

Seagrasses in the Reef can be separated into four major habitat types: estuary/inlet, coastal, reef and deepwater (Carruthers *et al.* 2002). Environmental variables that influence seagrass species composition within these habitats include depth, tidal exposure, latitude, current speed, benthic light, proportion of mud, water type, water temperature, salinity, and wind speed (Carter et al 2021). All but the outer reef habitats are significantly influenced by seasonal and episodic pulses of sediment-laden, nutrient-rich river flows, resulting from high volume summer rainfall. Cyclones, severe storms, wind and waves as well as macro grazers (e.g. fish, dugongs and turtles) influence all habitats in this region to varying degrees. The result is a series of dynamic, spatially and temporally variable seagrass meadows.

The seagrass ecosystems of the Reef, on a global scale, would be for the most part categorised as being dominated by disturbance-favouring colonising and opportunistic species (e.g. *Halophila* and *Halodule*), which typically have low standing biomass and high turnover rates (Carruthers *et al.* 2002, Waycott *et al.* 2007). In more sheltered areas, including reef top or inshore areas in bays, more stable and persistent species are found, although these are still relatively responsive to disturbances (Carruthers *et al.* 2002; Waycott *et al.* 2007; Collier and Waycott 2009).

1.1 Seagrass monitoring in the Marine Monitoring Program

The strategic priority for the Great Barrier Reef Marine Park Authority (the Authority) is to sustain the Reef's outstanding universal value, build resilience and improve ecosystem health over each successive decade (Great Barrier Reef Marine Park Authority 2014). Improving water quality is a key objective, because good water quality aids the resilience of coastal and inshore ecosystems of Reef (GBRMPA, 2014a, b).

In response to concerns about the impact of land-based run-off on water quality, coral and seagrass ecosystems, the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) (Australian Government and Queensland Government 2018b) was recently updated by the Australian and Queensland governments, and integrated as a major component of Reef 2050 Long-Term Sustainability Plan (Reef 2050 Plan) (Australian Government and Queensland Government 2018a), which provides a framework for integrated management of the *World Heritage Area*.

A key deliverable of the Reef 2050 WQIP is the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program), which is used to evaluate the efficiency and effectiveness of Reef 2050 WQIP implementation, and report on progress towards goals and targets (Australian Government and Queensland Government 2018b). The Great Barrier Reef Marine Monitoring Program (MMP) forms an integral part of the Paddock to Reef program. The MMP has three components: inshore water quality, coral and seagrass.

The overarching objective of the inshore seagrass monitoring program is to quantify the extent, frequency and intensity of acute and chronic impacts on the condition and trend of seagrass meadows and their subsequent recovery.

The inshore water quality monitoring program has been delivered by James Cook University (JCU) and the Authority since 2005. The seagrass sub-program is also supported by contributions from the Seagrass-Watch program (Wet Tropics, Burdekin, Mackay–Whitsunday and Burnett–Mary) and Queensland Parks and Wildlife Service (QPWS) through the Reef Joint Field Management Program (RJFMP).

Further information on the program objectives, and details on each sub-program are available on-line (GBRMPA 2019; http://bit.ly/2mbB8bE).

1.2 Conceptual basis for indicator selection

As seagrasses are well recognised as indicators of integrated environmental pressures, monitoring their condition and trend can provide insight into the condition of the surrounding environment (e.g. Dennison *et al.* 1997). There are a number of measures of seagrass condition and resilience that can be used to assess how they respond to environmental pressures, and these measures are referred to herein as indicators. We have developed a matrix of indicators that respond on different temporal scales (Figure 2). Indicators include:

- plant-scale changes
- meadow-scale changes
- state change.

These indicators also respond at different temporal scales, with sub-lethal indicators able to respond from seconds to months, while the meadow-scale effects usually take many months to be detectable. A state change refers to an ecological shift in which the core structures, functions and processes are affected (Unsworth et al 2015). A state changesignals risk of recalcitrant degradation and difficulty in returning to the original state (O'Brien et al 2018).

A robust monitoring program benefits from having a suite of indicators that can indicate sub-lethal stress that forewarns of imminent loss, as well as indicators of meadow-scale changes, which are necessary for interpreting broad ecological changes. Indicators included in the MMP span this range of scales, in particular for indicators that respond from weeks (tissue nutrients, isotopes), through to months (abundance and reproduction), and even years (composition and meadow extent). Furthermore, indicators are conceptually linked to each other and to environmental drivers of concern, in particular, water quality (p 34, in Kuhnert *et al.* 2014).

Measures of Environmental stressors

Climate and environment stressors are aspects of the environment, either physio-chemical or biological that affect seagrass meadow condition. Some environmental stressors change rapidly (minutes/days/weeks/months) but can also undergo chronic shifts (years) (Figure 2). Stressors include:

- climate (e.g. cyclones, seasonal temperatures)
- local and short-term weather (e.g. wind and tides)
- water quality (e.g. river discharge, plume exposure, nutrient concentrations, suspended sediments, herbicides)

- biological (e.g. epiphytes and macroalgae)
- substrate (e.g. grain size composition).

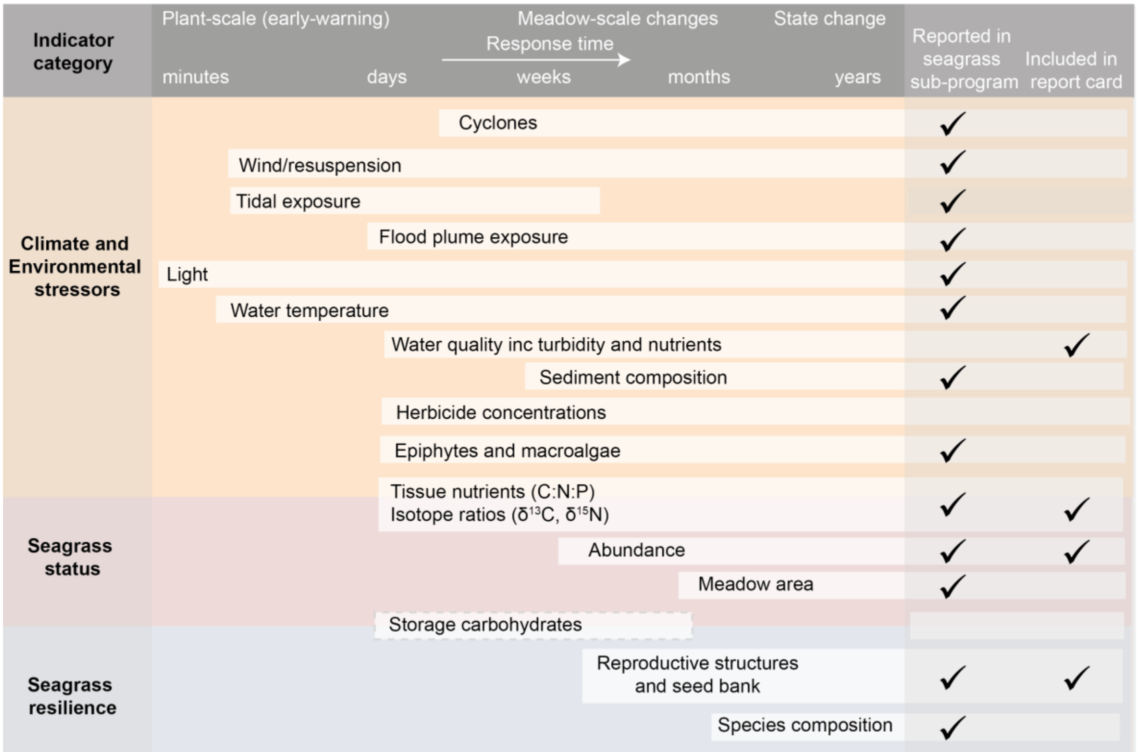


Figure 2. Climate, environmental, seagrass condition and seagrass resilience indicators reported as part of inshore seagrass monitoring. Regular text are indicators measured in the inshore seagrass program, white box with dashed line are indicators in development, and italicised text are indicators collected in other programs or by other institutions (see Table 2 for details on data source). All indicators are shown against their response time.

Indicators which respond more quickly (e.g. light) provide important early-warning of potentially more advanced ecological changes (as described below). However, a measured change in a fast-responding environmental indicator is not enough in isolation to predict whether there will be further ecological impacts, because the change could be short-term. These indicators provide critical supporting information to support interpretation of slower responding seagrass condition and resilience indicators. Epiphytes and macroalgae are an environmental indicator because they can compete with and/or block light reaching seagrass leaves, therefore compounding environmental stress.

These environmental indicators are interpreted according to the following general principles:

- Cyclones cause physical disturbance from elevated swell and waves resulting in meadow fragmentation and loss of seagrass plants (McKenzie *et al.* 2012). Seagrass loss also results from smothering by sediments and light limitation due to increased turbidity from suspended sediments. The heavy rainfall associated with cyclones results in flooding which exacerbates light limitation and transports pollutants (nutrients and pesticides), resulting in further seagrass loss (Preen *et al.* 1995).
- Benthic light level below 10 mol m^{-2} d^{-1} are unlikely to support long-term growth of seagrass, and periods below 6 mol m^{-2} d^{-1} for more than four weeks can cause loss (Collier *et al.* 2016b). However, it is unclear how these relate to intertidal habitats because very high light exposure during low tide can affect light. Therefore, it may be more informative to look at change relative to the sites.

- Water temperature can impact seagrasses through chronic effects in which elevated respiration at high temperatures can cause carbon loss and reduce growth (Collier et al 2017), while acute stress results in inhibition of photosynthesis and leaf death (Campbell *et al.* 2006; Collier and Waycott 2014)
- Daytime tidal exposure can provide critical windows of light for positive net photosynthesis for seagrass in chronically turbid waters (Rasheed and Unsworth 2011). However, during tidal exposure, plants are susceptible to extreme irradiance doses, desiccation, thermal stress and potentially high UV-A and UV-B leading to physiological damage, resulting in short-term declines in density and spatial coverage (Unsworth *et al.* 2012).
- Sediment grain size affects seagrass growth, germination, survival, and distribution (McKenzie 2007). Coarse, sand dominated sediments limit plant growth due to increased mobility and lower nutrients. However, as finer-textured sediments increase (dominated by mud (grain size <63μm)), porewater exchange with the overlaying water column decreases resulting in increased nutrient concentrations and phytotoxins such as sulphide, which can ultimately lead to seagrass loss (Koch 2001).

Measures of seagrass condition

Condition indicators such as meadow abundance and extent indicate the state of the plants/population and reflect the cumulative effects of past environmental conditions (Figure 2). Abundance can respond to change on time-scales ranging from weeks to months (depending on species) in the Reef, while meadow area tends to adjust over longer time-scales (months to years). Seagrass area and abundance are integrators of past conditions, and are vital indicators of meadow condition; however, these indicators can also be affected by external factors such as grazing by dugongs and turtles. Therefore, they are not suitable as stand-alone indicators of environmental change and indicators that can be linked more directly to specific pressures are needed. These condition indicators also do not demonstrate capacity to resist or recover from additional impacts (Unsworth *et al.* 2015).

Changing ratios of seagrass tissue nutrients provide an indication of seagrass condition and environmental conditions. Carbon to nitrogen (C:N) ratios have been found in a number of experiments and field surveys to be related to light levels, as leaves with an atomic C:N ratio of less than 20, may suggest reduced light availability when N is not in surplus (Abal *et al.* 1994; Grice *et al.* 1996; Cabaço and Santos 2007; Collier *et al.* 2009). Therefore, C:N ratio is reported within the seagrass component of the Marine Results report and report card, while other tissue nutrients are also presented as supporting information.

Measures of seagrass resilience

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 relates to the ability of a system to both resist and recover from disturbances (Unsworth *et al.* 2015) (Figure 3). Changes in resilience indicators show if the ecosystem is in transition (i.e. has already, or may undergo a state-change). Sexual reproduction (flowering, seed production and persistence of a seedbank) is an important feature of recovery (and therefore, of resilience) in seagrass meadows.

Coastal seagrasses are prone to small scale disturbances that cause local losses (Collier and Waycott 2009), and therefore disturbance-specialist species (i.e. colonisers) tend to dominate throughout the Reef. Community structure (species composition) is also an important feature conferring resilience, as some species are more resistant to stress than others, and some species may rapidly recover and pave the way for meadow development (Figure 4).

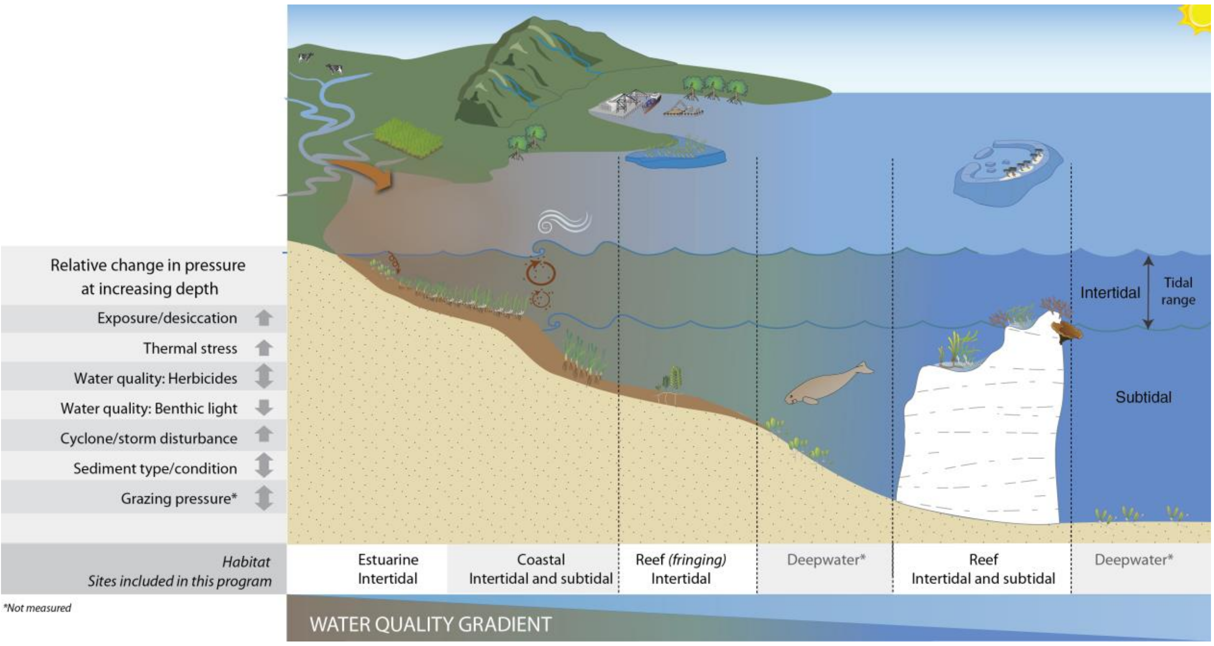


Figure 3. General conceptual model of seagrass habitats in north east Australia and the water quality impacts affecting the habitat (adapted from Carruthers et al., 2002, and Collier et al. 2014)

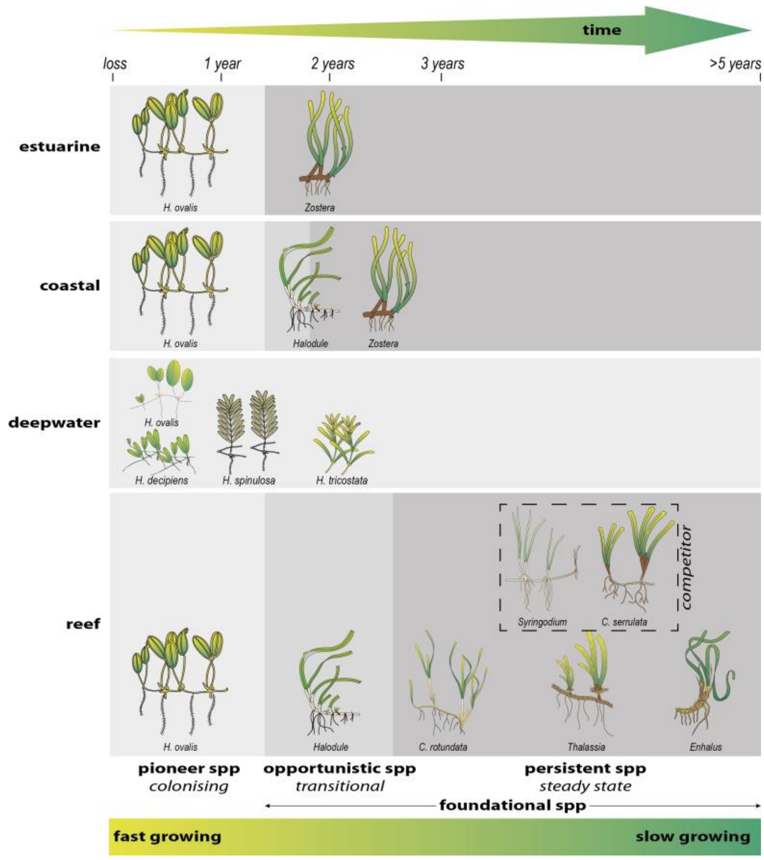


Figure 4. Illustration of seagrass recovery after loss and the categories of successional species over time. Figure developed from observed recovery dynamics (Birch and Birch 1984; Preen et al. 1995; McKenzie and Campbell 2002; Campbell and McKenzie 2004; McKenzie et al. 2014a; Rasheed et al. 2014).

1.3 Structure of the Report

This report presents data from the fourteenth period of monitoring inshore seagrass ecosystems of the Reef under the MMP (undertaken from June 2019 to May 2020; hereafter called 2019–20). The inshore seagrass monitoring sub-program of the MMP reports on:

- abundance and species composition of seagrass (including landscape mapping) in the late dry season of 2019 and the late wet season of 2020 at inshore intertidal and subtidal locations
- reproductive health of the seagrass species present at inshore intertidal and subtidal locations
- tissue nutrient concentrations (carbon, nitrogen and phosphorus) and epiphyte loads of foundation seagrass species (e.g. genus *Halodule, Zostera, Cymodocea*) at each inshore intertidal and subtidal location
- spatial and temporal patterns in light, turbidity and temperature at sites where autonomous loggers are deployed
- trends in seagrass condition
- seagrass community in relation to environment condition and trends
- seagrass report card metrics for use in the annual Reef Report Card produced by the Paddock to Reef program.

The next section presents a summary of the program's methods. Section 4 describes the condition and trend of seagrass in the context of environmental factors, referred to as drivers and pressures in Driver-Pressure-State-Impact-Response (DPSIR) framework.

In keeping with the overarching objective of the MMP, to *"Assess trends in ecosystem health and resilience indicators for the Great Barrier Reef in relation to water quality and its linkages to end-of-catchment loads",* key water quality results reported by Waterhouse et al. (2021) are replicated to support the interpretation of the inshore seagrass results.

2 Methods summary

In the following, an overview is given of the sample collection, preparation and analyses methods. Detailed documentation of the methods used in the MMP, including quality assurance and quality control procedures, is available in McKenzie *et al.* (2019).

2.1 Climate and environmental pressures

Climate and environmental pressures affect seagrass condition and resilience (Figure 3). The pressures of greatest concern are:

- physical disturbance (cyclones and benthic sheer stress)
- water quality (turbidity/light and nutrients)
- water temperature
- low tide exposure
- sediment grain size/type.

The measures are either climate variables, that are generally not collected at a site-specific level, and within-canopy measures, that are recorded at each site. The data source and sampling frequency is summarised in Table 1.

2.1.1. Climate

Total daily rainfall, 3pm wind speed, and cyclone tracks were accessed from the Australian Bureau of Meteorology from meteorological stations which were proximal to monitoring locations (Table 1).

As the height of locally produced, short-period wind-waves can be the dominant factor controlling suspended sediment on inner-shelf of the Reef (Larcombe *et al.* 1995; Whinney 2007), the number of days wind speed exceeded 25 km hr^{-1} was used as a surrogate for elevated resuspension pressure on inshore seagrass meadows.

Moderate sea state with winds >25 km hr^{-1} can elevate turbidity by three orders of magnitude in the inshore coastal areas of the Reef (Orpin *et al.* 2004). To determine if the tidal exposure regime may be increasing stress on seagrass and hence drive decline, tidal height observations were accessed from Maritime Safety Queensland and duration of annual exposure (hours) was determined for each meadow (i.e. monitoring site), based on the meadows height relative to the lowest astronomical tide (Appendix 2, Table 20).

The presence of inshore seagrass meadows along the Reef places them at high risk of exposure to waters from adjacent water basins and exposure to flood plumes is likely to be a significant factor in structuring inshore seagrass communities (Collier *et al.* 2014; Petus *et al.* 2016). Hence we used river discharge volumes as well as frequency of exposure to inshore flood plumes as indicators of flood plume impacts to seagrasses.

Plume exposure is generated by wet season monitoring under the water quality sub-program (Waterhouse et al. 2021). The inshore water quality sub-program includes a remote sensing component, which describes water quality characteristics for 22 weeks of the wet season (November–April). Water quality is described as colour classes of turbid, brown primary water (class 1–4), green secondary water (class 5), and waters influenced by flood plumes (salinity <30, coloured dissolved organic matter (CDOM) threshold of 0.24 m^{-1} class 6). Colour classes are derived from MODIS True colour satellite images. Exposure to flood plumes is described in this report as frequency of exposure to primary (turbid, sediment laden) or secondary (green, nutrient rich) water during the wet season. Methods are detailed in Devlin *et al.* (2015). Flood plume mapping (Devlin *et al.* 2015) interpreted to water type and frequency of exposure at seagrass sites has been confirmed as a predictor of changes in seagrass abundance (see case study 2, in McKenzie *et al.* 2016).

2.1.2. Environment within seagrass canopy

Autonomous iBTag™ submersible temperature loggers were deployed at all sites identified in Appendix 2, Table 19. The loggers recorded temperature (accuracy 0.0625°C) within the seagrass canopy every 30–90 minutes (Table 1). iBCod™22L submersible temperature loggers were attached to the permanent marker at each site above the sediment-water interface.

Submersible Odyssey™ photosynthetic irradiance autonomous loggers were attached to permanent station markers at 20 intertidal and 4 subtidal seagrass locations from the Cape York region to the Burnett–Mary region i.e. the light loggers are deployed at one site within the locations (Appendix 2, Table 19). Detailed methodology for the light monitoring can be found in McKenzie *et al.* 2018. Measurements were recorded by the logger every 15 minutes and are reported as total daily light (mol m^{-2} d^{-1}). Automatic wiper brushes clean the optical surface of the sensor every 15 minutes to prevent marine organisms fouling.

Sediment type affects seagrass community composition and vice versa (McKenzie et al 2007, Collier et al In Prep). Changes in sediment composition can be an indicator of broader environmental changes (such as sediment and organic matter loads and risk of anoxia), and be an early-warning indicator of changing species composition. Sediment type was recorded at the 33 quadrats at each site in conjunction with seagrass abundance measures using a visual/tactile estimation of sediment grain size composition (0–2 cm below the sediment/water interface) as per standard protocols described in McKenzie *et al.* (2003). Qualitative field descriptions of sediment composition were differentiated according to the Udden-Wentworth grade scale as this approach has previously been shown to provide an equivalent measure to sieve-derived datasets (Hamilton, 1999; McKenzie 2007).

Table 1. Summary of climate and environment data included in this report, showing historical data range, measurement technique, measurement frequency, and data source. *=variable duration of data availability depending on site

	Data range	Method	Measurement frequency	Reporting units	Data source
Climate					
Cyclones	1968–2020	remote sensing and observations at nearest weather station	yearly	No. yr^{-1}	Bureau of Meteorology
Rainfall	1889–2020*	rain gauges at nearest weather station	daily	mm mo^{-1} mm yr^{-1}	Bureau of Meteorology
Riverine discharge	1970–2020	water gauging stations at river mouth		L d^{-1} L yr^{-1}	DES#, compiled by Waterhouse et al. (2021)
Plume exposure	2006–2020 wet season (Dec–Apr)	remote sensing and field validation	weekly	frequency of water type (1–6) at the site	MMP inshore water quality program (Waterhouse et al. 2021)
Wind	1997–2019*	anemometer at 10 m above the surface, averaged over 10 minutes, at nearest weather station	3pm wind speed	days >25 km hr^{-1}	Bureau of Meteorology
Tidal exposure	1999–2020	wave height buoys at station nearest to monitoring site	3–10 min	hours exposed during daylight	Maritime Safety Queensland, calculated exposure by MMP Inshore Seagrass monitoring
Environment within seagrass canopy					
Water temperature	2002–2020	iBTag	30–90 min	°C, temperature anomalies, exceedance of thresholds	MMP Inshore Seagrass monitoring
Light	2008–2020	Odyssey 2Pi PAR light loggers with wiper unit	15 min	daily light (Id) mol m^{-2} d^{-1} frequency of threshold exceedance (per cent of days)	MMP Inshore Seagrass monitoring
Sediment grain size	1999–2020	visual / tactile description of sediment grain size composition	3 mo–1yr	proportion mud	MMP Inshore Seagrass monitoring

Department of Environment and Science

2.2 Inshore seagrass and habitat condition

2.2.1 Sampling design & site selection

Monitoring of inshore seagrass meadows occurred in the six natural resource management regions with catchments draining into the Reef: Cape York, Wet Tropics, Burdekin, Mackay–Whitsunday, Fitzroy and Burnett–Mary (Table 2, Figure 5). Sixty-nine sites at 31 locations were assessed during the 2019–20 monitoring period (Table 2, Appendix 2, Table 19). This covered fifteen coastal, four estuarine and twelve reef locations.

Table 2. Inshore seagrass monitoring locations and annual sampling. SW= Seagrass-Watch, RJFMP = Reef Joint Field Management Program, ● indicates late dry and late wet, ◐ indicates late dry only , and ◑ indicates late wet only. Shading indicates location not established. Blank cells indicate location not assessed. * indicates MMP assessments ceased in 2018.

NRM Region	Location	Program	2005–06	2006–07	2007–08	2008–09	2009–10	2010–11	2011–12	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18	2018–19	2019–20
Cape York	Shelburne Bay	MMP								●	●	◐	◐		◐	◐	◐
	Piper Reef	MMP								●	●	◐	◐	◐	◐	◐	◐
	Flinders Group	MMP, RJFMP								●	●	●	●	◐	◐	◐	◐
	Bathurst Bay	MMP, RJFMP								●	●	◐	●	◐	◐	◐	◐
	Weymouth Bay	SW							◑	◑		◐					
	Lloyd Bay	RJFMP											◐	◐	◐		◐
	Archer Point	MMP*, SW	●	●	●	●	●	●	●	●	●	◐	◐	◐	◐		
Wet Tropics	Low Isles	MMP				●	●	●	●	●	●	●	●	●	●	●	●
	Yule Point	MMP	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Green Island	MMP	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Mission Beach	MMP	●	●	●	●	●	●	●	●	●	●	●	●	●	●	◐
	Dunk Island	MMP			●	●	●	●	●	●	●	●	●	●	●	●	●
	Rockingham Bay	SW				◐	◐	◐	◐	◐			◐	◐			
	Missionary Bay	RJFMP											◐	◐	◐	◐	◐
Burdekin	Magnetic Island	MMP	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Townsville	MMP, SW	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Bowling Green Bay	MMP								●	●	●	●	●	●	●	●
	Bowen	SW															●
Mackay–Whitsunday	Shoal Bay	SW	●	●	●	●	●	●	●	◐	◐	◐	◐	●	●	●	●
	Pioneer Bay	MMP, SW	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Whitsunday Island	RJFMP											◐	◐	◐	◐	◐
	Hamilton Island	MMP			●	●	●	●	●	●	●	●	●	●	●	●	◐
	Lindeman Island	MMP													●	●	◐
	Repulse Bay	MMP	●	●	◑	◑	◑	◑	●	●	●	●	●	●	●	●	●
	St Helens Bay	SW													◐	◐	◐
	Newry Islands	RJFMP											◐	◐	◐	◐	◐
	Sarina Inlet	MMP	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Clairview	SW													◐	◐	◐
Fitzroy	Shoalwater Bay	MMP	●	●	●	●	●	●	●	●	●	◐	◐	◐	●	◐	●
	Keppel Islands	MMP			●	●	●	●	●	●	●	◐	◐	◐	●	●	●
	Gladstone Harbour	MMP	●	●	●	●	●	●	●	●	●	◐	◐	●	●	●	●
Burnett–Mary	Rodds Bay	MMP			●	●	●	●	●	●	●	●	◐	●	●	●	●
	Burrum Heads	MMP, SW	●	●	◐	●	◐	●	●	●	●	◐	●	●	●	●	●
	Hervey Bay	MMP	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

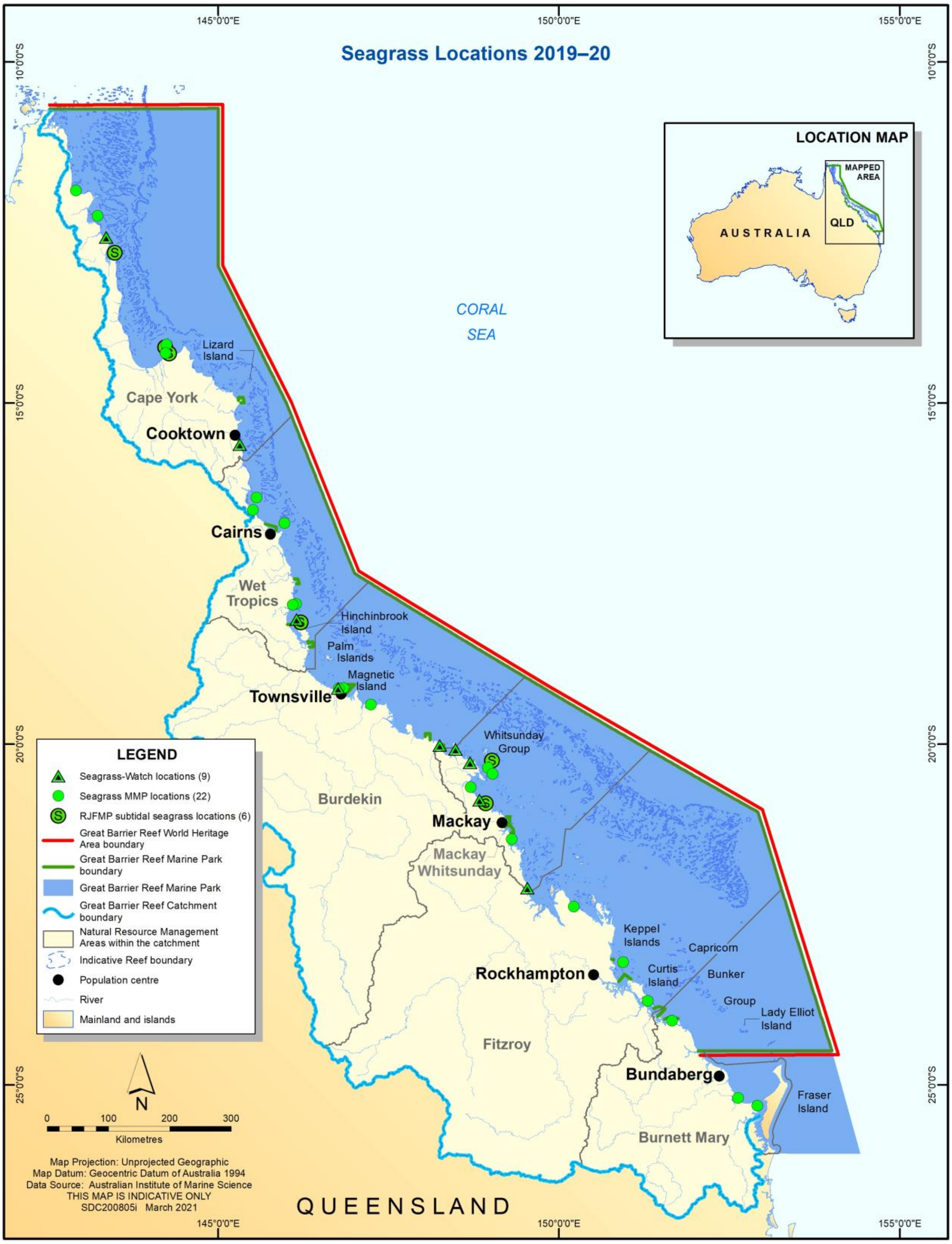


Figure 5. Inshore seagrass survey locations that exist as of 2019-20. However, not all locations were surveyed in 2019-20.

Sampling is designed to detect changes in inshore seagrass meadows in response to changes in water quality associated with specific catchments or groups of catchments (region) and to disturbance events. The selection of locations/meadows was based upon a number of competing factors:

- meadows were representative of inshore seagrass habitats and seagrass communities across each region (based on Lee Long *et al.* 1993, Lee Long *et al.* 1997, Lee Long *et al.* 1998; McKenzie *et al.* 2000; Rasheed *et al.* 2003; Campbell *et al.* 2002; Goldsworthy 1994)
- meadows that span a range in exposure to riverine discharge with those in estuarine and coastal habitats generally having the highest degree of exposure, and reef meadows
- where possible include legacy sites (e.g. Seagrass-Watch) or former seagrass research sites (e.g. Dennison *et al.* 1995; Inglis 1999; Thorogood and Boggon 1999; Udy *et al.* 1999; Haynes *et al.* 2000; Campbell and McKenzie 2001; Mellors 2003; Campbell and McKenzie 2004; Limpus *et al.* 2005; McMahon *et al.* 2005; Mellors *et al.* 2005; Lobb 2006)
- meadows that are not extremely variable in per cent cover throughout the survey area i.e. a Minimum Detectable Difference (MDD) below 20 per cent (at the 5 per cent level of significance with 80 per cent power) (Bros and Cowell 1987).

Sentinel sites were selected using mapping surveys across the regions prior to site establishment. Ideally mapping was conducted immediately prior to site positioning, however in most cases (60 per cent) it was based on historic (>5 yr) information.

Representative meadows were those which covered the greater extent within the inshore region, were generally the dominant seagrass community type and were within Reef baseline abundances (based on Coles *et al.* 2001a; Coles *et al.* 2001c, 2001b, 2001d). To account for spatial heterogeneity of meadows within habitats, at least two sites were selected at each location. If meadow overall extent was larger than ~15 hectares (0.15 km^2), replicate sites were often located within the same meadow (a greater number of sites was desirable with increasing meadow size, however not possible due to funding constraints).

From the onset, inshore seagrass monitoring for the MMP was focused primarily on intertidal/lower littoral seagrass meadows due to:

- accessibility and cost effectiveness (limiting use of vessels and divers)
- occupational Health and Safety issues with dangerous marine animals (e.g. crocodiles, box jellyfish and irukandji)
- occurrence of meadows in estuarine, coastal and reef habitats across the entire Reef
- where possible, providing an opportunity for citizen involvement, ensuring broad acceptance and ownership of Reef 2050 Plan by the Queensland and Australian community.

Some of the restrictions for working in hazardous waters are overcome by using drop cameras, however, drop cameras only provide abundance measures and do not contribute to the other metrics (e.g. tissue nutrients, reproductive effort).

The long-term median annual daylight exposure (the time intertidal meadows are exposed to air during daylight hours) was 1.7 per cent (all meadows pooled) (Table 20). This limited the time monitoring could be conducted to the very low spring tides within small tidal windows (mostly 1–4 hrs per day for 3–6 days per month for 6–9 months of the year).

Depth range monitoring in subtropical/tropical seagrass meadows has had limited success due to logistic/technical issues and non-conformism with traditional ecosystem models because of the complexity (Carruthers *et al.* 2002), including:

- a variety of habitat types (estuarine, coastal, reef and deepwater)
- a large variety of seagrass species with differing life history traits and strategies
- tidal amplitudes spanning 3.42m (Cairns) to 10.4m (Broad Sound) (www.msq.qld.gov.au; Maxwell 1968)
- a variety of sediment substrates, from terrigenous with high organic content, to oligotrophic calcium carbonate
- turbid nearshore to clearer offshore waters
- grazing dugongs and sea turtles influencing meadow community structure and landscapes
- near-absence of shallow subtidal meadows south of Mackay–Whitsunday due to the large tides which scour the seabed.

Deepwater (>15 m) meadows across the Reef are comprised of only *Halophila* species and are highly variable in abundance and distribution (Lee Long *et al.* 1999; York *et al.* 2015; Chartrand *et al.* 2018). Due to this high variability they do not meet the current criteria for monitoring, as the MDD is very poor at the 5 per cent level of significance with 80 per cent power (McKenzie *et al.* 1998).

Although considered intertidal within the MMP, the meadows chosen for monitoring were in fact lower littoral (rarely exposed to air). Predominately stable lower littoral and shallow (>1.5 m below lowest astronomical tide) subtidal meadows of foundation species (e.g. *Zostera, Halodule*) are best for determining significant change/impact (McKenzie *et al.* 1998). Where possible, shallow subtidal and lower littoral monitoring sites were paired when dominated by similar species.

Due to the high diversity of seagrass species it was decided to direct monitoring toward the foundation seagrass species across the seagrass habitats. A foundation species is the dominant primary producer in an ecosystem both in terms of abundance and influence, playing central roles in sustaining ecosystem services (Angelini *et al.* 2011). The activities of foundation species physically modify the environment and produce and maintain habitats that benefit other organisms that use those habitats (Ellison 2019).

Foundation species are the species types that are at the pinnacle of meadow succession. A highly disturbed meadow (due to wave/wind exposure, or low light regime) might only ever have colonising species as the foundational species, while a less disturbed meadow can have persistent species form the foundation. Also, whether *Zostera muelleri* is a foundation species is influenced by whether it grows in the tropics or in the sub-tropics, as it is more likely to form a foundation species in the sub-tropics even if it is disturbed.

For the seagrass habitats assessed in the MMP, the foundation seagrass species were those species which typified the habitats both in abundance and structure when the meadow was considered in its steady state (opportunistic or persistent) (Kilminster *et al.* 2015). The foundation species were all di-meristematic leaf-replacing forms from the following families: *Cymodocea, Enhalus, Halodule, Thalassia* and *Zostera* (Table 3).

As the major period of runoff from catchments and agricultural lands is the tropical wet season/monsoon (December to April), monitoring is focussed on the late dry (growing) season and late wet season to capture the condition of seagrass pre and post wet. Changes in indicators measured during the late dry only before the wet season (i.e. tissue nutrients at all sites) and changes in all indicators at sites sampled in the late dry only (Cape York) are most likely to be in response to wet season conditions in the previous reporting period.

At the reef locations in the Burdekin and Wet Tropics, intertidal sites were paired with a subtidal site (Table 3). Apart from the 47 MMP long-term monitoring sites, data included 10 sites from Seagrass-Watch and 12 sites from QPWS to improve the spatial resolution and representation of subtidal habitats (Table 4).

A description of all data collected during the sampling period has been collated by region, site, parameter, and the number of samples collected per sampling period (Table 19). The seagrass species (including foundation) present at each monitoring site is listed in Table 3 and Table 4. Sampling during the 2019–20 reporting year was affected as a consequence of the global COVID-19 pandemic. With travel resitictions in force from late March 2020, access to some island monitoring locations in the late wet 2020 was not permitted.

2.2.2 Seagrass abundance, composition and extent

Seagrass abundance, species composition and meadow spatial extent was assessed from samples collected in the late dry 2019 and late wet 2020 at locations identified in Table 3. Field survey methodology followed globally standardised protocols (detailed in McKenzie *et al.* (2003)). At each location, with the exception of subtidal sites, sampling included two sites nested within 500 m of each other. Subtidal sites were not always replicated within locations. Intertidal sites were defined as a 5.5 hectare area within a relatively homogenous section of a representative seagrass community/meadow (McKenzie *et al.* 2003).

Monitoring at sites in the late dry (September-November 2019) and late wet (March-May 2020) of each year was conducted by a qualified scientist who was trained in the monitoring protocols. In the centre of each site, during each survey, observers recorded the percentage seagrass cover within 33 quadrats (50 cm × 50 cm, placed every 5 m along three 50 m transects, located 25 m apart). The sampling strategy for subtidal sites was modified to sample along 50 m transects 2–3 m apart (aligned along the depth contour) due to logistics of SCUBA diving in waters of poor visibility.

Seagrass species were identified as per Waycott *et al.* (2004). Species were further categorised according to their life history traits and strategies and classified into colonising, opportunistic or persistent as broadly defined by Kilminister *et al.* (2015) (for detailed methods, see McKenzie *et al.* 2018).

Mapping of the meadow extent and landscape (i.e. patches and scars) within each site was also conducted as part of the monitoring in both the late dry and late wet periods. Mapping followed standard methodologies (McKenzie *et al.* 2001) using a handheld GPS on foot. Where the seagrass landscape tended to grade from dense continuous cover to no cover, over a continuum that included small patches and shoots of decreasing density, the meadow edge was delineated where there was a gap with the distance of more than 3 metres (i.e. accuracy of the GPS). Therefore, the entire 5.5 hectare site was mapped (seagrass and no seagrass).

Table 3. Inshore sentinel seagrass long-term monitoring site details including presence of foundation (■) and other (□) seagrass species by region * = intertidal, ^=subtidal. CR = *Cymodocea rotundata*, CS = *Cymodocea serrulata*, EA = *Enhalus acoroides*, HD = *Halophila decipiens*, HO = *Halophila ovalis*, HS = *Halophila spinulosa*, HU = *Halodule uninervis*, SI = *Syringodium isoetifolium*, TH = *Thalassia hemprichii*, ZM = *Zostera muelleri.*

Region	NRM region (*Board*)	Basin	Monitoring location	Site		Longitude	Latitude	CR	CS	EA	HD	HO	HS	HU	SI	TH	ZM
Far Northern	Cape York *(Cape York Natural Resource Management)*	Jacky Jacky / Olive-Pascoe	Shelburne Bay *coastal*	SR1*	Shelburne Bay	142.914	-11.887					□		■		■	
				SR2*	Shelburne Bay	142.916	-11.888										
			Piper Reef *reef*	FR1*	Farmer Is.	143.234	-12.256	■				□				■	
				FR2*	Farmer Is.	143.236	-12.257										
		Normanby / Jeannie	Flinders Group *reef*	ST1*	Stanley Island	144.245	-14.143	■		■		□		■	■	■	
				ST2*	Stanley Island	144.243	-14.142										
			Bathurst Bay *coastal*	BY1*	Bathurst Bay	144.233	-14.268	■				□		■	□	■	■
				BY2*	Bathurst Bay	144.232	-14.268										
Northern	Wet Tropics (*Terrain NRM*)	Daintree	Low Isles *reef*	LI1*	Low Isles	145.565	-16.385					□		■		■	
				LI2^	Low Isles	145.564	-16.383					□		■			
		Mossman / Barron / Mulgrave-Russell / Johnstone	Yule Point *coastal*	YP1*	Yule Point	145.512	-16.569					□		■			□
				YP2*	Yule Point	145.509	-16.564										
			Green Island *reef*	GI1*	Green Island	145.973	-16.762	■	□			□		■		■	
				GI2*	Green Island	145.976	-16.761										
				GI3^	Green Island	145.973	-16.755	■	■			□		■	□	■	
		Tully / Murray / Herbert	Mission Beach *coastal*	LB1*	Lugger Bay	146.093	-17.961					□		■			
				LB2*	Lugger Bay	146.094	-17.961										
			Dunk Island *reef*	DI1*	Pallon Beach	146.141	-17.944	■	■			□		■		■	
				DI2*	Pallon Beach	146.141	-17.946										
				DI3^	Brammo Bay	146.140	-17.932		■		□	□		■			
Central	Burdekin (*NQ Dry Tropics*)	Ross / Burdekin	Magnetic island *reef*	MI1*	Picnic Bay	146.841	-19.179					□		■			□
				MI2*	Cockle Bay	146.829	-19.177	■	■			□		■	□	■	
				MI3^	Picnic Bay	146.841	-19.179		■		□	□	□	■			
			Townsville *coastal*	SB1*	Shelley Beach	146.771	-19.186		□			□		■			■
				BB1*	Bushland Beach	146.683	-19.184										
			Bowling Green Bay *coastal*	JR1*	Jerona (Barratta CK)	147.241	-19.423					□		■			■
				JR2*	Jerona (Barratta CK)	147.240	-19.421										
	Mackay–Whitsunday (*Reef Catchments*)	Proserpine / O'Connell	Lindeman Island *reef*	LN1^	Lindeman Is.	149.028	-20.438					□		■			
				LN2^	Lindeman Is.	149.032	-20.434										
			Repulse Bay *coastal*	MP2*	Midge Point	148.702	-20.635					□		■			■
				MP3*	Midge Point	148.705	-20.635										
			Hamilton Island *reef*	HM1*	Catseye Bay - west	148.957	-20.344					□		■	□		■
				HM2*	Catseye Bay - east	148.971	-20.347										
		Plane	Sarina Inlet *estuarine*	SI1*	Point Salisbury	149.304	-21.396					□		□			■
				SI2*	Point Salisbury	149.305	-21.395										
Southern	Fitzroy (*Fitzroy Basin Association*)	Shoalwater / Fitzroy	Shoalwater Bay *coastal*	RC1*	Ross Creek	150.213	-22.382					□		■			■
				WH1*	Wheelans Hut	150.275	-22.397										
			Keppel Islands *reef*	GK1*	Great Keppel Is.	150.939	-23.196					□	□	■			■
				GK2*	Great Keppel Is.	150.940	-23.194										
		Calliope / Boyne	Gladstone Harbour *estuarine*	GH1*	Pelican Banks	151.301	-23.767					□		□*			■
				GH2*	Pelican Banks	151.304	-23.765										
	Burnett–Mary (*Burnett–Mary Regional Group*)	Baffle	Rodds Bay *estuarine*	RD1*	Cay Bank	151.655	-24.058					□		□			■
				RD3*	Turkey Beach	151.589	-24.038										
		Burrum	Burrum Heads *coastal*	BH1*	Burrum Heads	152.626	-25.188					□		■			■
				BH3*	Burrum Heads	152.639	-25.210										
		Mary	Hervey Bay *estuarine*	UG1*	Urangan	152.907	-25.301					□		□			■
				UG2*	Urangan	152.906	-25.303										

Table 4. Additional inshore sentinel seagrass long-term monitoring sites integrated from the Seagrass-Watch (intertidal sites)* and RJFMP (drop-camera subtidal sites)^ programs, including presence of foundation (■) and other (□) seagrass species. NRM region from www.nrm.gov.au. * = intertidal, ^ =subtidal.

Region	NRM region (*Board*)	Basin	Monitoring location	Site		Longitude	Latitude	CR	CS	EA	HD	HO	HS	HU	SI	TH	ZM
Far Northern	Cape York (*Cape York Nat Res Manage)*	Lockhart	Weymouth Bay *reef*	YY1*	Yum Yum Beach	143.36059	-12.571	■	■	■		□		■		■	
			Lloyd Bay *coastal*	LR1^	Lloyd Bay	143.485	-12.797					□	□	■			
				LR2^	Lloyd Bay	143.475	-12.825										
		Normanby / Jeannie	Flinders Group *reef*	FG1^	Flinders Island	144.225	-14.182					□	□	■			
				FG2^	Flinders Island	144.225	-14.182										
			Bathurst Bay *coastal*	BY3^	Bathurst Bay	144.285	-14.276					□		■			
				BY4^	Bathurst Bay	144.300	-14.275										
		Endeavour	Archer Point *reef*	AP1*	Archer Point	145.31894	-15.60832	■	■	□		□		■		■	□
				AP2*	Archer Point	145.31847	-15.60875										
Northern	Wet Tropics	Tully / Murray / Herbert	Rockingham Bay *reef*	GO1*	Goold Island	146.15327	-18.17395	■	■			□		■			
			Missionary Bay *coastal*	MS1^	Cape Richards	146.213	-18.216					□		■			
				MS2^	Macushla	146.217	-18.205										
Central	Burdekin (*NQ Dry Tropics*)	Ross / Burdekin	Townsville *coastal*	SB2*	Shelley Beach	146.763	-19.182		□			□		■			■
		Don	Bowen *coastal*	BW1*	Port Dennison	148.250	-20.017					□		■			■
				BW2*	Port Dennison	148.252	-20.017										
	Mackay–Whitsunday (*Reef Catchments*)	Proserpine	Shoal Bay *reef*	HB1*	Hydeaway Bay	148.482	-20.075	■				□		■		■	
				HB2*	Hydeaway Bay	148.481	-20.072										
			Pioneer Bay *coastal*	PI2*	Pigeon Island	148.693	-20.269					□	□	■			■
				PI3*	Pigeon Island	148.698	-20.271										
		Proserpine / O'Connell	Whitsunday Island *reef*	TO1^	Tongue Bay	149.016	-20.240					□		■		■	
				TO2^	Tongue Bay	149.012	-20.242										
		O'Connell / Pioneer	St Helens Bay *coastal*	SH1*	St Helens Bch	148.835	-20.822					□		■			■
			Newry Islands *coastal*	NB1^	Newry Bay	148.926	-20.868		■			□	□	■	■		
				NB2^	Newry Bay	148.924	-20.872										
		Plane	Clairview *coastal*	CV1*	Clairview	149.533	-22.104					□		■			■
				CV2*	Clairview	149.535	-22.108										

2.2.3 Seagrass reproductive status

Seagrass reproductive health was assessed from samples collected in the late dry 2019 and late wet 2020 at locations identified in Table 3. Samples were processed according to standard methodologies (McKenzie *et al.* 2019).

In the field, 15 haphazardly placed cores (100 mm diameter x 100 mm depth) of seagrass were collected within each site from an area adjacent (of similar cover and species composition) to the monitoring transects. In the laboratory, reproductive structures (spathes, fruits, female and male flowers) of plants from each core were identified and counted for each sample and species. Reproductive effort was calculated as number of reproductive structures (fruits, flowers, spathes; species pooled) per core for analysis.

Seeds banks and abundance of germinated seeds were sampled according to standard methods (McKenzie *et al.* 2019) by sieving (2mm mesh) 30 cores (50mm diameter, 100mm depth) of sediment collected across each site and counting the seeds retained in each. For *Zostera muelleri*, where the seed are <1 mm diameter, intact cores (18) were collected and returned to the laboratory where they were washed through a 710 µm sieve and seeds identified using a hand lens/microscope.

2.2.4 Seagrass leaf tissue nutrients

In the late dry season (October 2019), leaf tissue samples from the foundational seagrass species were collected from each monitoring site for nutrient content analysis (Table 3). For nutrient status comparisons, collections are made during the growth season (e.g. late dry when nutrient contents are at a minimum) (Mellors *et al.* 2005) and at the same time of the year and at the same depth at the different localities (Borum *et al.* 2004). Two to three handfuls of shoots from three haphazardly placed 0.25 m^2 quadrats were collected from an area adjacent (of similar cover and species composition) to the monitoring transects.

Species within the sample are separated, and all species (except *Halophila* spp.) were analysed for tissue nutrient content. All leaves within the sample were separated from the below ground material in the laboratory and epiphytic algae removed by gently scraping. Dried and milled leaf samples were analysed according to McKenzie *et al.* (2019). Elemental ratios (C:N:P) were calculated on a mole:mole basis using atomic weights (i.e. C=12, N=14, P=31).

2.2.5 Epiphytes and macroalgae

Epiphyte and macroalgae cover were measured in the late dry and late wet seasons according to standard methods (McKenzie *et al.* 2003). The total percentage of leaf surface area (both sides, all species pooled) covered by epiphytes and percentage of quadrat area covered by macroalgae, were measured each monitoring event. Values were compared against the Reef long-term average (1999-2010) calculated for each habitat type.

2.3 Data analyses

All seagrass condition indicators had uncertainties associated with their measurements at the lowest reporting levels (e.g. percentage, count, ratio, etc.) which was presented as Standard Error (calculated from the site, day, or core standard deviations). To propagate the uncertainty (i.e. propagation of error) through each higher level of aggregation (e.g. habitat, NRM region and GBR), the square root of the sum of squares approach (using the SE at each subsequent level) was applied (Ku 1966). The same propagation of error approach was applied to the annual seagrass report card scores to calculate a more exact measure of uncertainty in the three seagrass indicators and overall index.

Results are presented to reveal temporal changes in seagrass community attributes and key environmental variables. Generalised additive mixed effects models (GAMMs) are fitted to seagrass attributes for each habitat and NRM, to identify the presence and consistency of trends, using the mgcv (Wood 2020) package in R 3.6.1 (R Core Team 2020). GAMMs (Wood 2017) were used to interrogate the irregularly-spaced time-series into its trend cycles (long-term) and periodic (seasonal) components.

GAMMs are an extension of additive models, which allow flexible modelling of non-linear relationships by incorporating penalized regression spline types of smoothing functions into the estimation process. The degree of smoothing of each smooth term (and by extension, the estimated degrees of freedom of each smoother) is treated as a random effect and thus estimable via its variance as with other effects in a mixed modelling structure (Wood 2017). Results of these analyses are graphically presented in a consistent format: predicted values from the model were plotted as bold black lines, the 95 per cent confidence intervals of these trends delimited by grey shading.

Several GAMMs were used on seagrass cover and C:N ratio to tease out trends at the habitat, regional and location scale over time. The random effects were incorporated as a nested structure of quadrat within transect within site, to account for spatial correlation. As part of our regular validation process the residuals of all models were checked for violations of the generalised model assumptions. In few instances the random effects structure caused issues and the transect level had to be omitted.

Per cent seagrass cover data GAMMs were fitted using a quasi-binomial distribution due to the proportional (bound between 0 and 1) nature of the data. Raw data at the quadrat level was used to provide the maximum resolution for modelling. However, this led to a very large proportion of 0 in some data sets causing high heterogeneity of variance for some models. For this reason, GAMMs for reproductive effort, epiphytes, macroalgae cover are not presented and the inclusion in future reports of zero-inflated GAMMs is being investigated. C:N data models were fitted using a gamma distribution due to the strictly positive continuous nature of the data. Here the random effects consisted of species nested within site.

For the analyses of the various tissue nutrients and isotopes variables Generalised Linear Mixed Models (GLMMs) were used instead of GAMMs as these samples are only collected once a year, and due to the low frequency of sampling the use of a smoother (GAMM) is not recommended. The tissue nutrient variables (C:N, C:P, N:P, per cent N, per cent P) were analysed using the R-INLA (Rue *et al.* 2009) package with a gamma distribution and the isotopes variables ($\delta^{13}C$ and $\delta^{15}N$) with a Gaussian distribution. Similarly, to the C:N GAMMs, the random effects consisted of species nested within site.

Trend analysis was conducted to determine if there was a significant trend (reduction or increase) in seagrass abundance (per cent cover) at a particular site (averaged by sampling event) over all time periods. A Mann-Kendall test was performed using the “trend” package in R 3.6.1 (R Core Team 2020). Mann-Kendall is a common non-parametric test used to detect overall trends over time. The measure of the ranked correlation is the Kendall’s tau coefficient (Kendall-τ), which is the proportion of up-movements against time vs the proportion of down-movements, looking at all possible pairwise time-differences. As the test assumes independence between observations, data was checked for autocorrelation and if present a corrected p-value was calculated using the “modifiedmk” package (Hamed and Rao 1998).

The majority of meadows have been in a "recovery mode" since losses during the periods 2008–2009 to 2010–2011. As such, there have been periods of limited sample availability (e.g. for tissue nutrients), and the absence of data has restricted whether multivariate analysis can be undertaken routinely. Analysis is currently underway to more fully interrogate the temporal and covariate components of the data as the time series of observations lengthen.

2.4 Reporting Approach

The data is presented in a number of ways depending on the indicator and section of the report:

- Report card scores for seagrass condition are presented at the start of each section. These are a numerical summary of the condition within the region relative to a regional baseline (described further below)
- Climate and environmental pressures are presented as averages (daily, monthly or annual) and threshold exceedance
- Seagrass community data such as seagrass abundance, leaf tissue nutrients are presented as averages (sampling event, season or monitoring period with SE) and threshold exceedance data
- Seagrass ecosystem data such as sediment composition, epiphyte and macroalgae are presented as averages (sampling event, season or monitoring period) and relative to the long-term
- Trend analysis (GAMM plots) are also used to explore the long-term temporal trends in biological and environmental indicators.

Within each region, estuarine and coastal habitat boundaries were delineated based on the Queensland coastal waterways geomorphic habitat mapping, Version 2 (1:100 000 scale digital data) (Heap *et al.* 2015).

Reef habitat boundaries were determined using the AUSLIG (now the National Mapping Division of Geosciences Australia) geodata topographic basemap (1:100 000 scale digital data).

2.5 Calculating report card scores

Three indicators (presented as unitless scores) are used for the seagrass component of the Marine Results report and Reef report card:

- seagrass abundance (per cent cover)
- reproductive effort
- nutrient status (leaf tissue C:N ratio).

A seagrass condition index (score) is reported for each monitoring region based on changes in each of the indicators relative to a baseline. The methods for score calculation were chosen by the Paddock to Reef Integration Team and all report card scores are transformed to a five point scale from 0 to 100 to allow integration with other components of the Reef report card (Department of the Premier and Cabinet 2014). The methods and scoring system for the report card are detailed below. *Please note that the scale from 0 to 100 is unitless and should not be interpreted as a proportion or ratio.*

2.5.1 Seagrass abundance

Seagrass abundance state in the MMP is measured using the median seagrass per cent cover relative to the site or reference guideline (habitat type within each NRM region). Abundance guidelines (threshold levels) were determined using the long-term (>4 years) baseline where the percentile variance plateaued (generally 15-20 sampling events), thereby providing an estimate of the true percentile value (McKenzie 2009). Guidelines for individual sites were only applied if the conditions of the site aligned with reference conditions and the site had been subject to minimal/limited disturbance for 3–5 years (see Appendix 1, Table 18).

Abundance state at each site for each monitoring event was allocated a grade:

- *very good*, median per cent cover at or above 75th percentile
- *good*, median per cent cover at or above 50th percentile
- *moderate*, median per cent cover below 50th percentile and at or above low guideline
- *poor*, median per cent cover below low guideline
- *very poor*, median per cent cover below low guideline and declined by >20 per cent since previous sampling event).

The choice of whether the 20th or 10th percentile was used for the low guideline depended on the within-site variability; generally the 20th percentile is used, unless within-site variability was low (e.g. CV<0.6), whereby the 10th percentile was more appropriate as the variance would primarily be the result of natural seasonal fluctuations (i.e. nearly every seasonal low would fall below the 20th percentile). Details on the per cent cover guidelines can be found in Appendix 1.

A grade score from 0 to 100 (Table 5) was then assigned to enable integration with other seagrass indicators and other components of the Reef report card (Department of the Premier and Cabinet 2014). Annual seagrass abundance scores were calculated using the average grade score for each site (including all sampling events per year), each habitat and each NRM.

Table 5. Scoring threshold table to determine seagrass abundance status. low = 10th or 20th percentile guideline. NB: scores are unitless.

Grade	Percentile category	Score	Status
very good	75–100	100	81–00
good	50–75	75	61–80
moderate	low–50	50	41–60
poor	<low	25	21–40
very poor	<low by >20 per cent	0	0–20

2.5.2 Seagrass reproductive effort

As most seagrass species of the Reef flower in the late dry season, reproductive effort is sampled during the late dry season to capture the sexual reproductive peak.

During the current monitoring period, the total number of reproductive structures per core (inflorescence, fruit, spathe, seed) was measured at each site in the late dry season (September-November 2018), and a grade score determined after normalising against the Reef habitat baseline (see Appendix 1) and using the ratio to rank the score from very good to very poor (Table 6).

Table 6. Scores for late dry monitoring period reproductive effort average against Reef habitat baseline. NB: scores are unitless.

Grade	**Reproductive Effort** (monitoring period / baseline)	Ratio	Score	0-100 score	Status
very good	≥4	4.0	4	100	81–00
good	2 to <4	2.0	3	75	61–80
moderate	1 to <2	1.0	2	50	41–60
poor	0.5 to <1	0.5	1	25	21–40
very poor	<0.5	0.0	0	0	0–20

2.5.3 Seagrass nutrient status.

Tissue nutrient content of seagrass leaves including carbon (C), nitrogen (N) and phosphorus (P) were measured annually. The absolute tissue nutrient concentrations (per cent C, per cent N and per cent P) are used to calculate the atomic ratio of nutrients in seagrass leaves (see Appendix 1). The C:N ratio was chosen for the purpose of the report card score as it is the ratio that indicates a change in either light or nitrogen availability at the meadow scale. C:N ratios were compared to a global average value of 20:1 (Atkinson and Smith 1983; Fourqurean *et al.* 1992), with values less than 20:1 indicating either reduced light or excess N is available to the seagrass. Values higher than 20:1 suggest light saturation and low nitrogen availability (Abal *et al.* 1994; Grice *et al.* 1996; Udy and Dennison 1997b). C:N ratios from the late dry season (September-November 2018) were categorised on their departure from the guideline and transformed to a score (see Appendix 1) which was then graded from very good to very poor (Table 7).

Table 7. Scores for leaf tissue C:N against guideline to determine light and nutrient availability. NB: scores are unitless.

Grade	C:N ratio range	Score ($\bar{R}$) range and status
very good	C:N ratio >30*	81–00
good	C:N ratio 25–30	61–80
moderate	C:N ratio 20–25	41–60
poor	C:N ratio 15–20	21–40
very poor	C:N ratio <15*	0–20

2.5.4 Seagrass condition index

The seagrass condition index is an average score (0–100) of the three seagrass condition indicators:

- seagrass abundance (per cent cover)
- reproductive effort
- leaf tissue nutrients.

Each indicator is equally weighted, in accordance with the Paddock to Reef Integration Team's original recommendations. To calculate the overall score for seagrass of the Reef, the regional scores were weighted on the percentage of World Heritage Area seagrass (shallower than 15 m) within that region (Table 8). *Please note: Cape York omitted from the score in reporting prior to 2012 due to poor representation of inshore monitoring sites*.

Table 8. Area of seagrass shallower than 15 m in each region within the boundaries of the World Heritage Area.(from McKenzie et al. 2014b; McKenzie et al. 2014c; Carter et al. 2016; Waterhouse et al. 2016).

NRM	Area of seagrass (km^2)	Per cent of World Heritage Area
Cape York	2,078	0.60
Wet Tropics	207	0.06
Burdekin	587	0.17
Mackay–Whitsunday	215	0.06
Fitzroy	257	0.07
Burnett–Mary	120	0.03
World Heritage Area	**3,464**	**1.00**

3 Drivers and pressures influencing seagrass meadows in 2019–20

The following section provides detail on the overall climate and environmental pressures during the 2019–20 monitoring period, at a relatively broad level as context for understanding trends in seagrass condition. It includes:

- climate, river discharge and flood plume exposure
- within-canopy light
- within-canopy temperature and threshold exceedance
- seagrass meadows sediment characteristics.

The ensuing section contains data on local environmental pressures and supporting data is detailed within Appendix 2 and 3:

3.1 Summary

Long-term trends in the Water Quality Index indicate early signs of improvement to good water quality in the Wet Tropics after declining from good to moderate in 2008–2018. In the Burdekin there was a gradual decline from good in 2010 to moderate in 2015, and subsequent fluctuation between good and moderate until 2020. In contrast, there has been a steady decline from moderate to poor in the Mackay–Whitsunday regions (Waterhouse et al. 2021). The Water Quality Index is not reported in other regions.

Environmental stressors in 2019–2020 were below average for rainfall and river discharge, and relatively benign for within canopy light and water temperature (Table 9). River discharge was 1.7 times below the long-term median for the GBR catchment area, and below average in all regions, but were closest to the long-term average in the Fitzroy regions.

The frequency with which the sentinel seagrass sites were exposed to ‘brown’ sediment-laden (1–4) and ‘green’ phytoplankton-rich waters (5) during the wet season was also slightly elevated across the entire Reef, even in the southern regions where discharge was low (Figure 9). The presence of this coloured water is affected by resuspension-driven events as well as discharge and the relative attribution to these processes is discussed in further detail into the water quality report (Waterhouse et al. 2021).

Table 9. Summary of environmental conditions at monitoring sites across the Reef in 2019–20 compared to previous monitoring period and the long-term average (range indicated for each data set). *intertidal only.

Environmental pressure	Long-term average	2018–19	2019–20
Climate			
Cyclones (1968–2019)	4	3	0
Daily rainfall mm d^{-1} (1960–1991)	4.0	4.4	3.0
Riverine discharge ML yr^{-1} (1986–2016)	51,812,207	94,323,378	30,911,889
Wet season turbid water exposure (2003–2018)	89 per cent	94 per cent	92 per cent
Within seagrass canopy			
Temperature °C (±) (max) (2003–2019)*	25.7 ±0.1 (46.6)	25.7 ±0.1 (41.1)	25.8 ±0.2 (41.1)
Light mol m^{-2} d^{-1} (2008–2020) annual average	12.5	12.0	13.1
(min site–max site)	(3.3–20.8)	(3.5–22.1)	(4.2–22.2)
Proportion mud			
estuary intertidal (1999–2019)	45.3 ±2.1	46.2 ±3.5	42.0 ±2.9
coast intertidal (1999–2019)	28.4 ±2.1	28.4 ±4.7	22.3 ±1.7
coast subtidal (2015–2019)	53.8 ±2.3	46.7 ±4.7	48.2 ±2.4
reef intertidal (2001–2019)	4.3 ±1.3	4.5 ±2.7	4.0 ±0
reef subtidal (2008–2019)	12.4 ±0.6	10.2 ±1.0	12.8 ±2.5

Daily incident benthic light levels were higher in 2019–20, than the long-term average for the Reef. Light is measured at the location level and was higher than the long-term average at all but five out of 26 light monitoring locations. Light levels were higher than estimated annual light requirements for optimal growth (10 mol m^{-2} d^{-1}) at all but eight locations. Subtidal locations generally have lower light levels and account for four of the eight locations below light requirements.

Within canopy temperatures in 2019–20 were similar to the 2018–19 period, which were slightly cooler than the previous five reporting years in all regions, on average, except for the Burnett–Mary where they were slightly higher than average (Figure 8). The number of extreme heat days (days >40°C) were the fourth highest (equal with 2018-19) since monitoring commenced, but restricted to the most southern NRM regions (Mackay–Whitsunday, Fitzroy and Burnett–Mary) (Figure 12).

No tropical cyclones entered the Reef in 2019–20 (see Waterhouse et al. 2021). The tropical low which later formed into cyclone Gretel, however, passed through Reef waters on the 11 March near Lockhart River. The system originally formed as a tropical low in the Arafura Sea, and after crossing Cape York and the Reef, continued east-southeastwards before intensifying into TC Gretel (category 1) on 14 March 2020 in the Coral Sea. The system was likely to have had minimal impact to inshore Cape York before exiting Reef waters. The interaction of Gretel with a high-pressure ridge in the Coral Sea, however, exposed sections of the Burdekin and Mackay–Whitsunday regions to several days of sustained near-gale to gale-force winds (BOM 2021).

3.2 Rainfall

Rainfall was below the long-term average throughout the Reef catchments (Figure 6) (Figure 7). The largest deviations from the long-term averages occurred in southern Cape York and the Wet Tropics. It was slightly drier than the long-term average in the southern GBR basins.

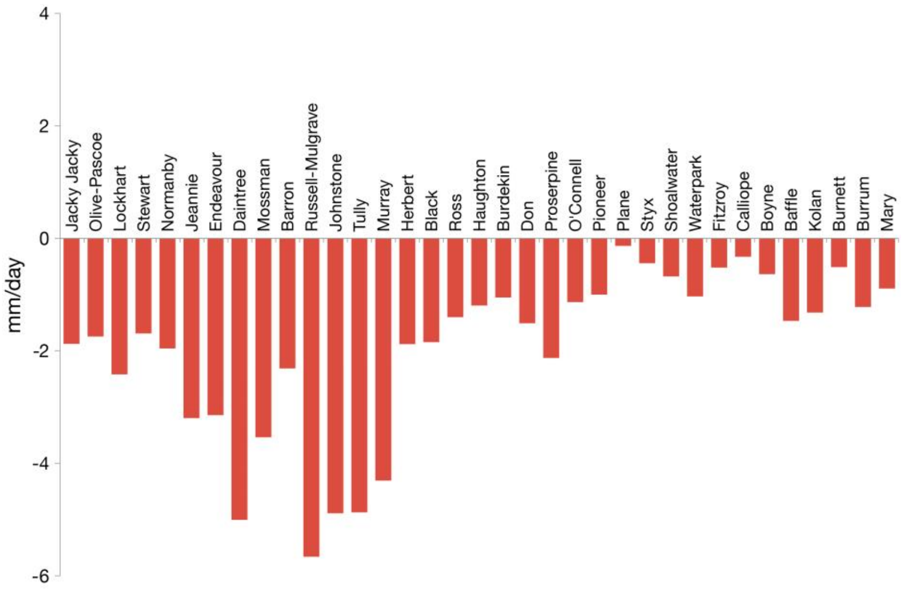


Figure 6. Difference between annual average daily wet season rainfall (December 2019–April 2020) and the long-term average (1961–1990). Red and blue bars denote basins with rainfall below and above the long-term average, respectively. Note that the basins are ordered from north to south (left to right). Compiled by Waterhouse et al. (2021).

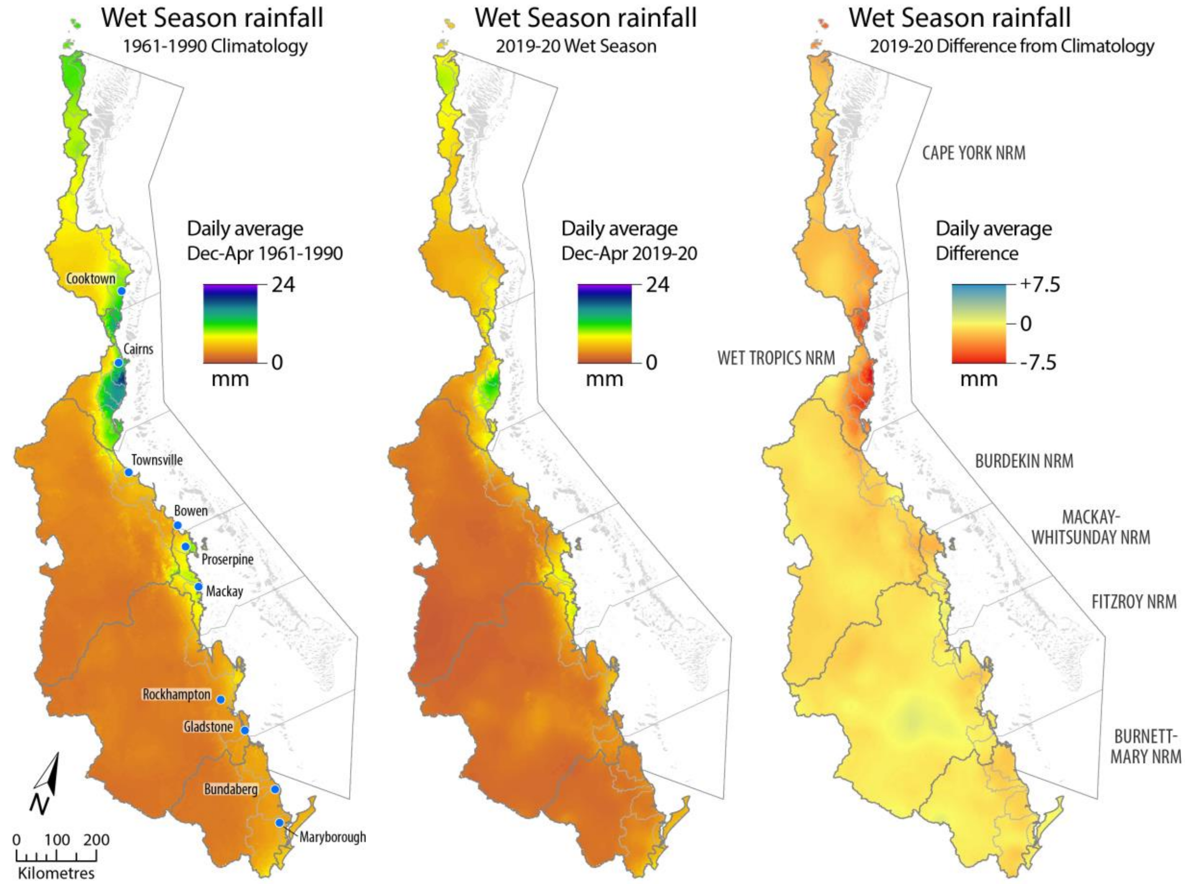


Figure 7. Average daily rainfall (mm/day) in the Reef catchment: (left) long-term annual average (1961–1990; time period produced by BOM), (centre) 2019–20 and (right) the difference between the long-term annual average and 2018–19 rainfall patterns. From Waterhouse et al. (2021).

3.3 River discharge

Annual river discharges for the entire GBR, and for each of the regions were below long-term averages in 2019–20 (Table 10). The only catchments with river discharges that were substantially elevated (i.e. >1.5 times the long-term median) were the Olive Pascoe River and Lockart River in Cape York, which were slightly above average and from three of the small catchments in the Fitzroy region which were more than 1.5 times above the long-term average.

Table 10. Annual water year discharge (ML) of the main GBR rivers (1 October 2019 to 30 September 2020, inclusive) compared to the previous seven wet seasons and long-term (LT) median discharge (1986–87 to 2018–19). Colours indicate levels above the long-term median: yellow = 1.5 to 2 times, orange = 2 to 3 times and red = greater than 3 times. Compiled by Waterhouse et al. (2021).

NRM	Basin	LT median	2016–17	2017–18	2018–19	2019–20
Cape York	Jacky Jacky Creek	2,047,129	1,701,199	2,689,450	3,124,009	1,920,007
	Olive Pascoe River	2,580,727	2,978,821	3,424,596	6,992,798	3,189,195
	Lockhart River	1,634,460	1,886,587	2,168,911	4,428,772	2,019,824
	Stewart River	674,618	685,263	826,499	3,109,052	584,988
	Normanby River	4,159,062	3,780,651	4,333,023	12,102,053	2,792,858
	Jeannie River	1,263,328	1,746,929	1,721,175	3,350,682	932,300
	Endeavour River	1,393,744	1,665,116	1,796,913	3,847,478	773,315
Wet Tropics	Daintree River	1,512,054	1,590,225	1,439,220	4,752,327	901,248
	Mossman River	858,320	812,585	1,069,336	1,885,921	555,280
	Barron River	574,567	313,952	946,635	1,535,892	320,056
	Mulgrave-Russell River	2,600,465	1,759,178	3,359,834	3,550,093	1,694,470
	Johnstone River	3,953,262	3,348,014	4,950,329	4,774,747	2,743,805
	Tully River	3,241,383	2,840,476	3,883,954	4,020,452	2,200,744
	Murray River	380,472	293,742	521,465	519,739	199,630
	Herbert River	3,556,376	2,248,436	6,385,655	5,707,209	1,472,338
Burdekin	Black River	208,308	64,449	386,030	965,544	102,296
	Ross River	377,011	41,177	83,113	2,371,556	371,019
	Haughton River	419,051	283,551	598,668	2,363,209	251,321
	Burdekin River	4,406,780	4,165,129	5,542,306	17,451,417	2,203,056
	Don River	508,117	1,081,946	321,875	1,356,004	398,312
Mackay–Whitsunday	Proserpine River	284,542	539,710	174,183	837,962	205,680
	O'Connell River	478,097	894,975	260,937	1,223,297	279,585
	Pioneer River	692,342	1,388,687	249,530	1,158,768	383,506
	Plane Creek	309,931	761,503	75,052	351,879	299,502
Fitzroy	Styx River	155,384	420,353	218,115	109,376	225,782
	Shoalwater Creek	129,487	350,294	181,763	91,147	188,152
	Water Park Creek	97,115	262,721	136,322	68,360	141,114
	Fitzroy River	2,852,307	6,170,044	954,533	1,339,964	2,533,631
	Calliope River	152,965	406,321	141,438	2,682	80,255
	Boyne River	38,691	102,775	35,775	678	20,300
Burnett–Mary	Baffle Creek	215,446	486,235	1,081,646	930	47,143
	Kolan River	52,455	190,476	325,578	4,958	5,304
	Burnett River	230,755	536,242	849,051	202,436	332,366
	Burrum River	79,112	387,027	715,449	63,972	70,928
	Mary River	981,183	499,295	1,630,741	658,014	472,580
	Sum of basins	43,099,046	46,684,083	53,479,101	94,323,378	30,911,889

3.4 Turbid water exposure and flood plume extent

The frequency of exposure to turbid water (colour classes 1–5), plume extent, and the within-canopy environmental pressures daily light and water temperature are summarised in Figure 8.

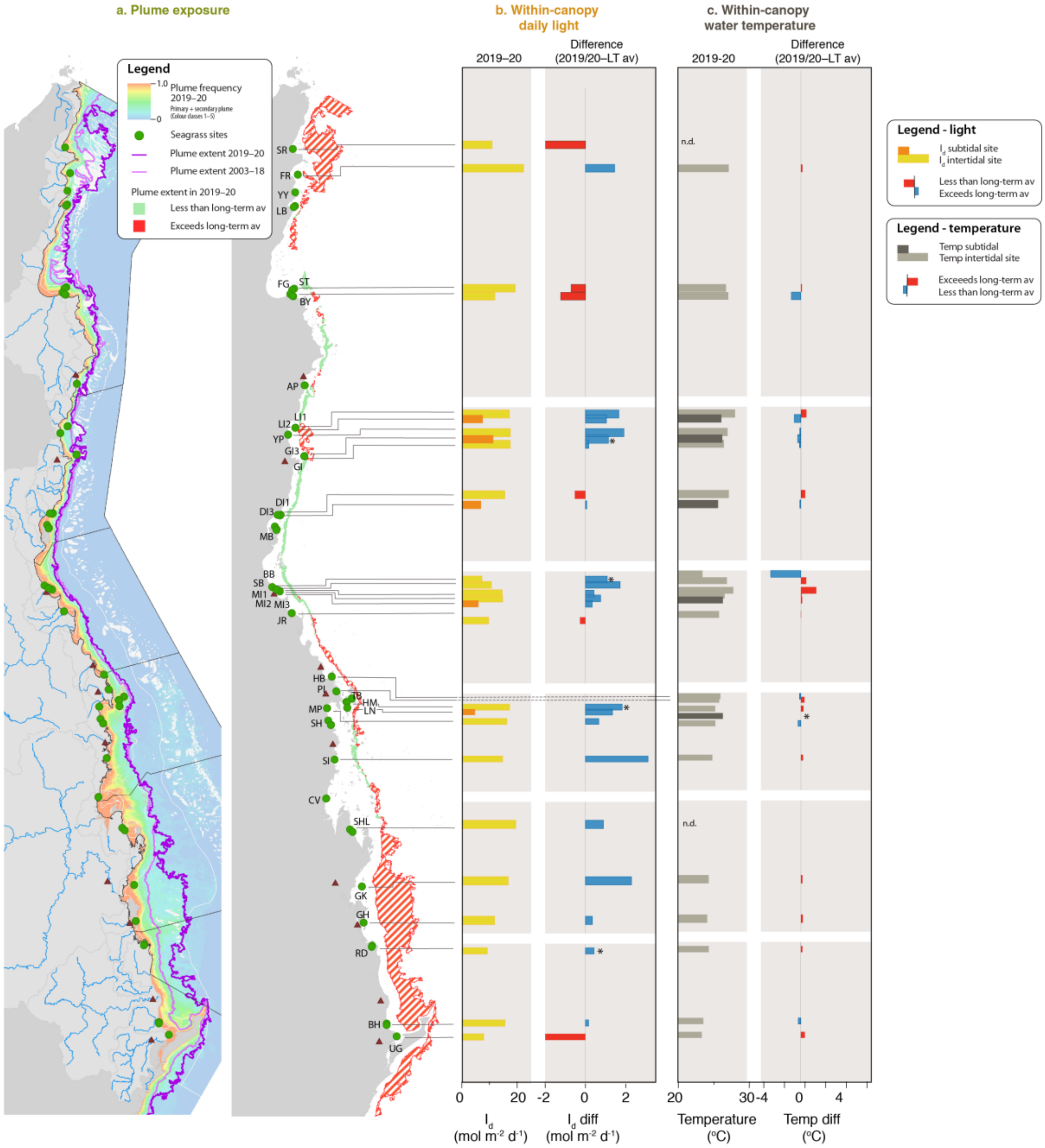


Figure 8. Environmental pressures in the Reef during 2019–20 and relative to long-term: a. Frequency of turbid water (colour classes 1–5, primary and secondary water) exposure shown in the left-hand panel in the Reef from December 2019 to April 2020 ranging from frequency of 1 (orange, always exposed) to 0 (pale blue, never exposed), and right-hand panel the distribution of primary, secondary and tertiary waters (10 per cent boundary) in 2019–20 relative to the long-term average, with red showing that that these water types extended further in 2019–20 and green showing they did not extend as far; b. within canopy daily light for all sites, and the deviation in daily light relative to the long-term average; and c. within canopy water temperature, and deviation water temperature from the long-term average.

Turbid coloured water ('brown' or 'green') reached all seagrass locations in 2019–20 as is characteristic of inshore conditions over the long-term (2003–19, Figure 8). Secondary water ('green water') extended considerably further than average in Cape York and throughout the southern Reef. The reasons for this is hypothesised to be a combination of environmental and image quality factors as discussed in Waterhouse et al. (2021). Throughout the rest of the Reef, the extent of these water types was lower than average (Figure 8, panel 2).

The frequency of exposure to colour classes 1 to 4 ('brown' turbid water) during the wet season weeks (December 2019–April 2020) is typically very high in the inshore regions of the Reef. It was slightly above multiannual conditions in all regions except the Fitzroy region, with the largest increase above the long-term average occurring in the Mackay–Whitsunday region (Figure 9). The sites exposed to higher frequency of brown water in the region were all coastal or estuarine. The frequency of exposure to colour classes 1 to 5 (including 'green' turbid water), shows that all regions were at or marginaly above the multiannual level of exposure. The largest increase was in Cape York, where all sites had a higher level of exposure to classes 1–5 (Figure 8).

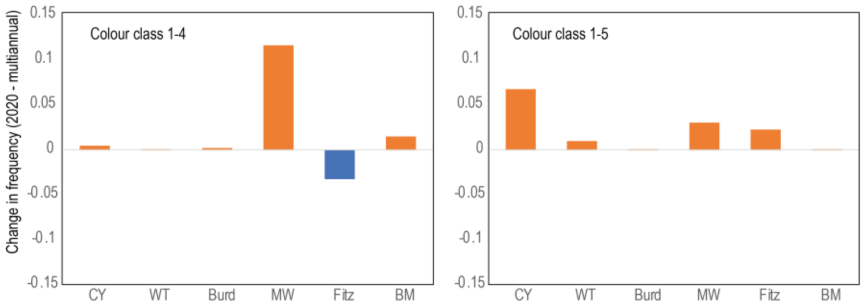


Figure 9. Difference in the frequency of exposure to water colour classes 1 to 4 (left) and 1 to 5 (right) at seagrass monitoring sites during the wet season (December 2019–April 2020) compared to the long-term multiannual exposure (2003–2018).

3.5 Daily incident light

Daily light in shallow habitats can be affected by water quality, depth of the site and cloudiness, which affects the frequency and duration of exposure to full sunlight at low tide (Anthony *et al.* 2004; Fabricius *et al.* 2012). Differences in daily light among seagrass meadows reported here are largely a reflection of site-specific differences in water quality, except in reef subtidal communities where depth results in lower benthic light compared to adjacent reef intertidal communities.

Daily light reaching the top of the seagrass canopy in the Reef in 2019–20 was 13.1 mol m^{-2} d^{-1} when averaged for all sites (Table 9), compared to a long-term average of 12.5 mol m^{-2} d^{-1}. There were only 6 locations in which daily light was lower than the long-term average, and these were in each region except the Fitzroy (Figure 8). There are regional, habitat and location levels differences.

Daily light in the regions in 2019–20 from north to south were (↓ = lower than, ↑ = greater than the long-term):

- Cape York (15.9 mol m^{-2} d^{-1}) ↓
- northern Wet Tropics (14.4 mol m^{-2} d^{-1}) ↑
- southern Wet Tropics (11.7 mol m^{-2} d^{-1}) ↑
- Burdekin (10.9 mol m^{-2} d^{-1}) ↑
- Mackay–Whitsunday (12.4 mol m^{-2} d^{-1}) ↑
- Fitzroy (15.9 mol m^{-2} d^{-1}) ↑
- Burnett–Mary (10.9 mol m^{-2} d^{-1}) ↓

Daily light in the habitats in 2019–20 from highest to lowest were (↓ = lower than, ↑ = greater than, ↕ = similar to long-term i.e. <0.5 mol m^{-2} d^{-1} difference):

- reef intertidal, n = 9 (16.8 mol m^{-2} d^{-1}) ↑
- coastal intertidal, n = 10 (13.7 mol m^{-2} d^{-1}) ↑
- estuarine, n = 3 (11.2 mol m^{-2} d^{-1}) ↓
- reef subtidal, n = 5 (7.0 mol m^{-2} d^{-1}) ↕.

Daily light for each of the sites is presented in Figure 8. There were eight locations in which the annual daily light level was lower than 10 mol m^{-2} d^{-1}, the light threshold that is likely to support optimal long-term growth requirements of the species in these habitats (Collier et al 2016). Four of these were the subtidal sites (all subtidal sites except Green Island). The other locations below 10 mol m^{-2} d^{-1} were intertidal at Bushland Beach and Jerona in the Burdekin and Rodds Bay and Urangan in the Burnett–Mary.

Long-term trends show a peak in within canopy daily light occurs in September to December as incident solar irradiation reaches its maximum and prior to wet season conditions (Figure 10). This also coincides with peak seagrass growth season, and the focus of sampling. The lowest light levels typically occur in the wet season, particularly in January to April. In 2019–20, daily light steadily increased from post-wet season minima to to a peak at the end of December and declined thereafter, this followed an extended period of low light in the wet season of 2018-19.

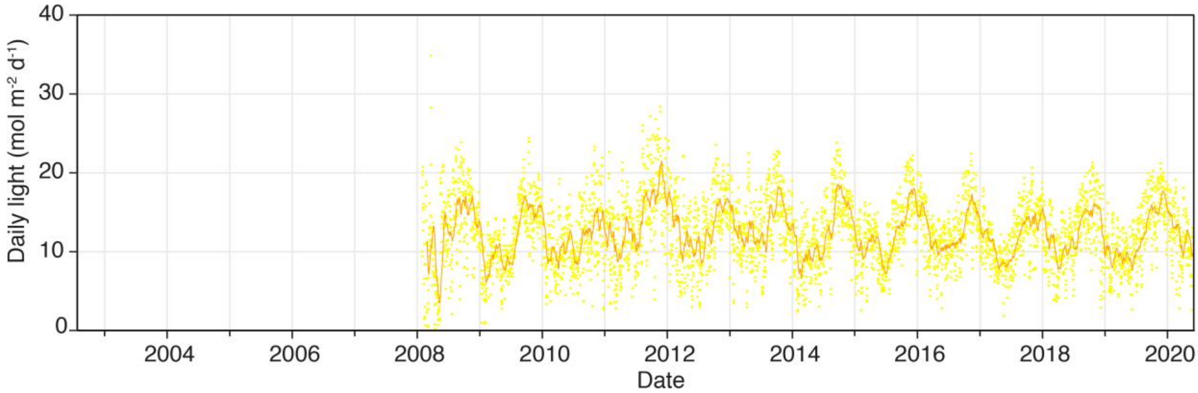


Figure 10. Daily light for all sites combined from 2008 to 2020. In 2008–2009, light data is from the Burdekin and Wet Tropics regions only. Other regions were included from 2009–2010, with Cape York added post 2012–2013 reporting period.

3.6 Within-canopy seawater temperature

Daily within-canopy seawater temperature across the inshore Reef in 2019–20 was warmer than the previous reporting period (Figure 11). Since 2013, the frequency of weekly warm water deviations appears to have increased, relative to cooler occurrences (Figure 11). The 2019–20 Reef temperature was on average (25.8 ±0.2°C) similar to the long-term (2003–19, 25.7°C) (Table 9). However, there were regional and habitat differences relative to the long-term (Figure 8).

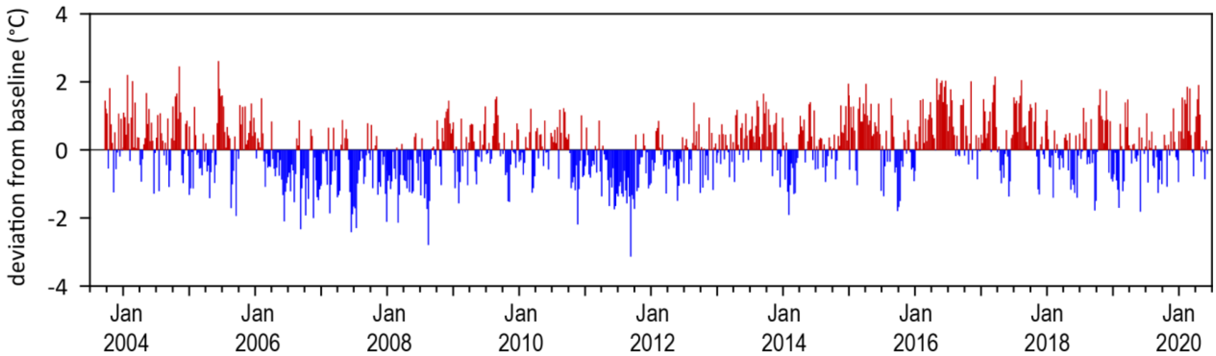


Figure 11. Inshore intertidal sea temperature deviations from baseline for Reef seagrass habitats from 2003 to 2020. Data presented are deviations from 14-year mean weekly temperature records (based on records from September 2003 to June 2019). Weeks above the long-term average are represented as red bars and the magnitude of their deviation from the mean represented by the length of the bars, blue bars represent weeks with temperatures lower than the average and are plotted as negative deviations.

Daily within-canopy seawater temperatures in the regions in 2019–20 (including number of days above 35°C and 40°C) from north to south as difference (* = greater than 0.5°C) relative to the long-term average (↑ = greater than, ↕ = similar to long-term) were:

- Cape York (avg = 27.2°C, max = 38.8°C, days$_{>35°C}$ = 28)↑
- northern Wet Tropics (avg = 26.9°C, max = 39.6°C, days$_{>35°C}$ = 54)↕
- southern Wet Tropics (avg = 27.4°C, max = 35.2°C, days$_{>35°C}$ =3)↕.
- Burdekin (avg = 26.4°C, max = 39.8°C, days$_{>35°C}$ =47)↕
- Mackay–Whitsunday (avg = 25.3°C, max = 41.1°C, days$_{>35\leq 40°C}$ =66, days$_{>40°C}$ =2)↕
- Fitzroy (avg = 24.3°C, max = 40.5°C, days$_{>35\leq 40°C}$ =60, days$_{>40°C}$ =3)↕
- Burnett–Mary (avg = 23.8°C, max = 40.9°C, days$_{>35\leq 40°C}$ =12, days$_{>40°C}$ =1)↑

Daily within-canopy seawater temperatures in each habitat in 2019–20 relative to respective long-term average (↑ = greater than, ↓ = greater than, ↕ = similar to long-term, * = greater than 0.2°C) were:

- estuarine habitat (avg = 24.2°C, max = 40.9°C)↑*
- coastal intertidal habitat (avg = 26.1°C, max = 41.1°C)↕
- reef intertidal habitat (avg = 26.3°C, max = 38.8°C)↕
- reef subtidal habitat (avg = 26.2°C, max = 33.8°C)↓*

The hottest seawater temperature recorded at inshore seagrass sites along the Reef during 2019–20 was 41.1°C in the Mackay–Whitsunday region, and only the southern regions (Mackay–Whitsunday, Fitzroy and Burnett–Mary), had at least one day above 40°C (Figure 12). Extreme temperature days (>40°C) can cause photoinhibition but when occurring at such low frequency, they were unlikely to cause burning or mortality. Subtidal temperatures remained below 35°C and the NRM long-term averages in 2019–20.

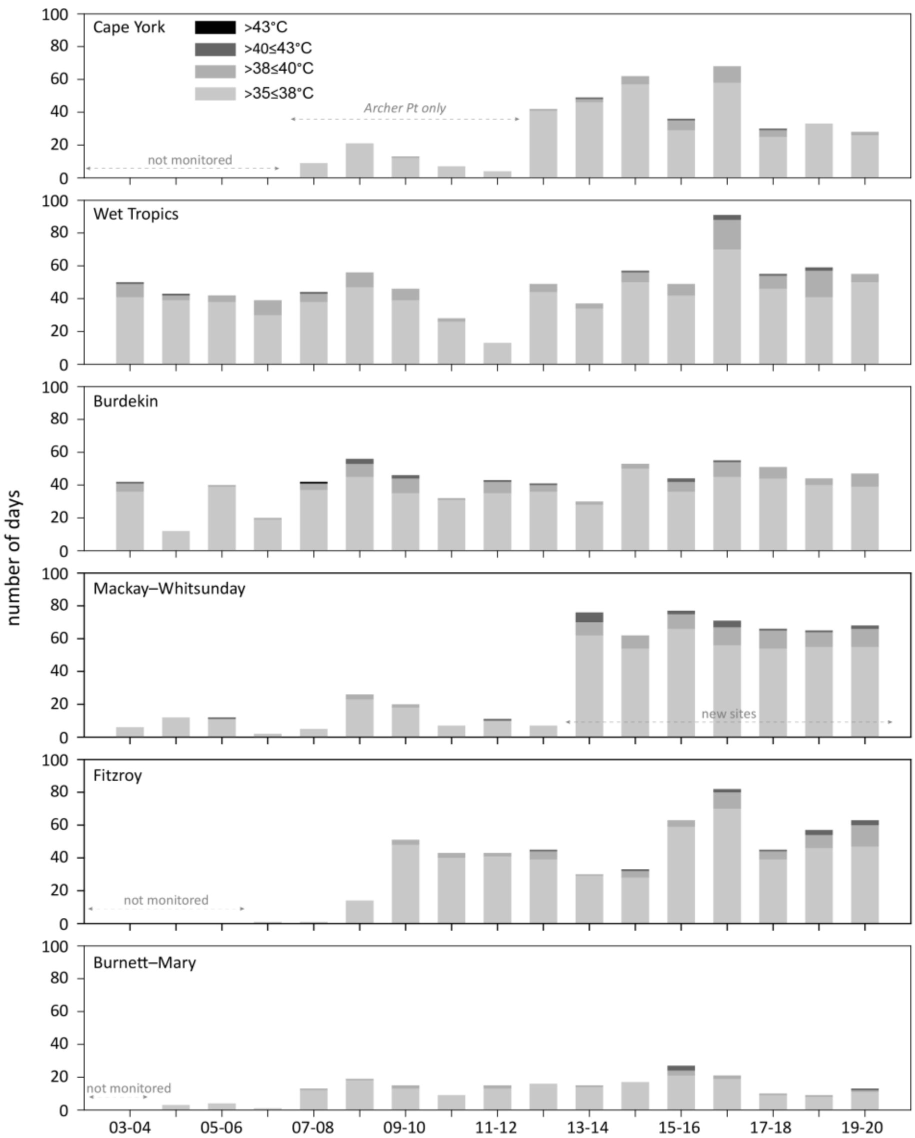


Figure 12. Number of days when inshore intertidal sea temperature exceeded 35°C, 38°C, 40°C and 43°C in each monitoring period in each NRM region.Thresholds adapted from Campbell et al. 2006; Collier et al. 2012a.

3.7 Seagrass meadow sediments

Coastal subtidal and estuarine seagrass habitats across the Reef had a greater proportion of fine sediments (i.e. mud) than other habitats (Table 11). Sediments at intertidal coastal habitats were predominately medium and fine sands, while reef habitats (intertidal and subtidal) were dominated by medium sands (Table 11).

Table 11. Long-term average (±SE) sediment composition for each seagrass habitat (pooled across regions and time) monitoring within the Reef (1999–2019). *only 5 years of data.

Habitat	Mud	Fine sand	Sand	Coarse sand	Gravel
estuarine intertidal	45.3 ±2.1	21.9 ±2.0	30.7 ±1.8	0.1 ±0.4	2.0 ±0.9
coastal intertidal	28.4 ±2.1	30.0 ±2.4	37.4 ±2.6	0.3 ±0.5	3.9 ±1.2
coastal subtidal*	53.8 ±2.3	9.5 ±0.4	18.4 ±2.5	7.7 ±1.1	10.6 ±0.0
reef intertidal	4.3 ±1.3	6.8 ±1.7	52.1 ±2.8	15.4 ±1.8	21.5 ±2.4
reef subtidal	12.4 ±0.6	18.0 ±1.1	56.2 ±5.9	1.4 ±0.6	11.9 ±5.9

During the 2019–20 monitoring period there were small fluctuations (generally decreases) in the contribution of mud sediments to sediment type relative to the previous year (Figure 13). Historically, the composition of sediments has fluctuated at all habitats, with the proportion of mud declining below the long-term average at estuary and coastal habitats immediately following periods of physical disturbance from storms (e.g. cyclones in 2006 and 2011). Conversely, the proportion of mud increased above the long-term average at reef (intertidal and subtidal) habitats during periods of extreme climatic events (e.g. cyclones and/or flood events).

Finer-textured sediments (i.e. mud) tend to have higher fertility, allowing rhizome elongation, and greater levels of anoxia. Although anaerobic conditions may stimulate germination in some species, the elevated sulfide levels generally inhibit leaf biomass production in more mature plants. Only seagrass species adapted for growth in anaerobic mud sediments (e.g. *Zostera*) are able to persist, providing sufficient light for photosynthesis is available.

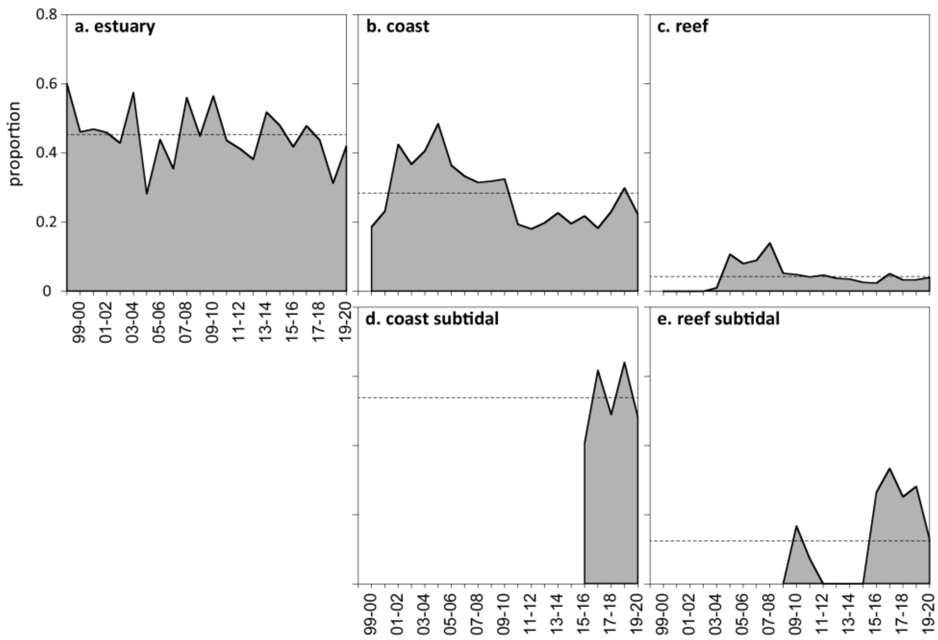


Figure 13. Proportion of sediment composed of mud (grain size <63µm) at inshore Reef seagrass monitoring habitats from 1999–2020.

4 Seagrass condition and trend

The following results section provides detail on the overall seagrass responses for the 2019–20 monitoring period, in context of longer-term trends. It is structured as an overall inshore Reef summary: condition and trend for each habitat type presented separately, including:

- a summary of the key findings from the overall section including a summary of the report card score
- seagrass abundance and extent
- seagrass species composition based on life history traits
- seagrass reproductive effort and seed banks
- seagrass leaf tissue content (C:N, N:P and C:P ratios)
- epiphyte and macroalgae abundance
- linkage back to broad-scale environmental pressures.

Detailed results for each region are presented in the next section. Supporting data identified as important in understanding any long-term trends is detailed within Appendix 3 and 4.

4.1 Overall inshore Reef seagrass condition and trend

Inshore seagrass meadows across the Reef remained unchanged in overall condition in 2019–20, with the condition grade remaining poor (Figure 14).

In summary, the unchanged overall condition was due to declines in overall abundance, while reproductive effort and tissue nutrients increased:

- Seagrass abundance (per cent cover) declined from 2018–19 to 2019–20, reaching the lowest score in six years. Seagrass abundance at meadows monitored in the MMP declined from 2005–2006 until 2011–2012, caused by multiple years of above-average rainfall, and resultant discharges of poor quality water, followed by extreme weather events, after which abundances increased (Figure 14, Figure 16b). Seagrass abundance increased until 2015–16, but has declined since then. Based on the average score against the seagrass guidelines (determined at the site level), the abundance of inshore seagrass in the Reef over the 2019–20 declined to a poor grade for the first time in six years (Figure 14).

- Although reproductive effort increased in the 2019–20 year, it was the seventh consecutive year that the score was very poor (Figure 14). Low reproductive effort will hinder replenishment of the depauperate seed banks, and seed reserves are therefore likely to remain low in coming years. Most meadows can be considered vulnerable to further disturbances because of their limited capacity to recover from seed. Meadow resilience is also determined by other habitat characteristics. A resilience score is presented in Collier *et al.* 2021 and will replace the reproductive metric in following years.

- The nutrient status score (C:N ratio) remained relatively unchanged in 2019–20 (Figure 14). The seagrass leaf tissue nutrient indicator remained in a poor state, as it has been for seven of the previous nine years (Figure 14). This indicates that the availability of nitrogen at some locations, is more than what is needed for seagrass leaves that are growing and incorporating carbon. In most locations, $\delta^{15}N$ values suggest diverse sources of nitrogen affecting nitrogen availability.

Trends in seagrass abundance and tissue nutrients demonstrate that until 2016–2017, the system was on a recovering trajectory. However, since 2017–18, declines in abundance and continued very low reproductive effort throughout most of the Reef, may signal that inshore seagrass resilience has decreased and recovery processes may be further hampered following future disturbances.

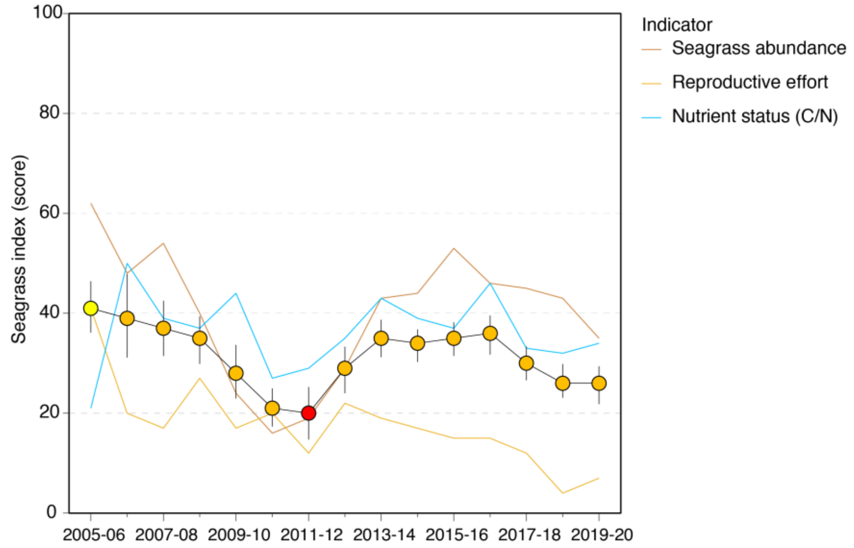


Figure 14. Overall inshore Reef seagrass condition index (± SE) with contributing indicator scores over the life of the MMP. The index is derived from the aggregate of metric scores for indicators of seagrass community health. Index scores scaled from 0–100 and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

4.2 Trends in seagrass condition indicators between regions

The overall inshore Reef score for seagrass is derived from the average of seagrass indicator scores in each of six Regions, weighted by seagrass area. In 2019–20 the score declined in Cape York and the Wet Tropics, and increased in other regions (Figure 15). Overall, the slight increases in the reproductive and tissue nutrient indicator scores were offset by declines in abundance, resulting in the overall inshore Reef score remaining unchanged in a poor state. Trends in indicators also varies among the six Regions:

- The seagrass abundance score was poor in the 2019–20 monitoring period in all regions (Figure 15). The score was also reduced in the 2019–20 monitoring period in all regions compared to the previous monitoring period, expcept in the Mackay–Whitsunday and Fitzroy where the score increased slightly. The largest changes to the abundance score have occurred in the Burdekin region, which reached a good rating in 2015–16, but declined to poor where it has remained since. The Fitzroy region has not achieved a rating greater than poor since 2010–11.
- Reproductive scores were poor in the Wet Tropics, Burdekin and Mackay–Whitsunday regions in 2019–20, and very poor (score = 0) in the other regions (Figure 15). Reproductive effort declined in the Burdekin and Mackay–Whitsunday and increased in the Wet Tropics, but was relatively stable in all other regions (Figure 15).
- Seagrass nutrient status scores (using only C:N) were poor in 2019–20 in all regions except the Burdekin region where it was moderate (Figure 15). However, there was some improvement in the score compared to 2018–19, in all regions except Cape York.

Inshore seagrass condition scores across the Regions reflect a system that is being impacted by heatwaves, cyclones, and elevated discharge from rivers. Regional differences in condition and indicator scores appear due to the legacy of significant environmental conditions in 2016–17 (e.g. cyclone Debbie in Mackay–Whitsunday, above-average riverine discharge throughout the southern and central Reef, and a marine heatwave in the northern and central Reef) and in 2018–19 in the Burdekin region (above-average riverine discharge).

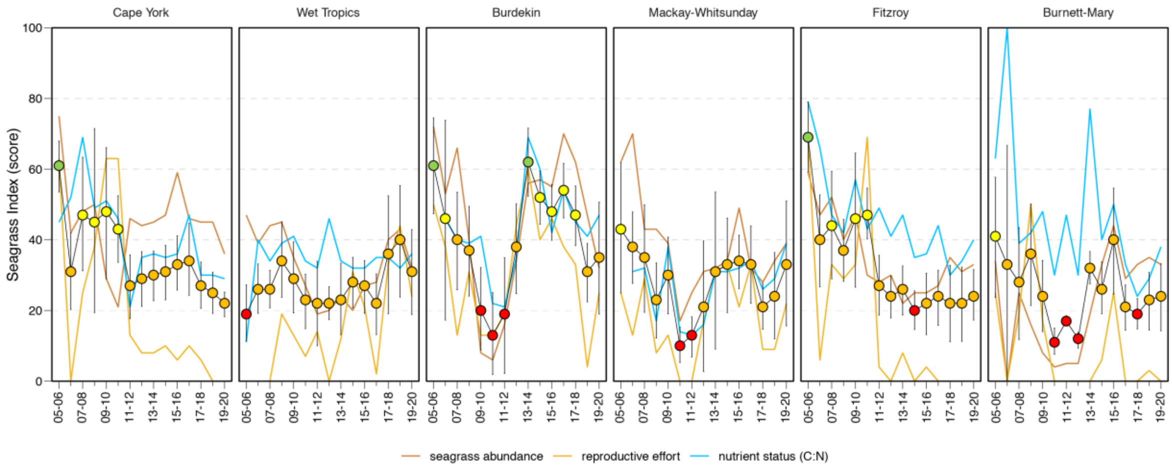


Figure 15. Seagrass condition index (± SE) with contributing indicator scores for each NRM region over the life of the MMP. The index is derived from the aggregate of metric scores for indicators of seagrass community health. Values are indexed scores scaled from 0–100 and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

The long-term trends in the seagrass condition index, and the data for each of the contributing indicators are shown in Figure 16. Generalised additive models are presented for per cent cover and tissue nutrients to show long-term trends in these indicators. These models could not be constructed on the reproductive data due to the large number of zeroes. Instead, reproductive effort is displayed as mean and standard errors, which highlights the large seasonal variability in reproductive effort. The seagrass abundance indicator has varied over decadal time-scales, declining in the 2009–10 through 2011–12 monitoring periods, then recovering to some extent depending on region, and subsequently declining over recent years. The reproductive and nutrients status indicators similarly declined to their lowest levels in the 2009–10 through 2011–12 monitoring periods. However, those indicators vary more on annual or multi-annual time-scales.

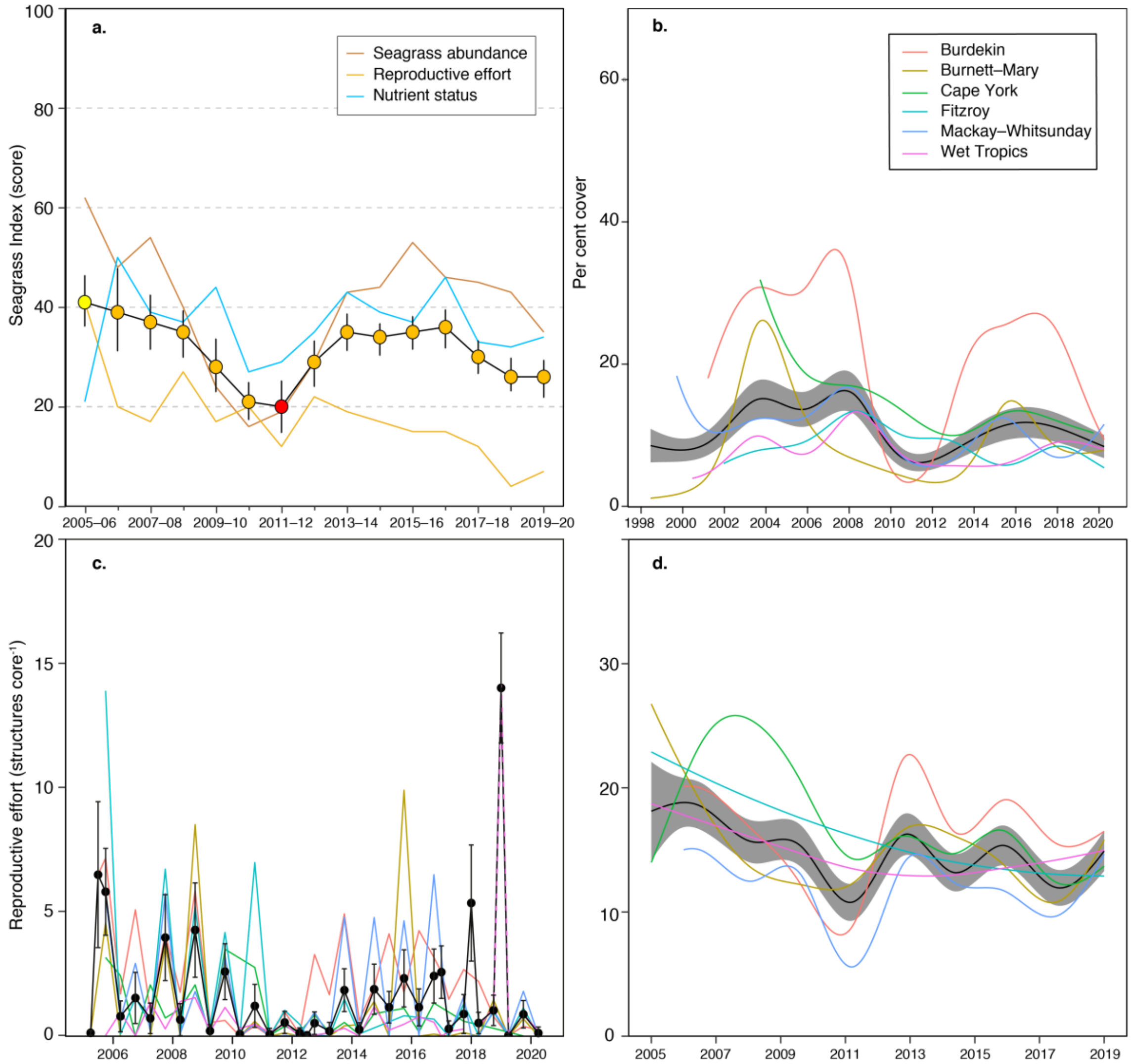


Figure 16. Trends in the seagrass condition index and indicators used to calculate the index including: a. Overall inshore Reef seagrass index (circles, ± SE) and regional indicators (lines); b. trends in seagrass abundance (per cent cover, ± SE) represented by a GAM plot as dark lines with shaded areas defining 95 per cent confidence intervals of those trends (Reef), and coloured lines representing NRM trends; c. reproductive structures (GAM is not possible due to high count of zeroes); and d. tissue nutrient content represented by a GAM plot as dark lines with shaded areas defining 95 per cent confidence intervals of those trends (Reef), and coloured lines representing NRM trends.

4.3 Trends in seagrass condition indicators by habitat type

4.3.1 Seagrass abundance, composition and extent

Seagrass abundance state has fluctuated since monitoring was established. An examination of long-term abundances across the Reef indicates:

- no significant trends at 71 per cent of long-term monitoring sites assessed, however 9 per cent of sites significantly increased in abundance and 20 per cent decreased (Appendix 3, Table 21)
- the rate of change in abundance was higher at sites increasing (0.7 ±0.4 0.9 ±0.5 per cent, sampling event^{-1}) than decreasing (-0.2 ±0.1 per cent sampling event^{-1}) (Appendix 3, Table 21)

- the most variable Reef seagrass habitat in abundance (since 2005) was intertidal estuary (CV=109.3 per cent), followed by reef habitats (intertidal CV=56.6 per cent and subtidal CV=47.2 per cent), and lastly, coastal habitats (intertidal CV=41.5 per cent and subtidal CV=30.3 per cent).

Since 1999, the median percentage cover values for the Reef were mostly below 25 per cent cover, and depending on habitat, the 75th percentile occasionally extended beyond 50 per cent cover (Figure 17). These long-term percentage cover values were similar to the Reef historical baselines, where surveys from Cape York to Hervey Bay (between November 1984 and November 1988) reported most (three-quarters) of the per cent cover values fell below 50 per cent (Lee Long *et al.* 1993). The findings highlight the need to use locally-relevant reference sites and score thresholds.

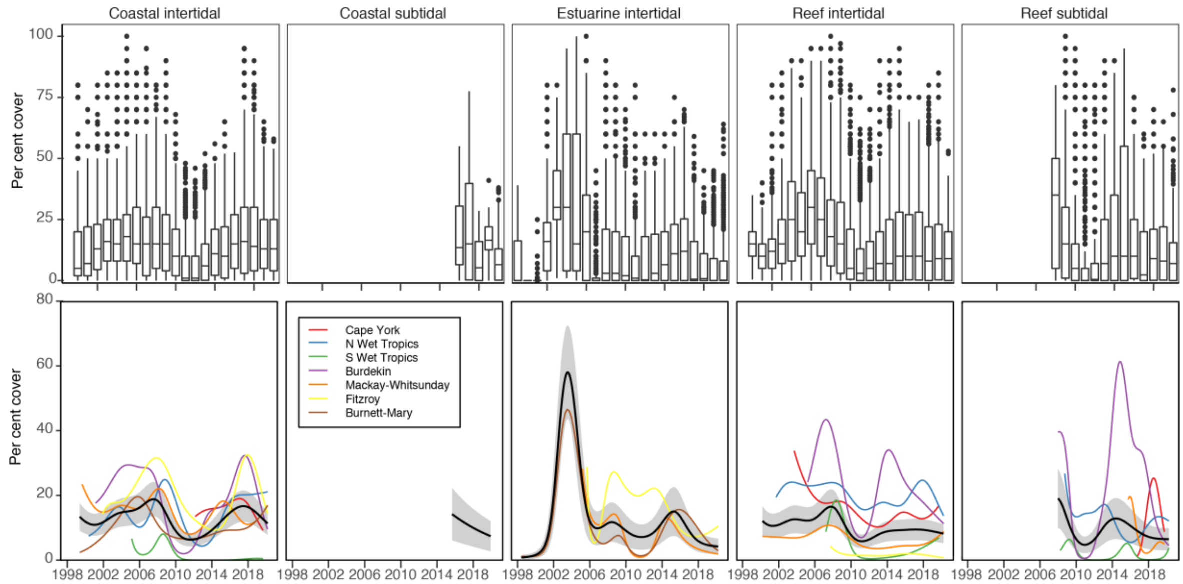


Figure 17. Seagrass per cent cover measures per quadrat from meadows monitored from June 1999 to May 2020 (sites and habitats pooled). The box represents the interquartile range of values, where the boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, 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, and the dots represent outlying points. GAM plots (bottom), also showing trends for each NRM, (coloured lines) and combined as dark lines with shaded areas defining 95 per cent confidence intervals of those trends.

In 2019–20, coastal sites had the highest average abundance of the habitat types, and estuarine sites had the lowest (Figure 17). Over the past decade, the patterns of seagrass abundance in each habitat have been similar between coastal and reef sites; gradually increasing from 2001 to 2008 (with a mild depression in 2006-07 as a consequence of cyclone Larry), then declining from 2009 to 2011 due to above average rainfall and river discharge (Figure 16). The extreme weather events of early 2011 (e.g., cyclone Yasi) resulted in further substantial decline in inshore seagrass meadows throughout much of the Reef.

Estuarine habitats, which are monitored only in the southern Reef, reached record per cent cover in 2002 to 2003, but have remained low since 2005–06. Trends have fluctuated at a site level in estuary habitats, most often at smaller localised scales where there have been some acute event related changes (McKenzie *et al.* 2012).

Post 2011, seagrasses have progressively recovered, although have still remained below the 2008 levels on average in each year since, except in coastal sites which have recovered (Figure 16).

In 2019–20, the overall inshore Reef relative meadow extent was similar to the previous year, however these remain lower than the baseline (2005), 2014 and 2015 (Figure 18).

Since the MMP was established in 2005, meadow extent across inshore monitoring sites declined in early 2011, recovering within 3–4 years (Figure 18). Similar to seagrass abundance, this decline in relative extent was a consequence of extreme weather and associated flooding. Since 2014, the meadows monitored across the Reef have varied in extent within and between years. The changes in extent over the last four years appear a consequence of severe weather events (e.g. cyclones) and location specific climate (frequency of strong wind days).

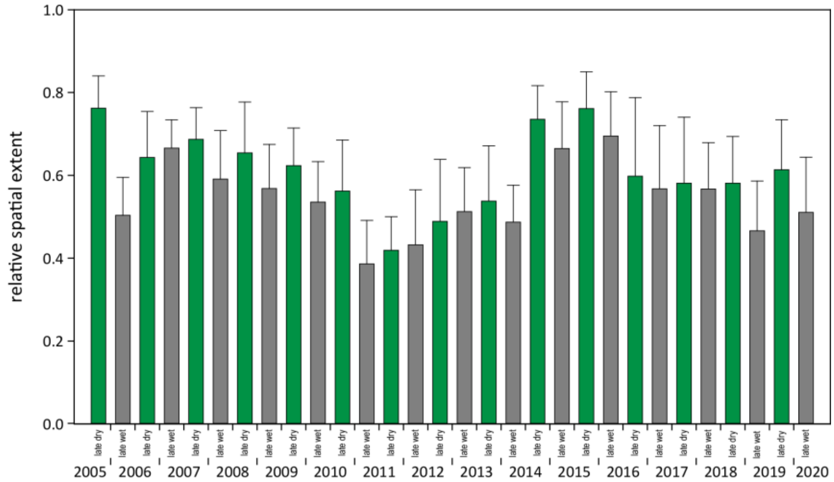


Figure 18. Average relative spatial extent of seagrass distribution at monitoring sites across inshore Reef (locations, habitats and NRM regions pooled, + SE).

After the extreme weather events in 2009 to 2011 that caused widespread declines in seagrass extent (Figure 18) and abundance, there was increasing proliferation of species displaying colonising traits, such as *Halophila ovalis,* at coast and reef sites (Figure 19). Over the 2019–20 monitoring period, the proportion of species displaying colonising traits remained around or lower than the overall inshore Reef average for each habitat type in coastal and estuarine habitats in favour of species displaying opportunistic or persistent traits (*sensu* Kilminster *et al.* 2015). The displacement of colonising species is a natural part of the meadow progression expected during the recovery of seagrass meadows. This is a positive sign of recovery for these habitats/meadows. At reef subtidal habitats, the proportion of colonising species was the second and third highest in 2018-19 and 2019–20, but this was due to the addition of new sites with high levels of colonising species.

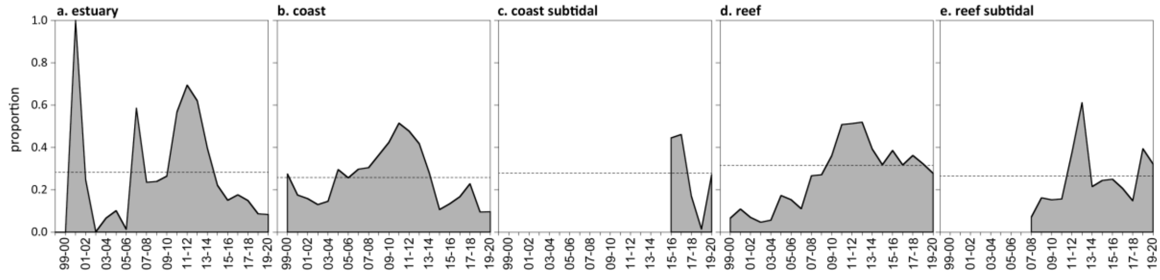


Figure 19. Proportion of total seagrass abundance composed of species displaying colonising traits (e.g. *Halophila ovalis*) in: a) estuary intertidal, b) coastal intertidal, c) coast subtidal, d) reef intertidal and e) reef subtidal habitats (sites pooled) for the Reef (regions pooled) each monitoring period. Dashed line illustrates Reef average proportion of colonising species in each habitat type.

4.3.2 Seagrass reproductive status

Seagrass reproductive effort remained very low in reef intertidal and subtidal habitats, although there was a small increase at reef subtidal habitats compared to the previous three years (Figure 20). In coastal and estuarine habitat, reproductive effort declined for the first and second years in a row, respectively. This resulted in the reproductive effort score remaining very poor in the Reef.

Since the implementation of the MMP, the maximum reproductive effort and the inter-annual variability in reproductive effort has differed between habitats, and varied within and between years. Reproductive effort across the inshore Reef meadows are typically higher in the late dry, while seed density fluctuates less seasonally (Figure 20 Figure 21).

Reproductive effort had gradually been increasing at estuary and coastal habitats since 2011, with large rises from 2013–14, however, it decreased significantly in estuaries in 2018–19 and remained low in 2019–20 (Figure 20). This trend was observed in all three southern regions where estuaries are monitored and reflects trends in abundance in estuarine habitats. Seed banks, however, remain largely unchanged over the previous 8 years in estuaries (Figure 21).

In coastal habitats, reproductive effort and seed density varies inter-annually, more than in other habitats. The historically high reproductive effort in coastal habitats is due to a record number of reproductive structures in the northern Wet Tropics (Yule Point), Burdekin (Bushland Beach and Jerona) and Mackay–Whitsunday (Midge Point). Overall inshore Reef reproductive effort declined markedly in 2019–20 with reductions occurring in most regions but largest reductions occurring in the northern Wet Tropics and Burdekin regions, even as abundance increased in the former (Figure 20). Seed density in seed banks have also declined in coastal habitats (Figure 21).

Reef habitats have had the lowest reproductive effort of all habitats (Figure 20), while seed density in seed banks have typically been the lowest in reef intertidal habitats, with no seeds having ever been found at sites in Cape York, northern Wet Tropics, Mackay–Whitsundays and Fitzroy regions (Figure 21). In 2019–20, reproductive effort remained low in reef habitats, but there was a small increase, most notably with the appearance of structures in subtidal habitats in the southern Wet Tropics (Dunk Island) for the first time since 2015 and the highest levels in intertidal reef habitats since 2013, albeit they were very low.

Reductions in seed density could have been caused by reduced reproductive success (failure to form seeds) or loss of seed bank (germination or grazing). It indicates vulnerability of these habitats to future disturbances, as recovery may be hampered although the actual count of seeds needed to initiate or optimise recovery is not known.

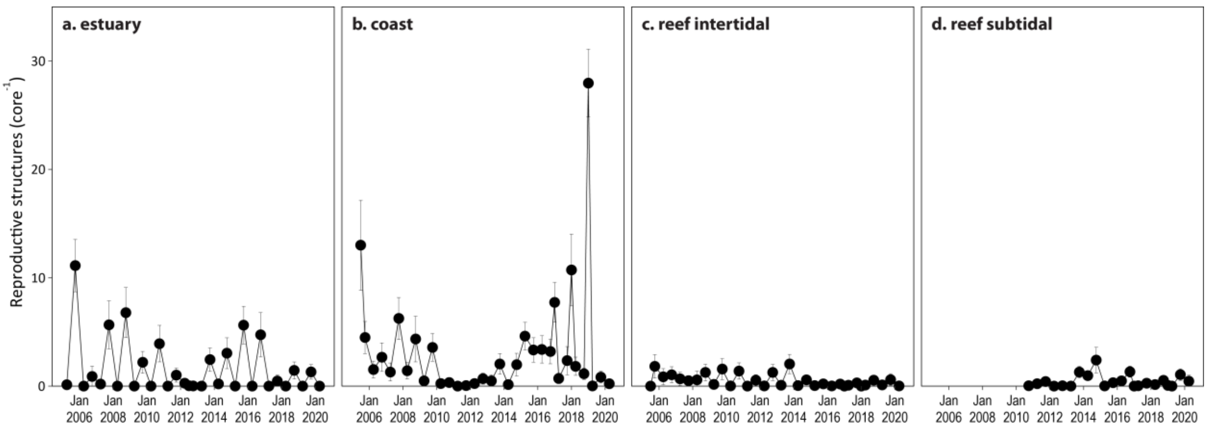


Figure 20. Seagrass reproductive effort (number of reproductive structures produced by all seagrass species, ± SE) during the late dry of each monitoring period for a) estuary intertidal; b) coast intertidal; c) reef intertidal; d) reef subtidal.

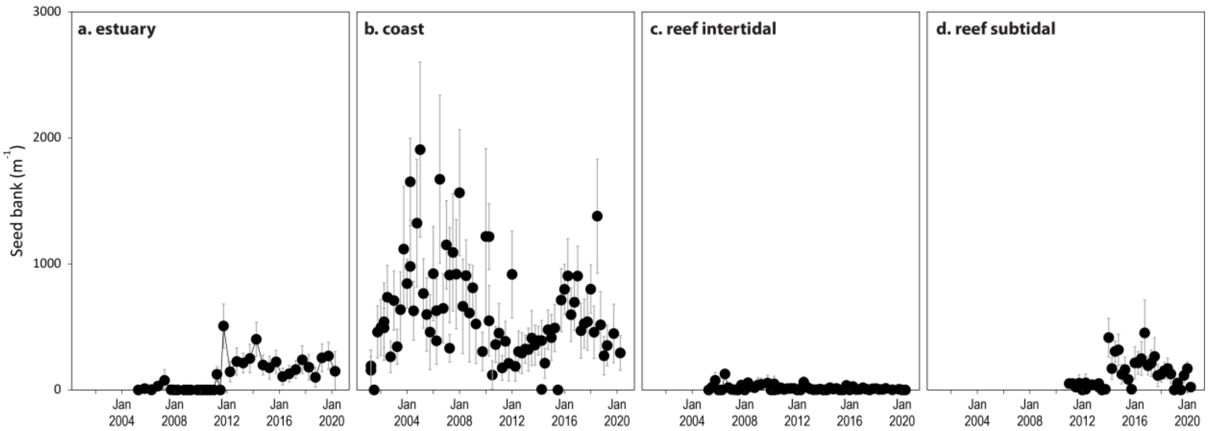


Figure 21. Average seeds banks (seeds per square metre of sediment surface, all sites and species pooled, ± SE) in Reef seagrass habitats: a) estuary intertidal; b) coast intertidal; c) reef intertidal; d) reef subtidal.

4.3.3 Seagrass leaf tissue nutrients

In 2019–20, the average ratio of carbon (C) to nitrogen (N) increased slightly, but was below the guideline value of 20 in all habitats except reef subtidal habitat where it was slightly above the guideline. The C:N ratio is used as an indicator of water quality and seagrass condition because elevated carbon (and elevated C:N) suggests high light availability, while elevated N (lower C:N), indicates elevated nitrogen supply rates relative to growth requirements (Abal *et al.* 1994; Grice *et al.* 1996). Therefore, in all habitats other than reef subtidal, there was an oversupply of N relative to growth requirements.

In 2019–20, C:N ratio of seagrass leaves increased at approximately half of the sites from the previous period, but this was not significant due to variation in this trend among regions and between sites, and the number of sites remaining above the threshold of 20 was the highest in three years, equalling the highest since monitoring was established. The lowest C:N values on average continue at Yule Point (10.6), Lugger Bay (11.8) and Hamilton Island (12.3).

Tissue nutrients are measured in the late dry (~October 2019) of the reporting period, and are therefore related to the previous water quality reporting year (01 October 2018–31 September 2019) (Waterhouse *et al.* 2021). In 2019, river discharge exceeded the long-term median in the four northern regions, with particularly high discharge in Cape York and the Burdekin, relative to the long-term average (Table 10). Despite this, C:N increased in all habitat types, albeit only very slightly in coastal intertidal habitats, which is indicative of lower

N, and/or higher light. Indeed dissolved inorganic nitrogen as nitrate/nitrite was stable or declining in all regions in 2019–20 (Waterhouse *et al.* 2021). Furthermore as previously described, daily light levels in the seagrass canopy were above the long-term average, and had increased from the previous reporting year in all regions except Cape York and the Burnett–Mary. Site-specific changes in C:N are likely related to local conditions, in particular localised variations in benthic light.

Seagrasses are passive indicators of $\delta^{15}N$ enrichment, as they integrate the signature of their environment over time throughout their growth cycle. $\delta^{15}N$ values can indicate the source of nitrogen. Very low (~0‰) or negative values of $\delta^{15}N$ can indicate nitrogen sourced from nitrogen fixation (Peterson and Fry 1987; Owens 1988); which can supply one third to one half of seagrass demand (O'Donohue *et al.* 1991). Low to moderate values (i.e. $\delta^{15}N$ >0 - ~3‰) indicate internal sources from remineralisation (Peterson and Fry 1987; Owens 1988) and N fertilizer, produced by industrial fixation of atmospheric nitrogen (Udy and Dennison 1997a). Higher values (>3‰) can indicate septic and aquaculture sources (Jones *et al.* 2001) and further biological fractionation results in sewage nitrogen having a $\delta^{15}N$ signature greater than 9 or ~10‰ (Lajtha and Marshall 1994; Udy and Dennison 1997b; Dennison and Abal 1999; Costanzo *et al.* 2001; Jones *et al.* 2018). In general, $\delta^{15}N$ in inshore Reef seagrass tissues are variable but low (Figure 22), suggesting multiple sources of nitrogen. There is currently no indication or concern that anthropogenic sources are strongly influencing seagrass N supply.

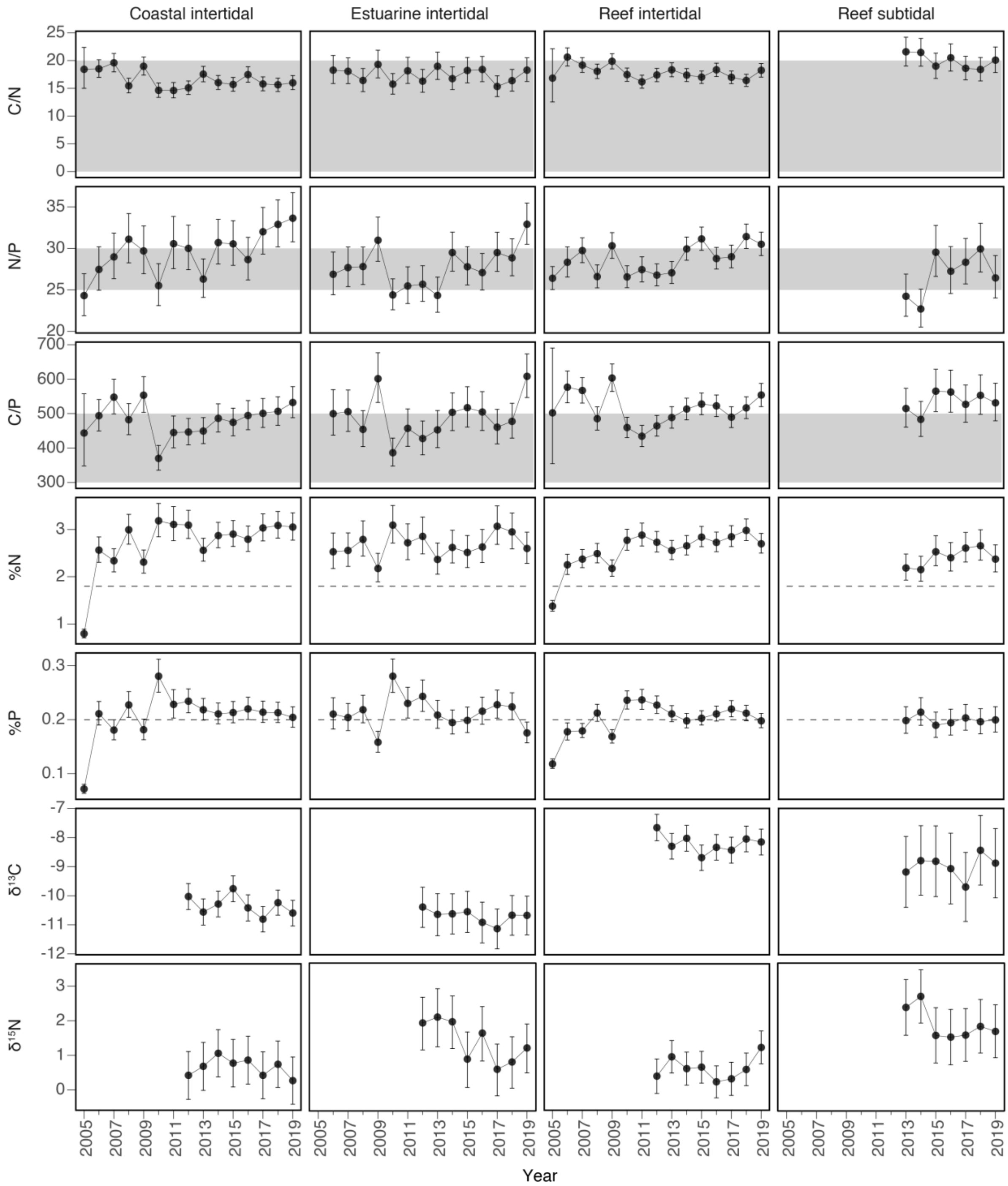


Figure 22. Reef seagrass leaf tissue nutrient elemental ratios (C:N:P) and concentrations (per cent N, per cent P, $\delta^{13}C$ and $\delta^{15}N$) for each seagrass habitat each year (± SE) (foundation species pooled). Horizontal shaded bands or dashed lines represents the accepted seagrass guideline values, where: C:N ratios within the band may indicate reduced light availability and/or N enrichment; N:P ratios above the band indicate P limitation, below indicate N limitation and within indicates replete, and; C:P ratios within the band may indicate nutrient rich habitats (large P pool). Dashed lines in per cent N and per cent P indicate global median values of 1.8 per cent and 0.2 per cent for tissue nitrogen and phosphorus, respectively (Duarte 1990).

4.3.4 Epiphytes and macroalgae

Epiphyte cover on seagrass leaves during 2019–20 was above the overall inshore Reef long-term average in estuary and coast habitats, below in reef intertidal habitats, and seasonally variable in reef subtidal habitats (Figure 23). Epiphytes historically varied the most in estuary habitats (by 50%), but over the previous 10 years epiphytes have mostly varied by a small amount (<20%) around the long-term average in both estuaries and coasts. Reef intertidal habitats have remained the most consistently low in epiphyte coverage since 2009-10, and reef subtidal habitats have reminaed the most consistently high since 2014-15.

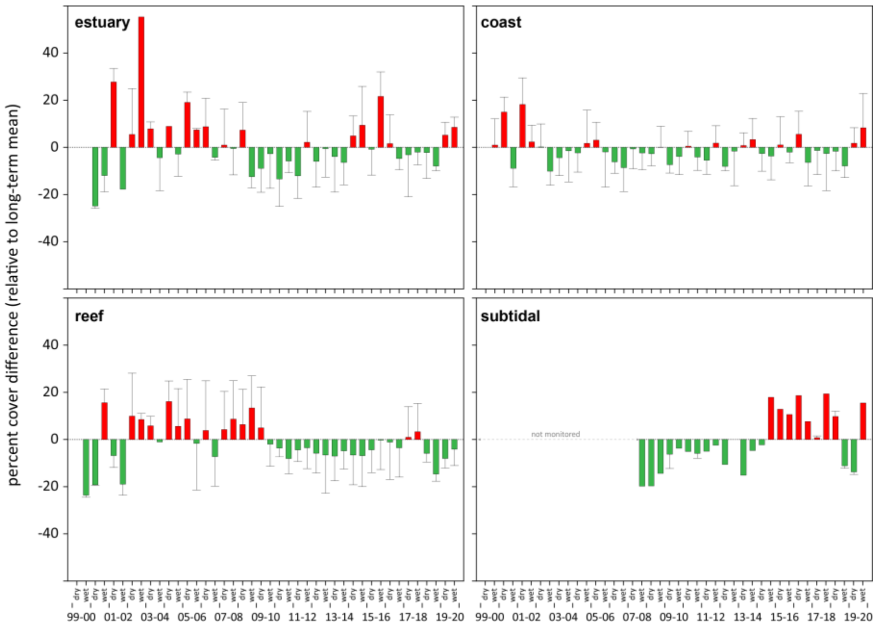


Figure 23. Epiphyte abundance (per cent cover) relative to the long-term average (the zero axis) for each Reef seagrass habitat (sites pooled, ± SE). Reef long-term average (2005 to 2019); estuarine = 25.1±5.6 per cent coastal=17.8±3.7 per cent, reef = 22.8±4.2 per cent, subtidal= 20.6±3.1 per cent.

Macroalgae abundance in 2019–20 followed the general trends of the previous 10 years in reef and coast habitats, remaining below the overall inshore Reef long-term average for each of the habitats (Figure 24). Macroalgae abundance remained above the long-term average at reef intertidal sites, in particular at Magnetic Island (MI2), Hamilton Island (HM2), Low Isles (LI1) and Hydeaway Bay (HB1). In contrast, macroalgal abundance at reef subtidal sites continued a declining trend occurring over the last five years, and was below the long-term average.

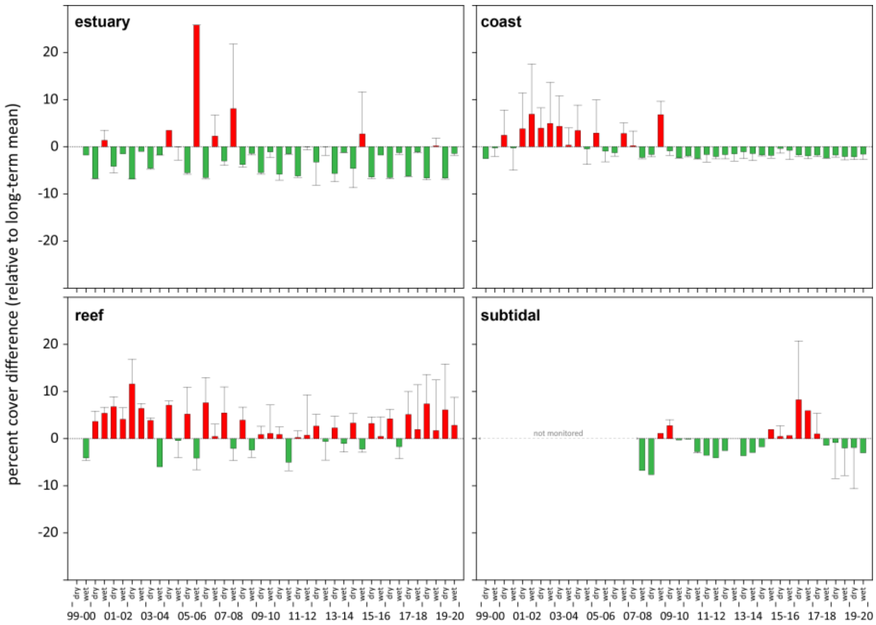


Figure 24. Macroalgae abundance (per cent cover) relative to the long-term average for each inshore Reef seagrass habitat. (sites pooled, ± SE). Reef long-term average; estuarine = 2.3±1.0 per cent, coastal=2.5±1.2 per cent, reef = 6.9±1.9 per cent, subtidal = 6.6±2.0 per cent.

5 Regional Reports

This section presents detailed results on the condition and trend of indicators within Regions, and relates the results to local environmental factors including:

- annual daytime tidal exposure at each monitoring site
- daily light each monitoring location
- sediment grain size composition at each monitoring site
- tables detailing statistical analysis.

5.1 Cape York

5.1.1 2019–20 Summary

The region experienced below average rainfall and river discharge (except in two of the major catchments) yet above average turbid water exposue and below average light levels. There were above average elevated within-canopy water temperatures for the eighth consecutive year.

Seagrass meadow condition across the Cape York NRM region in 2019–20 declined slightly from 2018–19. The reduction was due to lower scores in the abundance score and continued low scores for the reproductive effort and nutrient status indicators. For the three indicators:

- abundance score was poor
- tissue nutrient score was poor
- reproductive effort score was very poor.

On average, seagrass abundance (per cent cover) reduced relative to the previous period. Seagrass abundance decreased at half of the Cape York sites, but only in coastal and subtidal habitats. The only increases occurred at intertidal reef meadows throughout the region.

Seagrass leaf tissue nutrient concentrations in 2019–20 were largely unchanged compared to previous years, remaining poor. The exception was at Bathurst Bay, where C:N declined and %N increased following above average river discharge in 2019.

There were no reproductive structures observed in Cape York in 2019–20 for the third time in the 15 year monitoring history and the decreased reproductive effort may weaken capacity to recover from seeds in the near future. However, there were persistent and/or increasing seed banks at intertidal coastal meadows, which could aid recovery in the short term, if environmental conditions are favourable for germination. The lack of seeds in most intertidal reef meadows currently limits recovery.

An assessment of long-term trends in other Cape York habitats is affected by changes in the number, onset and duration of monitoring at individual sites. Per cent cover progressively decreased at intertidal reef habitats across Cape York from 2003 to 2012, with signs of improvement since, particularly at Stanley Island. Coastal intertidal and subtidal habitats monitored since 2012 and 2015 respectively, declined over the last two years in all locations except Shelburne Bay in the north of Cape York. Similarly, meadow extent across the region has been relatively stable since 2012.

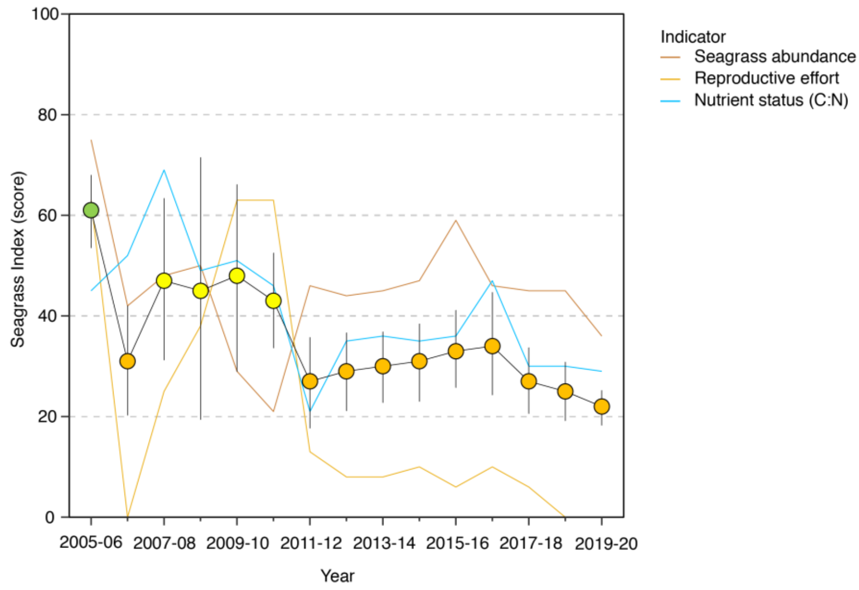


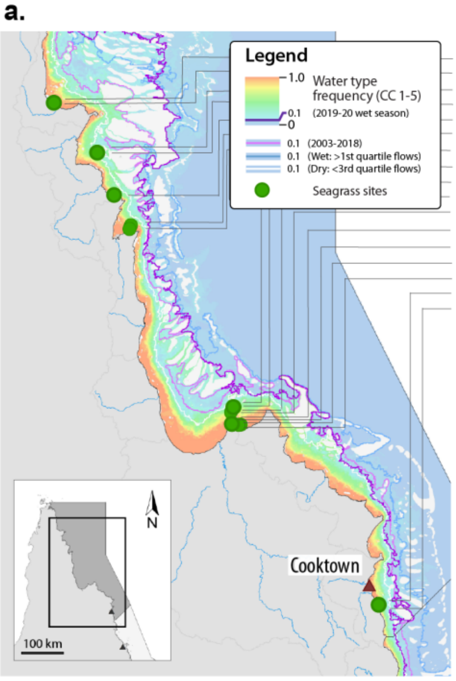
Figure 25. Seagrass condition index (± SE) with contributing indicator scores for the Cape York NRM region (averaged across habitats and sites). Index scores scaled from 0-100 and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

5.1.2 Climate and environmental pressures

Tropical cyclone Gretel affected the central region of Cape York in March 2020 (Waterhouse et al. 2021). Rainfall was below the long-term average in Cape York in 2019–20, while river discharge was around the long-term average for the region as a whole. Discharge from the Olive–Pascoe and Lockhart Rivers in central Cape York, which likely influence Piper Reef and Shelburne Bay, were slightly above the long-term average, while other rivers were below it (Table 10).

The extent of turbid water influence on the Reef (using model tracers), and the exposure levels and risk from turbid primary ('brown', sediment laden colour classes one to four) and secondary water type ('green', phytoplankton rich water, colour classe five) using MODIS satellite products is detailed in Waterhouse et al. (2021). The inshore waters of Cape York had predominantly secondary water type ('green', phytoplankton rich water), and some brown turbid water exposure through the wet season (December-April; Figure 26). Shelburne Bay sites (SR1 and SR2) had the highest exposure to turbid primary water, consistent with previous years, followed closely by Bathurst Bay intertidal sites (BY1 and BY2). Piper Reef (FR1 and FR2) has the lowest level of exposure amongst the inshore seagrass monitoring sites, but it was also higher than average in 2019–20. The frequency of exposure to both primary and secondary water ranged from 57 per cent to 100 per cent of wet season weeks at seagrass monitoring sites (Figure 26), and was on average, higher than the long-term average due mostly to increased secondary 'green' water (Figure 8 and Figure 9). The reasons for this are discussed in further detail in the water quality report (Waterhouse et al. 2021).

Daily incident light (I_d, mol m^{-2} d^{-1}) reaching the top of the seagrass canopy is generally very high at all Cape York sites, largely because they are all intertidal (long-term average = 16.4 mol m^{-2} d^{-1}) (Figure 99). However in 2019–20, daily incident light (15.9 mol m^{-2} d^{-1}) was slightly below the long-term average (Figure 26). This was influenced primarily by the persistently low light levels at Bathurst Bay in 2019–20 (Figure 99). However the shorter/incomplete logging duration (approximately half of data missing) at reef intertidal sites also contributed. Cape York sites are surveyed only once per year, and the instruments are not able to function for a full year due to battery life, and inevitable fouling.



b.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
SR1	4	4	5	5	5	4	4	4	5		4	4	4	4		5	3	1	1	2	1	
SR2	4	4	5	5	5	4	4	4	5		4	4	4	4		5	3	1	1	2	1	
FR1	6	5	6	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	6	5	
FR2	6	5	6	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	6	5	
YY1	4	4	5	5	5	5	5	5	5	5	5	5	5	5		5	5		5	5	5	
LR1	5	5	5	5	5	5	5	5	6	5	5	5	5	5	5	5	5	6	5	5	5	5
LR2	5	5	5	5	5	5	4	4		4	5	4	4	4	5	4	5	4	5	5	4	
ST2	5	5	5	5	6	5	5	5		5	5	5	5	5		5	5	5	5	5	5	5
ST1	5	5	5	5	6	5	5	5		5	5	5	5	5		5	5	5	5	5	5	5
FG2	5	5	5	5	6	5	5	5		5	5	5	5	5	6	5	5	5	5	5	5	5
FG1	5	5	5	5	6	5	5	5		5	5	5	5	5	6	5	5	5	5	5	5	5
BY1	1	5	5	4	5	5	5	4	5		4	2	5	4		4	4	4	4	5	4	5
BY2	1	5	5	4	5	5	5	4	5		4	2	5	4		4	4	4	4	5	4	5
BY3	5	5	5	5	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5
BY4	5	5	5	5	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5
AP1	5	4	5	4	5		5	5	5	5	5	6	5	4	5	5	5	4	5		4	4
AP2	5	4	5	4	5		5	5	5	5	5	6	5	4	5	5	5	4	5		4	4

1-4 = turbid primary water (brown), 5 = nutrient/chlorophyll-enriched secondary water (green), 6 = some freshwater/CDOM influence tertiary water (blue), 7 = no plume influence (white), blank = no data, clouds (grey)

c.

	Long-term average	2019-20
Rainfall (1961-1990)	7.5 mm d^{-1}	5.5 mm d^{-1}
River discharge (1970-2016)	13,753,068 L yr^{-1}	12,212,486 L yr^{-1}
Turbid water exposure (2006-2018)	85%	92%
Daytime tidal exposure (1999-2019)	59 hr yr^{-1}	58 hr yr^{-1}
Wind (1998-2019)	106 days yr^{-1}	149 days yr^{-1}
Within-canopy temperature - intertidal (2003-19)	26.9ºC (41.3ºC)	27.2ºC (38.8ºC)
Within-canopy light (2012-2019)	16.4 mol m^{-2} d^{1}	15.9 mol m^{-2} d^{1}

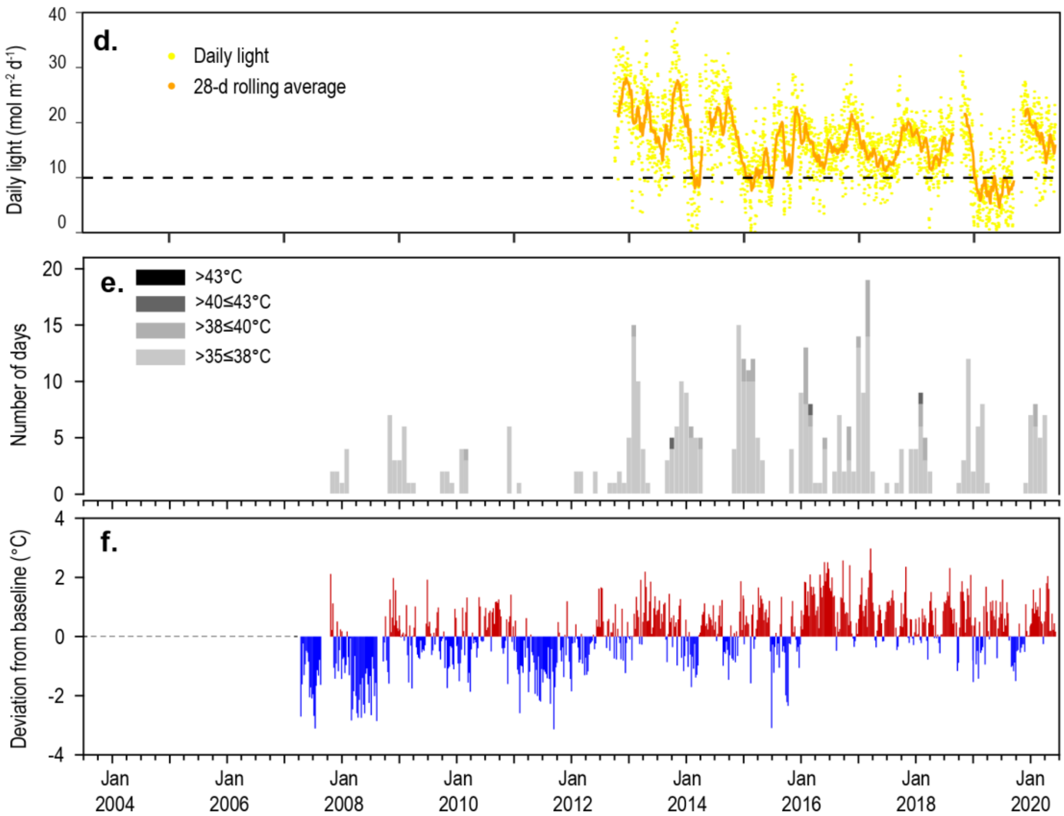


Figure 26. Environmental pressures in the Cape York region including: a. frequency of exposure to turbid water (colour classes 1-5, white = no data) (from Waterhouse et al. 2021), b. wet season water type at each site; c. average conditions over the long-term and in 2019–20; d. daily light and the 28-day rolling mean of daily light for all sites; e. number of day temperature exceeded 35°C, 38°C, 40°C and 43°C, and; f. deviations from 13-year mean weekly temperature records.

Notably, 2019–20 was the eighth consecutive year intertidal within-canopy temperatures were above the long-term average (Figure 26). Maximum within-canopy temperatures exceeded 35°C for a total of 28 days (in total among all sites where temperature is monitored) during 2019–20 (Figure 26), with the highest temperature recorded at 38.8°C (ST1, 2pm 18Feb20). Daily tidal exposure (hours water has drained from the meadow) was around the long-term average for (Figure 26, Figure 91), which may have provided some respite from the elevated temperatures.

In the Cape York NRM region, reef habitats remain dominated by sands and coarser sediments, while coastal habitats contained a greater proportion of mud (Appendix 2, Figure 106, Figure 107).

5.1.3 Inshore seagrass and habitat condition

There are 17 seagrass monitoring sites in Cape York from 9 locations (Table 12). Four seagrass habitat types were assessed across the Cape York region in 2019–20, with data from 14 of the 17 long-term monitoring sites (Table 12, Table 19).

Table 12. *List of data sources of seagrass and environmental condition indicators for each seagrass habitat type in the Cape York NRM region. For site details see Table 3 and Table 4. Open square indicates not measured in 2019–20. † drop camera sampling (RJFMP), *Seagrass-Watch.*

Habitat	Site		abundance	composition	extent	reproductive effort	seed banks	leaf tissue nutrients	meadow sediments	epiphytes	macroalgae
coastal intertidal	BY1	Bathurst Bay	■	■	■	■	■	■	■	■	■
	BY2	Bathurst Bay	■	■	■	■	■	■	■	■	■
	SR1	Shelburne Bay	■	■	■	■	■	■	■	■	■
	SR2	Shelburne Bay	■	■	■	■	■	■	■	■	■
coastal subtidal	BY3†	Bathurst Bay	■	■							■
	BY4†	Bathurst Bay	■	■							■
	LR1†	Lloyd Bay	■	■							■
	LR2†	Lloyd Bay	■	■							■
reef intertidal	AP1	Archer Point	□	□			□		□	□	□
	AP2	Archer Point	□	□			□		□	□	□
	FR1	Farmer Is. (Piper Reef)	■	■	■	■	■	■	■	■	■
	FR2	Farmer Is. (Piper Reef)	■	■	■	■	■	■	■	■	■
	ST1	Stanley Island (Flinders Group)	■	■	■	■	■	■	■	■	■
	ST2	Stanley Island (Flinders Group)	■	■	■	■	■	■	■	■	■
	YY1*	Yum Yum Beach (Weymouth Bay)	□	□			□		□	□	□
Reef subtidal	FG1†	Flinders Island (Flinders Group)	■	■							■
	FG2†	Flinders Island (Flinders Group)	■	■							■

5.1.3.1 Seagrass index and indicator scores

In the 2019–20 monitoring period, the seagrass condition index score for the Cape York region reduced slightly since the previous monitoring period, but the overall grade remained **poor** (Figure 27).

The greatest score reduction occurred in abundance, which declined from moderate in 2018–19 to poor in 2019–20. This is the first time a poor abundance score has been recorded since new sites were commissioned in 2012–13 and 2016–17.

The reproductive effort score was zero for the second year in a row and it is the first time that no reproductive structures were observed at any of the sites in the late dry sampling (Figure 27). Other counts with zero reproductive effort have been observed in the wet season but wet season data is not used in the metric, because it is a time that counts are typically low. Tissue nutrients remained poor and at the second lowest level recorded in Cape York.

Overall, the Cape York seagrass condition index remains well below the 2005–06 baseline and in 2019–20 was the lowest score since the addition of new sites in 2012–13.

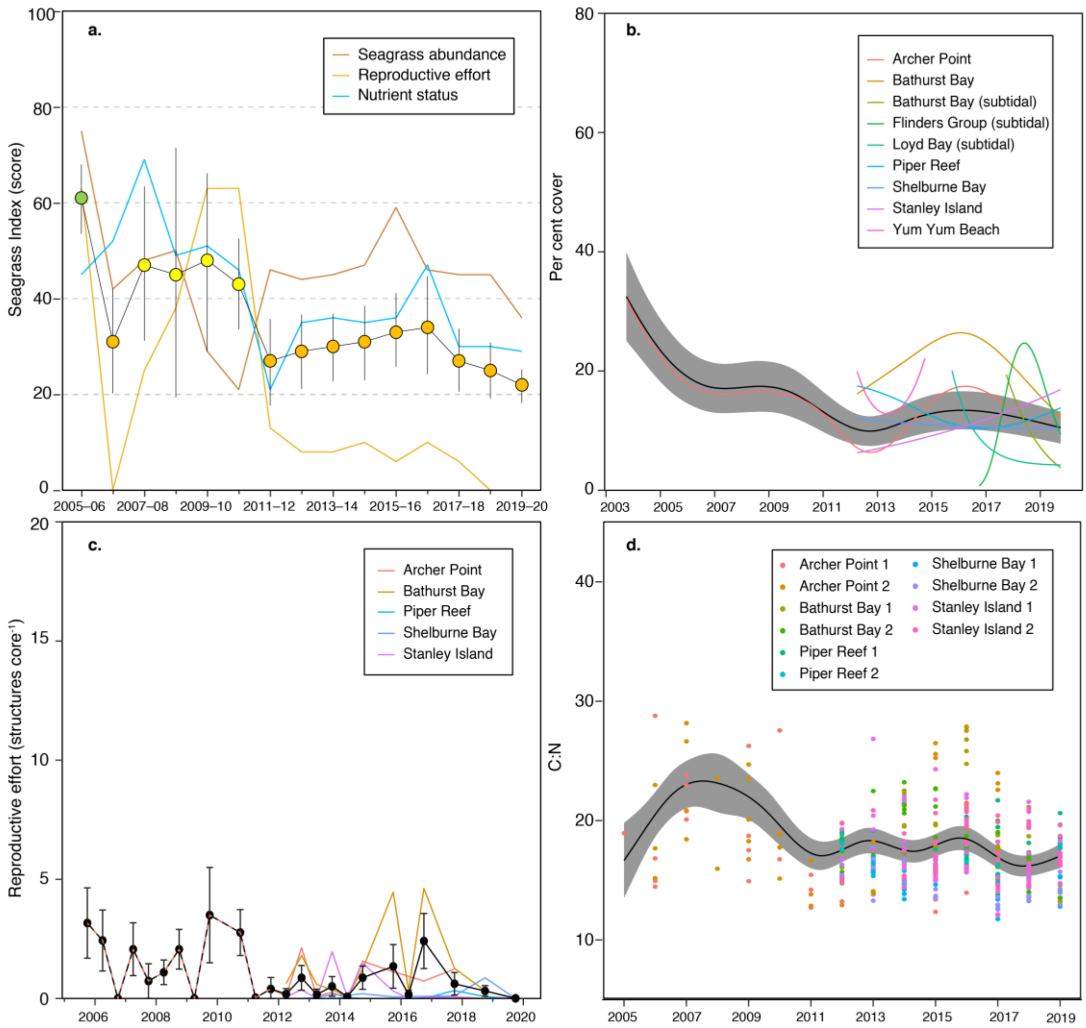


Figure 27. Temporal trends in the Cape York seagrass condition index and the indicators used to calculate the index: a. seagrass condition index (circles, ± SE) and indicator trends (lines); b. GAM plots of seagrass abundance (per cent cover) trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); c. average number of reproductive structures (± SE) (GAM not possible due to high count of zero values); and d. elemental ratios (atomic) of leaf tissue C:N nutrient content at each site (coloured circles) and regional trend represented by a GAM plot as dark line with shaded areas defining 95 per cent confidence intervals of the trend.

An examination of the long-term trends across the Cape York NRM region needs to be interpreted carefully as new sites were included in 2012–13, which are associated with consistently lower abundance and tissue nutrients compared to the highest levels recorded for the region. Archer Point, which was the only location monitored prior to 2012–13, is now only monitored as part of the Seagrass-Watch due to logistical difficulties (Figure 27).

5.1.3.2 Seagrass abundance, composition and extent

The reduction in seagrass abundance in 2019–20 is a consequence of reductions in per cent cover at coastal intertidal and subtidal sites at Bathurst Bay and reef subtidal sites in the Flinders Group (Figure 28). All of those sites are adjacent to the Normanby River mouth, which in the 2018–19 wet season, discharged at 2–3 times its annual median volume. Stanley island — within the same region — had more stable abundance. Seagrass abundance was either unchanged or slightly increased in the more northern regions of Cape York even though rivers discharged above the long-term median throughout the region and cyclones (TC Penny and Trevor) affected the region in the 2018–19 wet season.

An examination of the long-term trend in seagrass abundance shows seagrass per cent cover progressively decreased at intertidal reef habitats across Cape York from 2003 to 2012, with relatively little improvement (i.e. no trend) until 2019–20 (Figure 28, Table 21). Coastal intertidal and subtidal habitats which have only been monitored since 2012 and 2015 respectively, generally showed no trend until 2019–20, when abundance declined (Figure 28, Table 21).

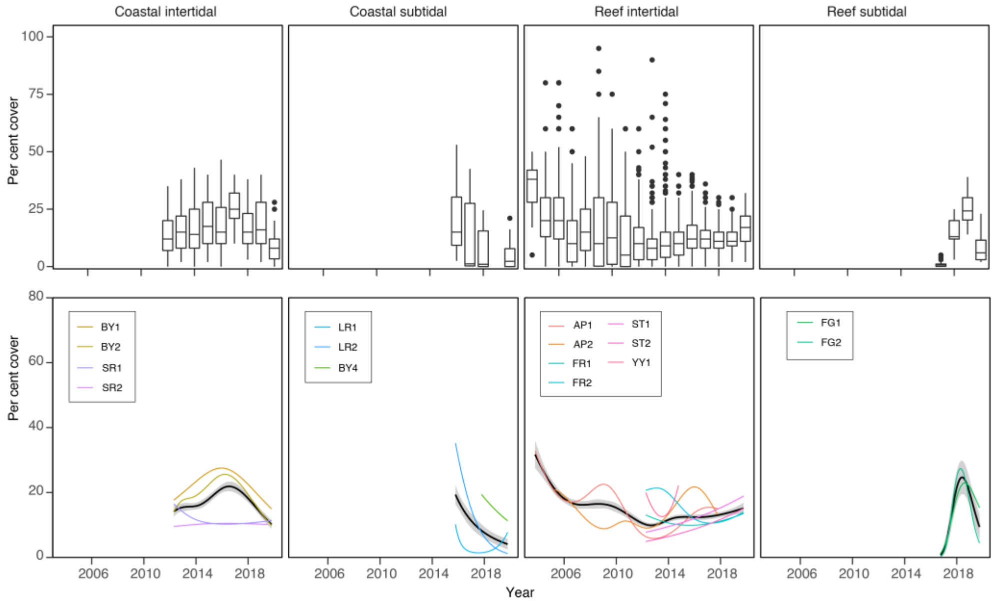


Figure 28. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends for each habitat monitored in the Cape York region from June 2005 to May 2020. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero indicates 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, and the dots represent outlying points. GAMM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

In 2019–20, the proportions of species displaying colonising species traits (largely *Halophila ovalis*) were similar to the previous reporting year in all habitats in the Cape York NRM region. With the exception of reef habitats, the proportions of colonising species were above GBR long-term averages for all other habitats in 2019–20. Reef subtidal habitats were exclusively colonising species (Figure 29).

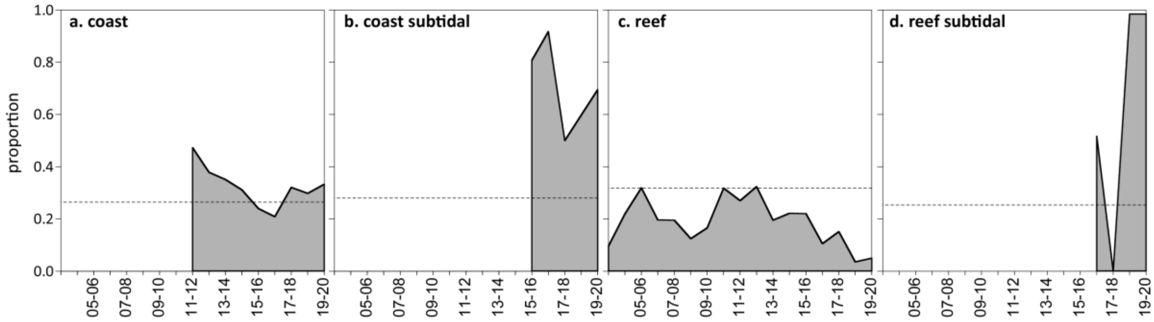


Figure 29. Proportion of seagrass abundance composed of species displaying colonising traits at inshore habitats in the Cape York region.The dashed line represents Reef long-term average for each habitat type.

Seagrass spatial extent mapping was conducted within meadows to determine if changes in abundance were a consequence of the meadow landscape changing and to indicate if plants were allocating resources to colonisation (asexual reproduction). Prior to 2012, the only meadow extent mapping in the Cape York region was conducted at reef intertidal meadows at Archer Point. The meadows within monitoring sites on the reef flat at Archer Point have fluctuated within and between years (Figure 30), primarily due to changes in the landward edge and appearance of a drainage channel from an adjacent creek (data not presented). As of 2012–13, additional reef and coastal meadows in the Cape York region were included. Overall, meadow extent has been relatively stable since 2012 (Figure 30), though extent has reduced in coastal meadows, also due primarily to changes in drainage channels.

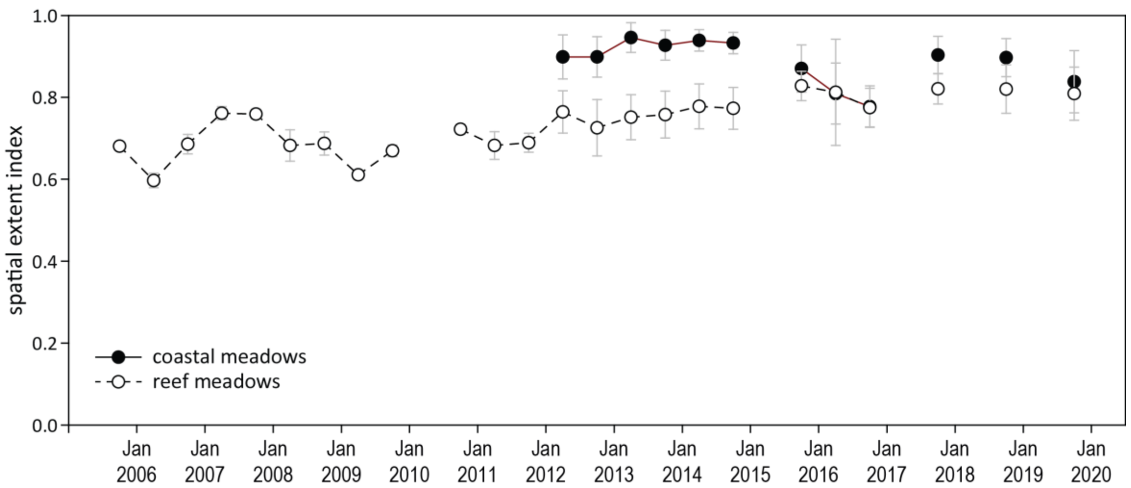


Figure 30. Change in spatial extent (± SE) of seagrass meadows within monitoring sites for each intertidal coastal and reef habitat and monitoring period across the eastern Cape York NRM region.

5.1.3.3 Seagrass reproductive status

Total reproductive effort is only monitored at intertidal meadows in Cape York. Reproductive effort declined at reef habitats in 2018–19, and remained low in 2019–20. Historically, from 2006 to 2012, reproductive effort in reef intertidal habitats was recorded only at Archer Point, which was decommissioned in 2018, and is now based on sites introduced in 2012, which have consistently low numbers of reproductive structures. Reproductive effort declined at coastal habitats across the region and were the lowest on record in 2018–19 (Figure 31).

Seed banks are also only measured at intertidal sites across Cape York and are dominated by *Halodule uninervis*. Seeds are typically low in density in reef intertidal habitats, and were absent in 2019–20. Seed density in seed banks also declined at coastal habitats in 2019–20 but remains at relatively high levels compared to coastal sites in other regions, and remains much higher than those found in reef habitats.

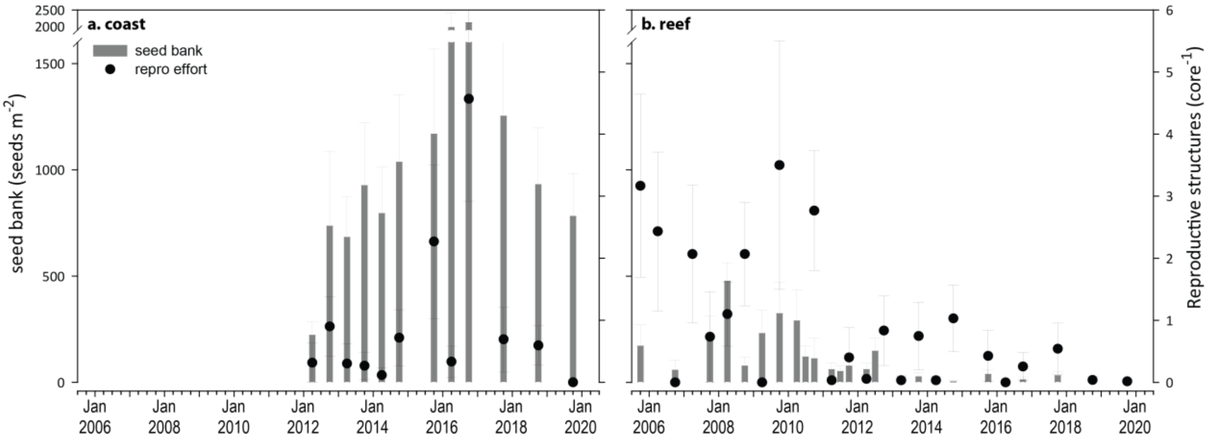


Figure 31. Seed banks and reproductive effort at inshore intertidal coastal (a) and reef (b) habitats in the Cape York region(species and sites pooled). Seed banks (bars, ± SE) presented as the total number of seeds per m^2 sediment surface. Reproductive effort for late dry season (dots, ± SE) presented as the average number of reproductive structures per core.

5.1.3.4 Seagrass leaf tissue nutrients

Seagrass leaf molar C:N ratios in 2019–20 remained similar, on average, to the previous year and within range of those observed since the introduction of additional sites in 2012–13 (Figure 32). However; there was a decline in C:N at Bathurst Bay (coastal intertidal) associated with increased %N, and high riverine discharges in the region in the previous wet season. Leaf N:P ratios were largely unchanged, and remained above guideline and global median values in 2019–20 (Figure 32), indicating that nitrogen remains high in the seagrass habitats of Cape York, but the low and/or negative $\delta^{15}N$ (Figure 32) suggests this is not an anthropogenic source of N. C:P ratios were largely unchanged in 2019–20 compared to the previous three years and remained above guideline values, indicating P limitation.

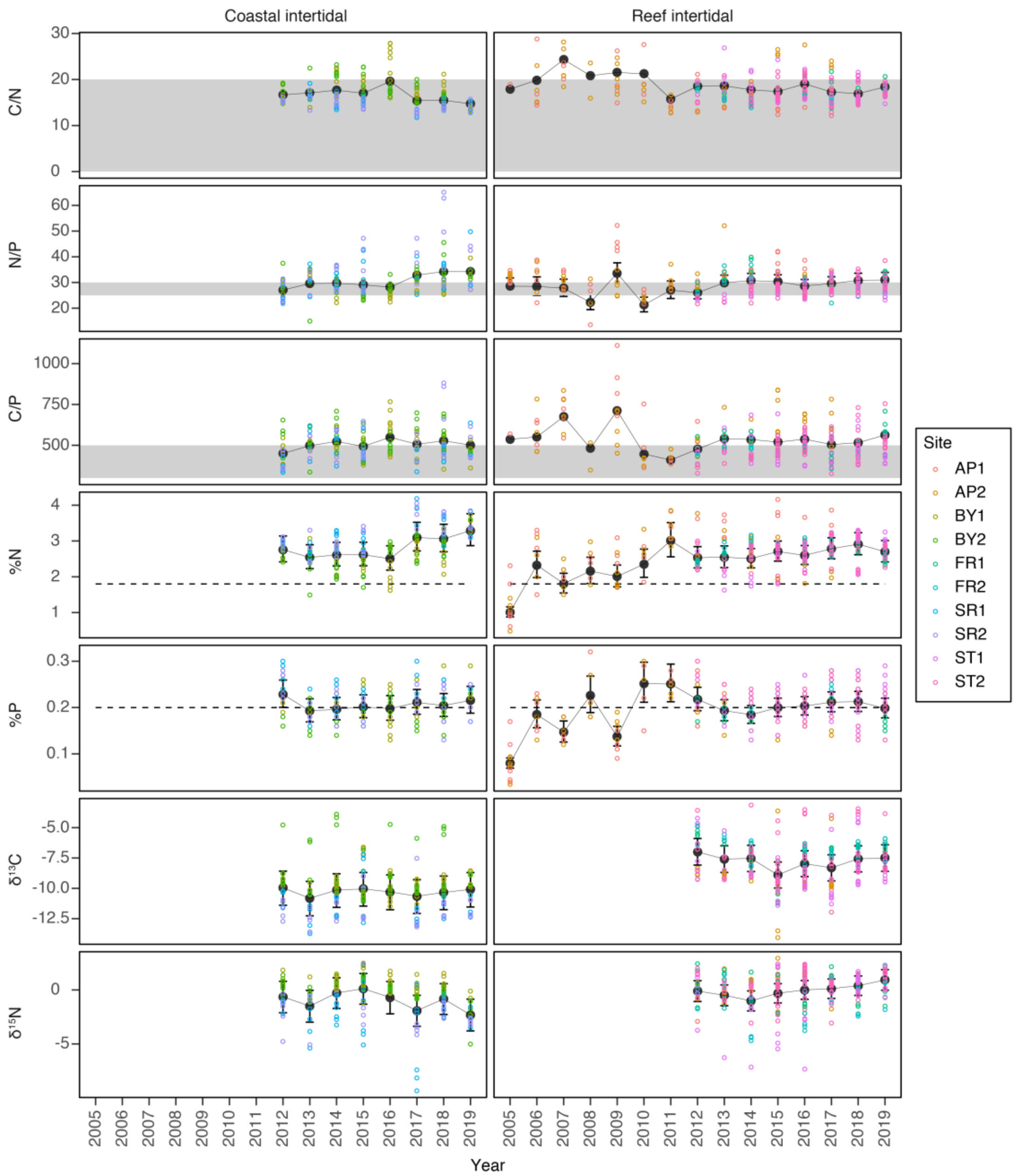


Figure 32. Seagrass leaf tissue nutrient elemental ratios (C:N:P) and concentrations (per cent N, per cent P, $\delta^{13}C$ and $\delta^{15}N$) for each habitat in the Cape York NRM region (± SE) (foundation species pooled). Horizontal shaded bands or dashed lines represent the accepted seagrass guideline values, where: C:N ratios within the band may indicate reduced light availability and/or N enrichment; N:P ratios above the band indicate P limitation, below indicate N limitation and within indicates replete, and; C:P ratios within the band may indicate nutrient rich habitats (large P pool). Dashed lines in per cent N and per cent P indicate global median values of 1.8 per cent and 0.2 per cent for tissue nitrogen and phosphorus, respectively (Duarte 1990).

5.1.3.5 Epiphytes and macroalgae

Epiphyte cover on seagrass leaf blades at intertidal meadows remained below the long-term average at both coastal and reef habitats (Figure 33).

Per cent cover of macroalgae was variable between locations. Macroalgae cover at coastal sites has varied little and this year remained near to the overall inshore Reef long-term average (Figure 33). At intertidal reef habitats, macroalgae cover remained above the Reef long-term average in the central and north of the region for the sixth consecutive year (Figure 33) with macroalgae growing attached to coral rubble in the meadow, and not considered be at nuisance levels. Macroalgae at reef subtidal sites continued to remain below the overall inshore Reef long-term average.

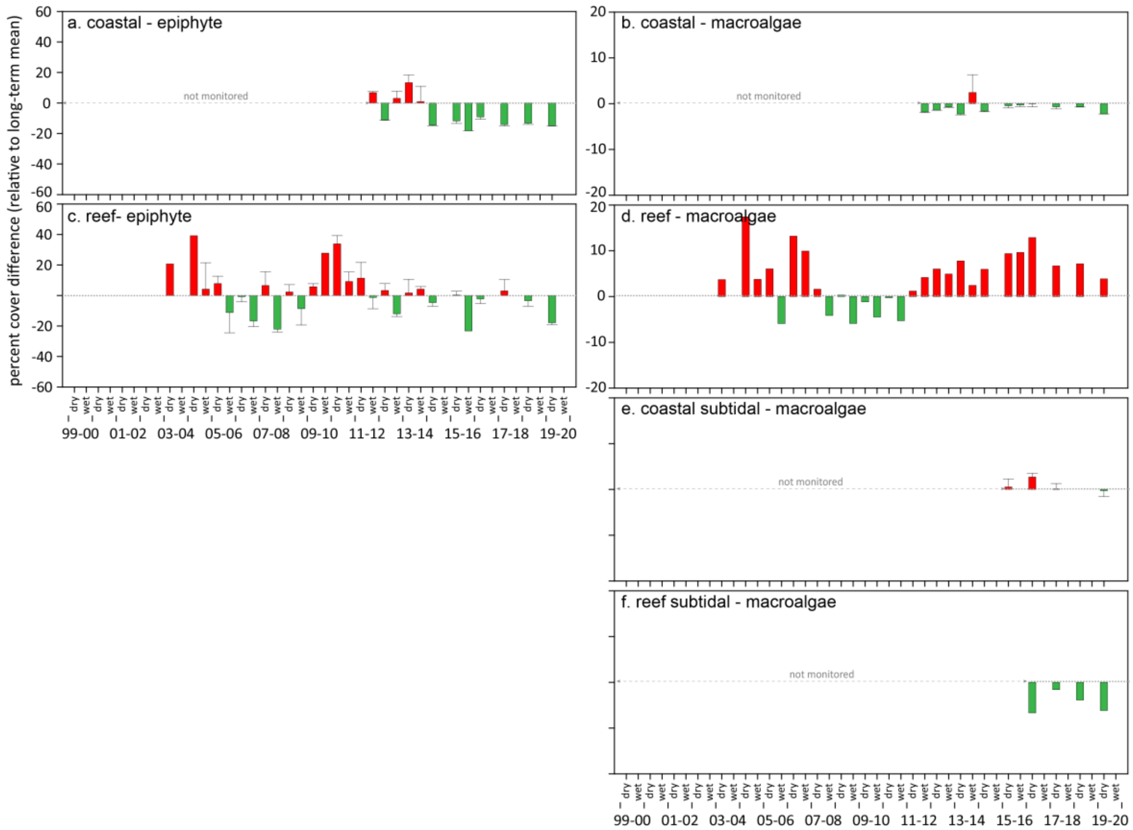


Figure 33. Deviations in mean epiphyte and macroalgae abundance (per cent cover) at monitoring habitats in the Cape York region, relative to the Reef long-term average (sites pooled, ± SE). Green bars indicate positive deviations for condition, red bars negative.

5.2 Wet Tropics

5.2.1 2019–20 Summary

Environmental conditions were relatively benign in 2019–20 in the northern and southern Wet Tropics compared to the long-term average.

Seagrass meadows within the Wet Tropics showed an overall decline in the seagrass condition index in 2019–20, and remain in a vulnerable state, particularly in the southern Wet Tropics region. Seagrass condition in the northern Wet Tropics NRM region decreased to **poor** following on from the highest score ever recorded for the region in 2018–19. By contrast, seagrass condition improved slightly, but remained **poor** in the southern Wet Tropics (Figure 34). The combined regional condition was **poor** (Figure 15).

Contributing indicators in the north were:

- abundance was moderate
- reproductive effort was very poor
- tissue nutrient was poor.

Contributing indicators in the south were:

- abundance was poor
- reproductive effort was poor
- tissue nutrient was poor.

An examination of temporal trends in seagrass abundance across the region shows a high degree of variability reflecting a complex range of environmental and biological processes.

In the northern Wet Tropics sites, seagrass abundance decreased slightly in 2019–20 relative to the previous period because of declining trends at two intertidal reef sites, despite mild conditions across the sub-region.

In the south, seagrass abundance is on an increasing trajectory on average, although the seagrass abundance score decreased slightly in 2019–20. Abundance is low compared to the north, and abundances have significantly declined over the long-term at intertidal sites. The declines are a legacy of losses that occurred from 2009 to 2011, the result of multiple years of above-average rainfall and severe weather. Recovery of seagrass meadows post 2011 has been challenged, particularly in the south, by unstable substrates, chronic poor water quality compared to the north (high turbidity, light limitation) and limited recruitment capacity.

Coastal habitats in the north have maintained a healthy seed bank, and in 2019–20 seed density was the second highest on record. Reproductive effort was low at coast and reef intertidal sites signalling a potential future decline in seeds, but high at reef subtidal sites. In the south, reproductive effort was the third and second highest on record at intertidal and subtidal sites respectively, but sexual reproduction remained absent in coastal habitat. There were no seeds recorded in the south, as is typical for the sub-region. The absence of sexual propagules indicates low resilience is likely a contributor to slow recovery in the sub-region.

Leaf tissue nutrients (C:N) have remained relatively unchanged in the north for a number of years, and suggest an excess of nitrogen relative to photosynthetic C uptake (C:N <20), which is consistent with the high frequency of exposure to secondary water particularly in coastal habitat. Nutrient status therefore remained poor. In the south, the nutrient status indicator increased slightly at reef sites, resulting in the 2019–20 score increasing, but remaining poor.

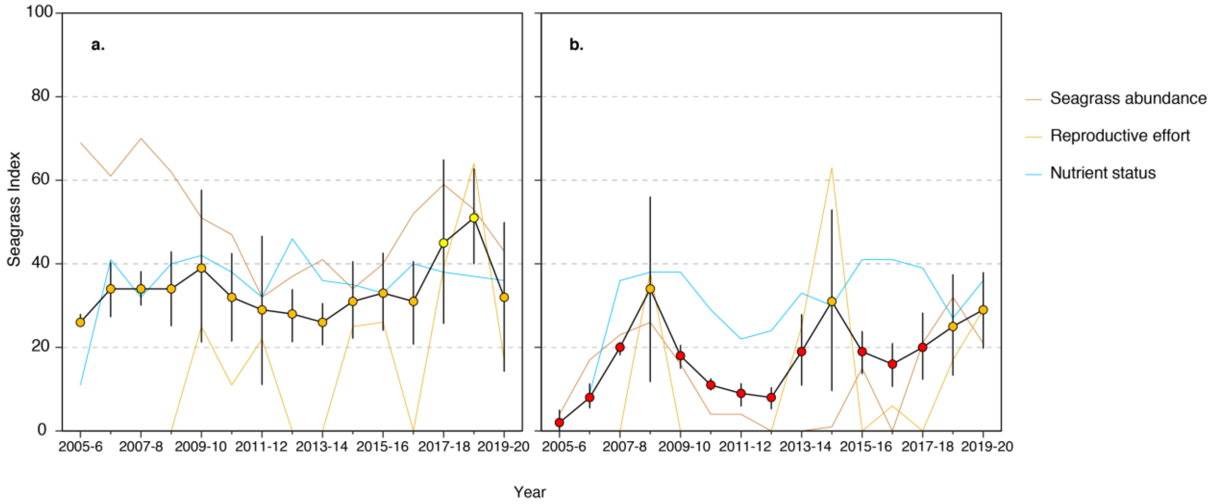


Figure 34. Report card of seagrass index and indicators for the northern (a.) and southern (b.) Wet Tropics NRM region (average across habitats and sites). Values are indexed scores scaled 0–100 (± SE) and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

5.2.2 Climate and environmental pressures

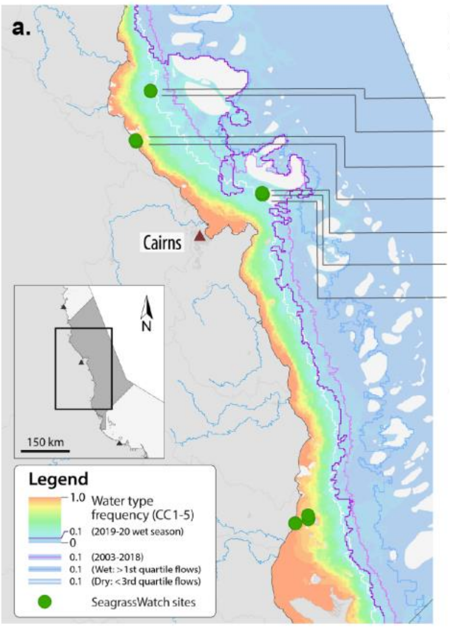
There were no tropical cyclones to affect the Wet Tropics region in 2019–20 (Waterhouse et al. 2021). Annual rainfall and river discharge were lower than average in the northern and southern Wet Tropics in 2019–20 across the region, and lower in each catchment and river entering the sub-regions.

Exposure to primary (‘brown’ sediment laden) or secondary (‘green’, phytoplankton rich) turbid water were around the long-term average across the northern Wet Tropics during 2019–20 (Figure 35). This occurred, despite the lower than average discharge, and lower than average high wind days. Sites were primarily exposed to ‘green’ water (class 5), which allows more light to reach the seagrass habitats than ‘brown’ water (Waterhouse et al. 2021). Despite this, benthic light levels (14.4 mol m^{-2} d^{-1} in 2019–20) were higher than the long-term average in the northern Wet Tropics (12.8 mol m^{-2} d^{-1}) (Figure 35). This increase in the annual average was due to higher peak light levels in late spring, as well as higher than average light levels in the wet season in all habitats. Light levels were also above 10 mol m^{-2} d^{-1} for a greater proportion of the year.

Intertidal within-canopy temperatures in the northern Wet Tropics were at the above the long-term average in intertidal habitats, and below it in subtidal habitats in 2019–20 (Figure 35). Maximum intertidal within-canopy temperatures exceeded 35°C for a total of 54 days during 2019–20, with the highest temperature recorded at 39.6°C (YP2, 3:30pm 08Feb20).

This was the third year since 2016–17 where annual subtidal within-canopy temperatures in the north were below the long-term average and the thrid lowest average annual temperature (26.3°C) since 2008. The maximum subtidal temperature recorded this year was 33.1°C (GI3, midday 08Oct19), which was below temperatures expected to stress seagrass.

Daily tide exposure in the north was below the long-term average for the third consecutive year (Figure 35, Figure 92, Figure 93), which may have provided some respite from the elevated temperatures, particularly in coastal habitats.



b.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
LI2	6	6	6	6	6		6	6	6	6	5	6	6	5	6	5	6	5	6	4	6	5
LI1	6	6	6	6	6		6	6	6	6	5	6	6	5	6	5	6	5	6	4	6	5
YP2	5	4	5	5	5		5	5	4	5	5	5	5	5	5	5	5	4	5	4	5	4
YP1	5	4	5	5	5		5	5	4	5	5	5	5	5	5	4	5	2	5	3	5	4
GI3	7	7	7	5	6	7	6	6	6	6	7	7	6	6	6	5	6	6	6	5	6	5
GI2	7	7	7	5	6	7	6	6	6	6	7	7	6	6	6	5	6	6	6	5	6	5
GI1	7	7	7	5	6	7	6	6	6	6	7	7	6	6	6	5	6	6	6	5	6	5

1-4 = turbid primary water (brown), 5 = nutrient/chlorophyll-enriched secondary water (green), 6 = some freshwater/CDOM influence tertiary water (blue), 7 = no plume influence (white), blank = no data, clouds (grey)

c.

	Long-term average	2019-20
Rainfall (1961-1990)	12.3 mm d^{-1}	7.9 mm d^{-1}
River discharge (1970-2016)	9,859,507 L yr^{-1}	6,214,859 L yr^{-1}
Turbid water exposure (2006-2018)	47%	49%
Daytime tidal exposure (1999-2019)	137 hr yr^{-1}	125 hr yr^{-1}
Wind (1998-2019)	172 days yr^{-1}	144 days yr^{-1}
Within-canopy temperature - intertidal (2003-19)	26.9°C (41.5°C)	26.9°C (39.6°C)
- subtidal (2008-19)	26.8°C (32.3°C)	26.3°C (34.1°C)
Within-canopy light (2008-2019)	12.8 mol m^{-2} d^{1}	14.4 mol m^{-2} d^{1}

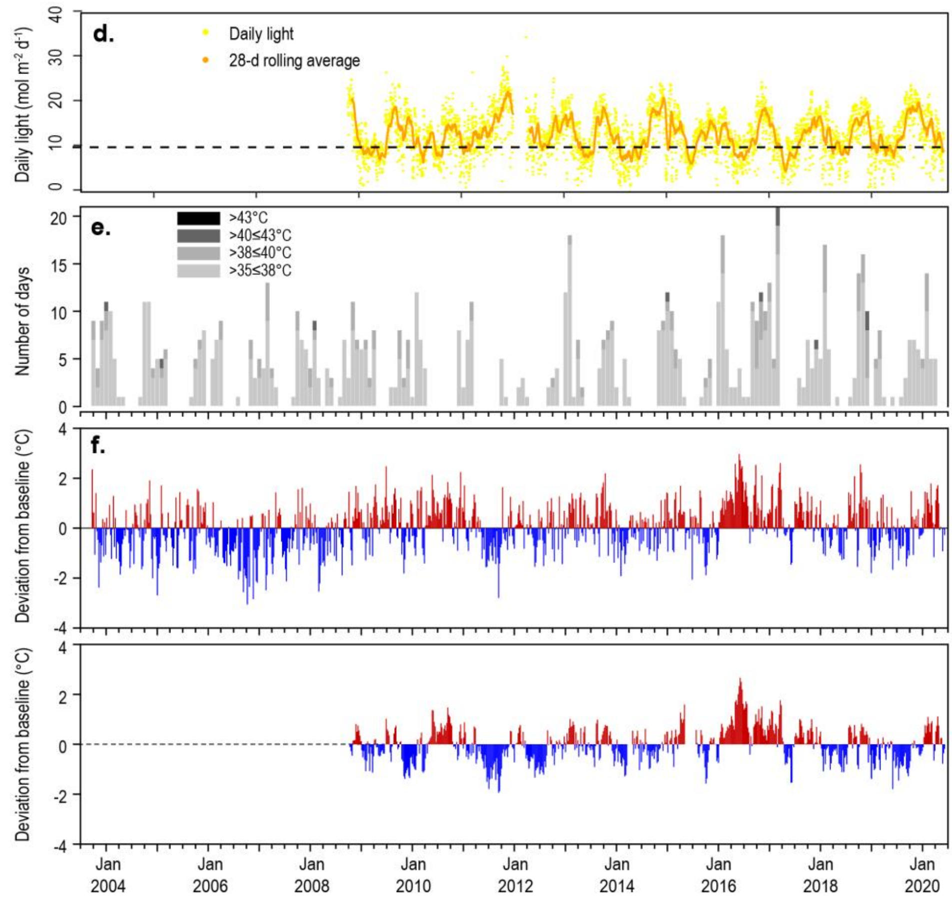


Figure 35. Environmental pressures in the northern Wet Tropics region including: a. frequency of exposure to turbid water (colour classes 1–5) (from Waterhouse et al. 2021); b. wet season water type at each site; c. average conditions over the long-term and in 2019–20; d. daily light and the 28-day rolling mean of daily light for all sites; e. number of days temperature exceeded 35°C, 38°C, 40°C and 43°C; f. intertidal temperature deviations from 13-year mean weekly records, and; g. subtidal temperature deviations from 13-year mean weekly records.

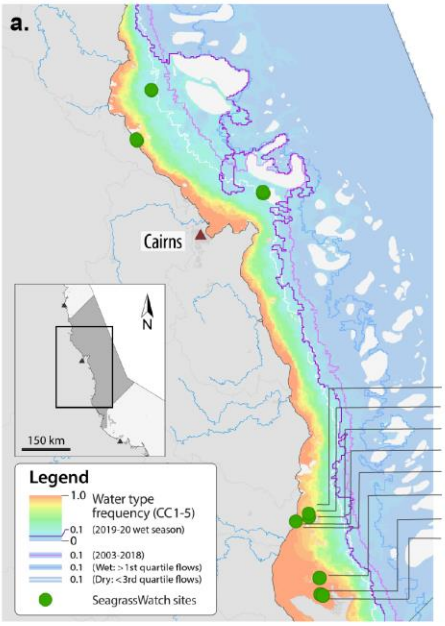
Annual rainfall and river discharge were also lower than average across the southern Wet Tropics during 2019–20. Exposure to 'brown' or 'green' turbid water during the wet season is typically higher in the southern Wet Tropics sites than the northern sites, with a long-term average exposure across the wet season of 99%. The frequency of exposure in 2019–20 was similar to the long-term average with 97% exposure; however, there was less frequent exposure to the 'brown' turbid water (classes 1-4) at the reef sites (Dunk and Goold Island) but more exposure to the 'green' (class 5) waters that allow greater light penetration. Coastal sites at Lugger Bay (LB1 and LB2) and Missionary Bay (MS1 and MS2) experienced the highest exposure to 'brown' turbid water.

Light levels are only measured at Dunk Island in the southern Wet Tropics. At the subtidal site, the annual average (6.85 mol m^{-2} d^{-1}) was similar to the long-term average and was below both acute (6 mol m^{-2} d^{-1}) and long-term light thresholds (10 mol m^{-2} d^{-1}), particularly during the wet season (Figure 36, Figure 101). However, light levels were higher during the wet season than they have been for the past 3 years. At the intertidal sites, light levels were slightly higher than the long-term average.

In the southern Wet Tropics, within-canopy temperatures in 2019–20 were higher than the long-term average for the third year since 2014–15 (Figure 36). Maximum intertidal within-canopy temperatures exceeded 35°C for only three days during 2019–20, with the highest temperature recorded at 35.1°C (DI2, 4pm 19Feb19). The maximum subtidal within-canopy temperature recorded during 2018–19 was 31.5°C (1pm 19Dec18). Daily tide exposure was around the long-term average (Figure 35, Figure 92, Figure 93).

Overall, the inshore seagrass habitats throughout the southern Wet Tropics experienced greater environmental pressures in 2019–20 than those in the northern Wet Tropics, but it remained an average year based on most indicators.

In 2019–20, sediments appeared similar to the long-term and the proportion of fine sediments (i.e. mud) was well below the overall inshore Reef long-term average across all habitats (Figure 108, Figure 109). Across the Wet Tropics region, coastal sediments were composed primarily of fine sand, while reef habitats were composed of sand and coarser sediments (Figure 108, Figure 109). Subtidal reef sediments were predominately sand, which in the southern region often included coarser grains (Figure 110).



b.

	Long-term average	2019-20
Rainfall (1961-1990)	5.0 mm d^{-1}	3.4 mm d^{-1}
River discharge (1970-2016)	7,442,791 L yr^{-1}	3,872,712 L yr^{-1}
Turbid water exposure (2006-2018)	99%	97%
Daytime tidal exposure (1999-2018)	38 hr yr^{-1}	39 hr yr^{-1}
Within-canopy temperature - intertidal (2003-19)	26.9°C (43.5°C)	27.4°C (35.2°C)
- subtidal (2008-19)	25.8°C (35.7°C)	25.9°C (33.2°C)
Within-canopy light (2008-2019)	11.2 mol m^{-2} d^{1}	11.7 mol m^{-2} d^{1}

c.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
DI3	5	5	5	5	5	5	5	5	6	5	5	5	5	4	5	5	5	5	5	5	5	5
DI1	5	5	5	5	5	5	5	5	6	5	5	5	5	4	5	5	5	5	5	5	5	5
DI2	5	5	5	5	5	5	5	5	6	5	5	5	5	4	5	5	5	5	5	5	5	5
LB1	4	4	5	4	5	5	5	5	5	4	5	5	4	4	5	4	4	4	4	5	4	2
LB2	4	4	5	4	5	5	5	5	5	4	5	5	4	4	5	4	4	4	4	5	4	2
GO1	5	5	5	5	5	5	5	5		5	5	5	5	4	5	5	5	5	5	5	5	5
MS2	4	5	5	5	5	5	5	5		4	4	5	5	4	5	4	5	4	4	4	4	5
MS1	4	4	5	5	5	5	4	5		4	4	5	5	1	5	4	5	4	4	5	4	5

1-4 = turbid primary water (brown), 5 = nutrient/chlorophyll-enriched secondary water (green), 6 = some freshwater/CDOM influence tertiary water (blue), 7 = no plume influence (white), blank = no data, clouds (grey)

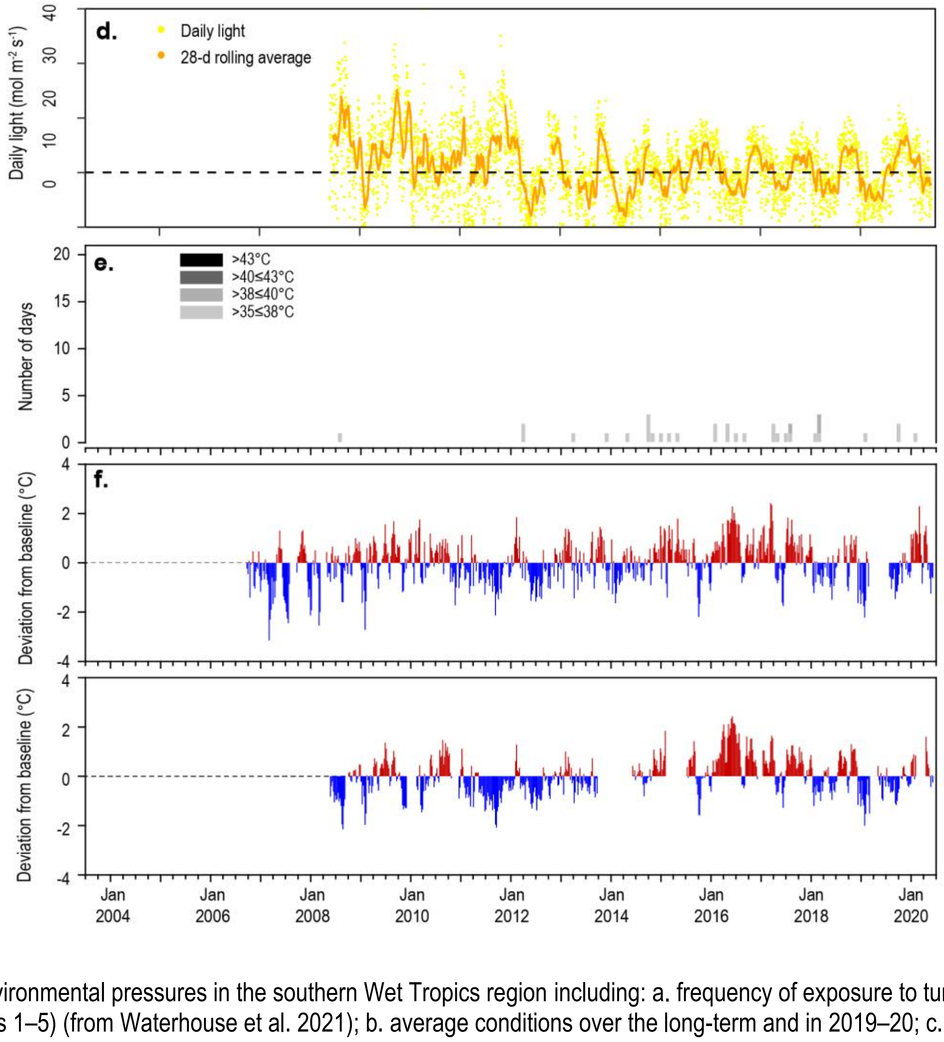


Figure 36. Environmental pressures in the southern Wet Tropics region including: a. frequency of exposure to turbid water (colour classes 1–5) (from Waterhouse et al. 2021); b. average conditions over the long-term and in 2019–20; c. wet season water type at each site; d. daily light and the 28-day rolling mean of daily light for all sites; e. number of days temperature exceeded 35°C, 38°C, 40°C and 43°C; f. intertidal temperature deviations from 13-year mean weekly records, and; g. subtidal temperature deviations from 13-year mean weekly records.

5.2.3 Inshore seagrass and habitat condition

Three seagrass habitat types were assessed across the Wet Tropics region with data from 12 sites (Table 13).

Table 13. List of data sources of seagrass and environmental condition indicators for each seagrass habitat type in the Wet Tropics NRM region.Open square indicates not measured in 2019–20. † drop camera sampling (RJFMP), *Seagrass-Watch. For site details see Table 3 and Table 4.

Sub region	Habitat	Site		abundance	composition	distribution	Reproductive effort	seed banks	Leaf tissue nutrients	Meadow sediments	Epiphytes	Macroalgae
north	coastal intertidal	YP1	Yule Point	■	■	■	■	■	■	■	■	■
		YP2	Yule Point	■	■	■	■	■	■	■	■	■
	reef intertidal	LI1	Low Isles	■	■	■	■	■	■	■	■	■
		GI1	Green Island	■	■	■	■	■	■	■	■	■
		GI2	Green Island	■	■	■	■	■	■	■	■	■
	reef subtidal	LI2	Low Isles	■	■	■	■	■	■	■	■	■
		GI3	Green Island	■	■	■	■	■	■	■	■	■
south	coastal intertidal	LB1	Lugger Bay	■	■	■	■	■	■	■	■	■
		LB2	Lugger Bay	■	■	■	■	■	■	■	■	■
	coastal subtidal	MS1†	Missionary Bay	■	■							■
		MS2†	Missionary Bay	■	■							■
	reef intertidal	DI1	Dunk Island	■	■	■	■	■	■	■	■	■
		DI2	Dunk Island	■	■	■	■	■	■	■	■	■
		GO1*	Goold Island	□	□			□		□	□	□
	reef subtidal	DI3	Dunk Island	■	■	■	■	■	■	■	■	■

Seagrass index and indicator scores

In the 2019–20 monitoring period, the seagrass condition index for the overall Wet Tropics region declined, but remained poor (Figure 15). The decrease was due to two indicators — abundance and reproductive effort — decreasing from moderate to poor. Both indicators had increased in the previous 2018–19 reporting period. Examination of the sub-regional scores highlights the differences between seagrass condition in the north and south of the Wet Tropics (Figure 34).

In the northern Wet Tropics, the seagrass condition index dropped to a poor rating in 2019–20 following the highest score (in 2018–19) since reporting was established (Figure 37). Similar to the overall NRM regional grade, the decline was primarily due to reduced reproductive effort and reduced abundance scores.

The seagrass abundance score has progressively declined since 2017–18, but remains graded as moderate in 2019–20 (Figure 37). The long-term trend in seagrass per cent cover is variable between monitoring locations (Table 21), but closely reflects the sub-regional scores with improved cover from 2014–15.

Reproductive effort has fluctuated the most of the three condition indicators, and in 2019–20 was rated very poor, after reaching the highest score since monitoring was established in 2018–19 (Figure 37). Due to the variable nature of sexual reproduction in seagrass systems, no long term trends are apparent.

In contrast, seagrass leaf nutrient (C:N) status has varied the least of all indicators, and although declined marginally in 2019–20, has remained in a poor grade (Figure 37).

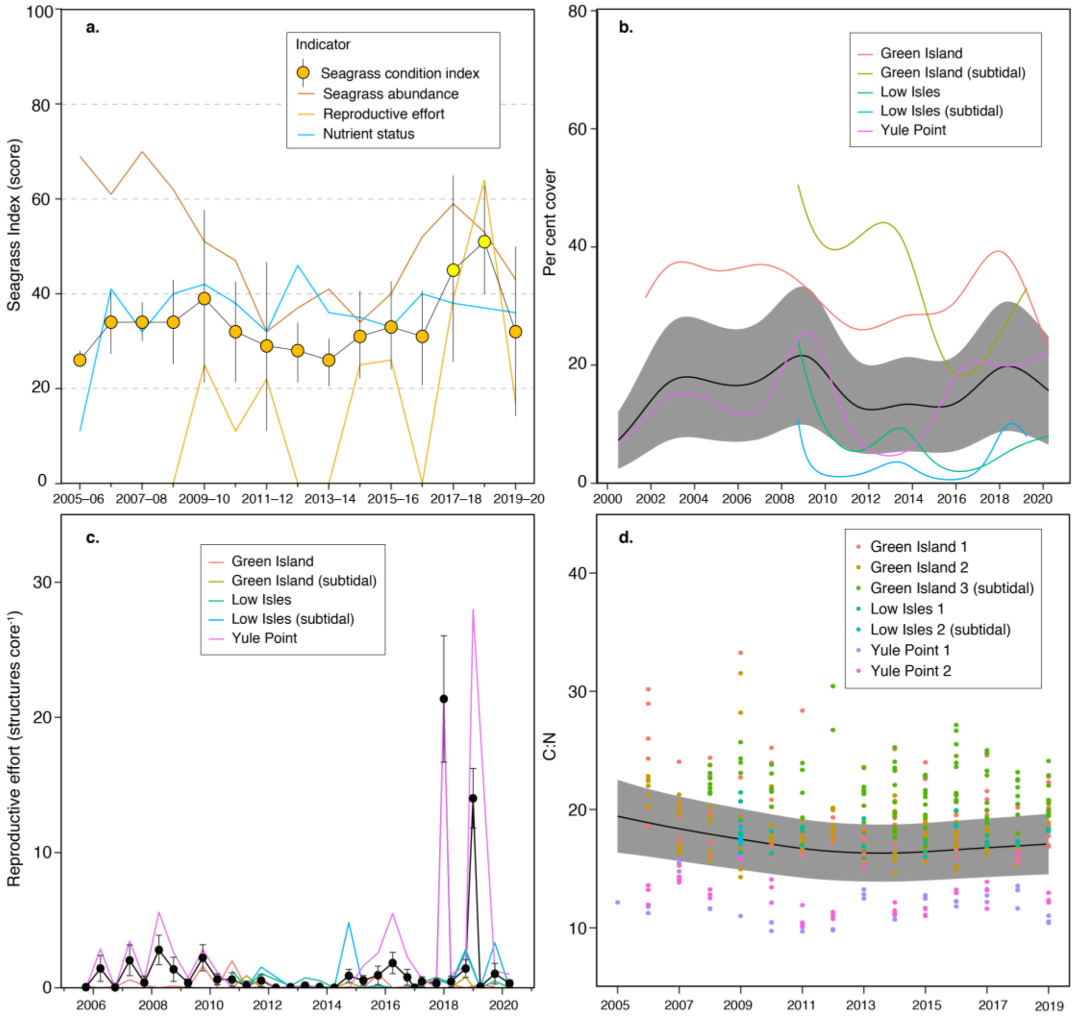


Figure 37. Temporal trends in the northern Wet Tropics seagrass condition index and the indicators used to calculate the index: a. seagrass condition index (circles, ± SE) and indicator trends (lines); b. GAM plots of seagrass abundance (per cent cover) trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); c. average number of reproductive structures (±SE) (GAM not possible due to high count of zero values); and d. elemental ratios (atomic) of leaf tissue C:N nutrient content at each site (coloured circles) and regional trend represented by a GAM plot as dark line with shaded areas defining 95 per cent confidence intervals of the trend.

In the southern Wet Tropics, the seagrass condition index improved slightly, but remained poor in 2019–20; a consequence of improved abundance, but primarily due to improved reproductive effort scores (Figure 38).

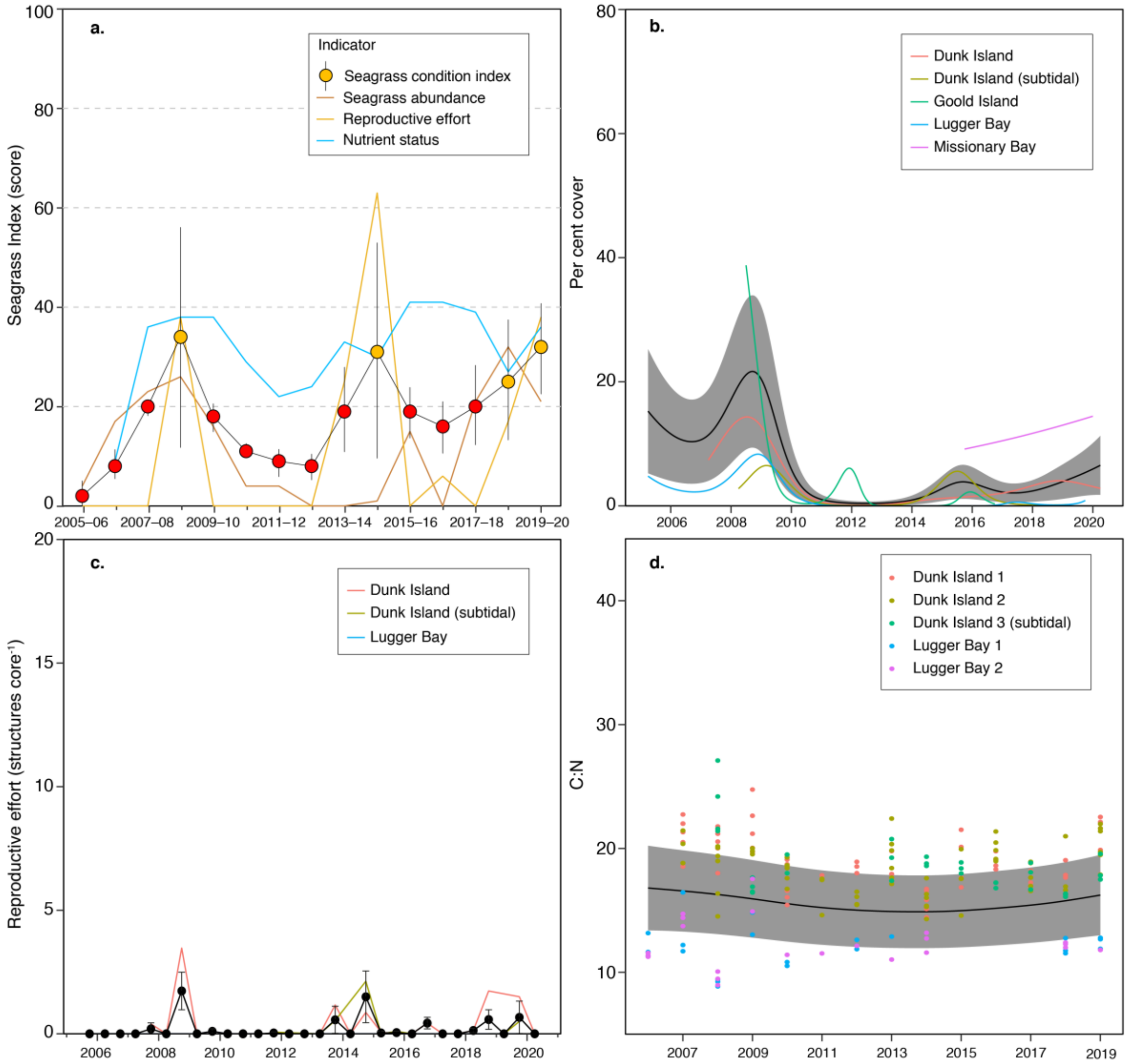


Figure 38. Temporal trends in the southern Wet Tropics seagrass condition index and the indicators used to calculate the index: a. seagrass condition index (circles, ± SE) and indicator trends (lines); b. GAM plots of seagrass abundance (per cent cover) trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); c. average number of reproductive structures (±SE) (GAM not possible due to high count of zero values); and d. elemental ratios (atomic) of leaf tissue C:N nutrient content at each site (coloured circles) and regional trend represented by a GAM plot as dark line with shaded areas defining 95 per cent confidence intervals of the trend.

5.2.3.1 Seagrass abundance, community and extent

Seagrass meadows are more abundant (higher per cent cover) across all habitats in the northern than the southern Wet Tropics (Figure 39, Figure 40). In the northern Wet Tropics, seagrass abundance over the long-term is higher at intertidal reef (28.3 ±2.1 per cent) than subtidal reef (17.1 ±2.4 per cent) or coastal habitats (14.8 ±1.6 per cent). In 2019–20, although seagrass abundances remained steady at 4 of the 7 sites assessed, with the increase in abundance observed at only one site, offset by declines experienced at the remaining sites, resulting in a decrease in abundance overall.

Although seagrass losses have occurred at the local level (e.g. individual sites) for some period over the duration of the monitoring, complete loss has not occurred at the habitat level. Nevertheless, abundance has fluctuated between and within years. For example, seagrass cover at coastal habitats differs between seasons (9.5 ±1.3 per cent in the dry and 19.8 ±2.1 per cent in the late dry-monsoon) and years (from 3.9 per cent to 24.9 per cent annual average).

In the southern Wet Tropics, although long-term seagrass abundance is similarly higher at intertidal reef (4.5 ±1.0 per cent) than subtidal reef (1.9 ±0.8 per cent) or coastal habitats (1.8 ±0.6 per cent), the abundances are only a tenth of those observed in the north. This is a consequence of periods of complete loss occurring at all habitats for at least 3-6 months since early 2011. At coastal habitats in Lugger Bay, complete loss was sustained for periods of years. Although recovery is very slow, isolated seagrass shoots appeared at Lugger Bay sites in 2016–17, and by 2018–19 small patches had established which have changed little in the following 12 months. Abundances similarly improved at the reef intertidal habitats, but remain well below historical levels.

An examination of temporal trends in seagrass abundance across the Wet Tropics NRM region show no significant trend over the long-term i.e. from the first year of monitoring to 2020 (Table 21). In the northern Wet Tropics, changes in seagrass abundance were variable among habitats, with 2 of the 7 of sites significantly declining over the long-term, while no trend was apparent for the remaining sites. The declines in the north are all in reef habitats, at both intertidal and subtidal sites. In the southern sub-region, 2 of the 8 sites have significantly declined over the long-term, but these only occurred at the coastal intertidal sites (Lugger Bay). No long-term trend was apparent in the reef habitats of the southern sub-region.

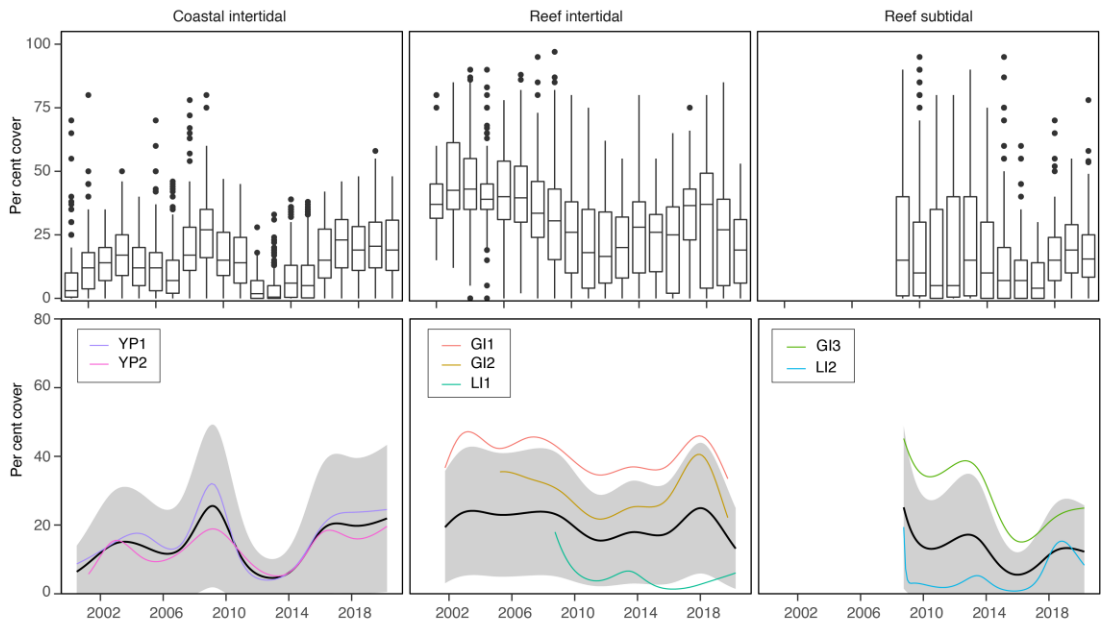


Figure 39. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the northern Wet Tropics NRM region from 2001 to 2020. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero 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, and the dots represent outlying points. GAMM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

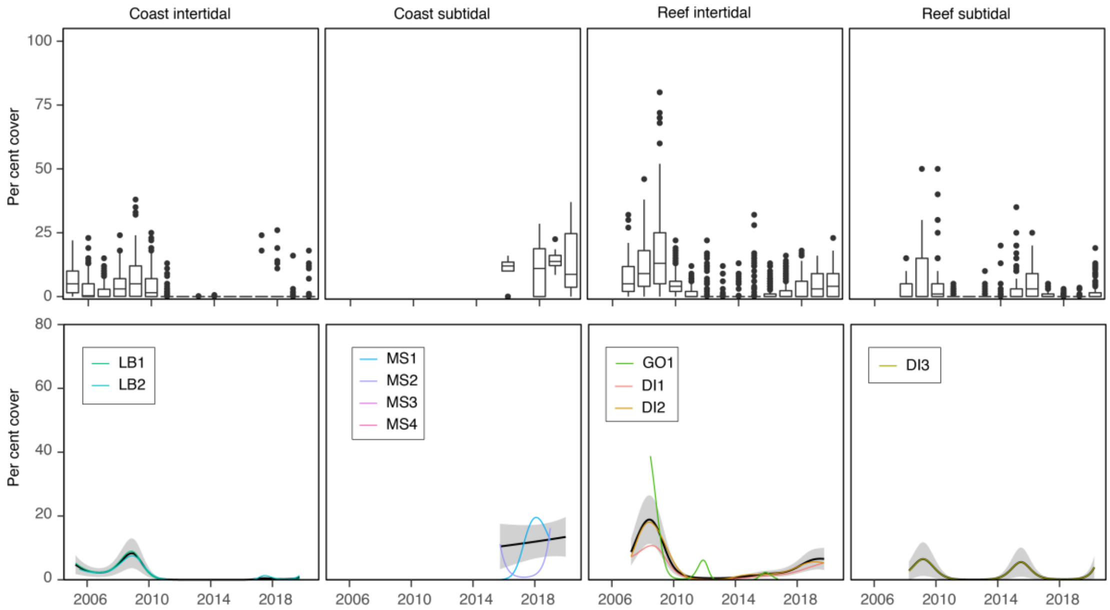


Figure 40. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the southern Wet Tropics NRM region from 2001 to 2020. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero 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, and the dots represent outlying points. GAMM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

The proportion of seagrass species displaying colonising traits varied across habitats in the northern Wet Tropics (Figure 41). In 2019–20 the proportion was unchanged at coastal intertidal habitats (Yule Point), suggesting some recovery and reduced physical disturbance. On reefs, colonising species increased slightly in intertidal habitat and was above the overall inshore Reef average. In reef subtidal habitats, the proportion of colonising species remained high in the reporting year.

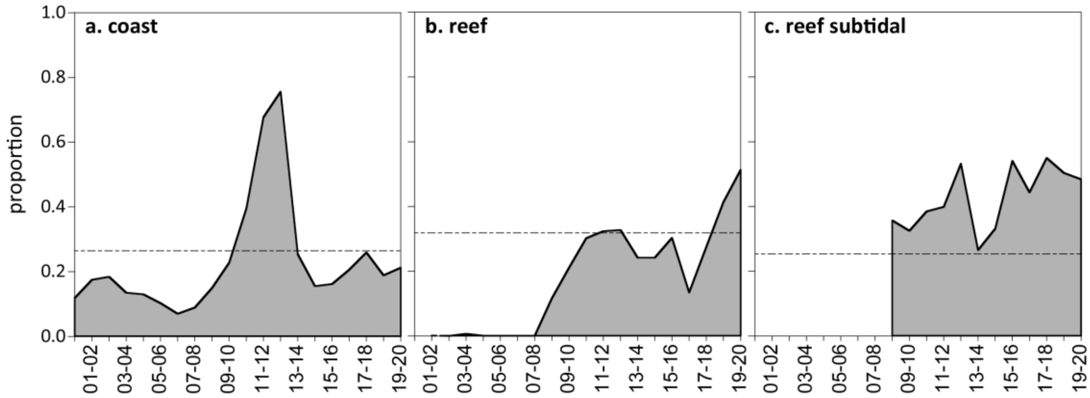


Figure 41. Proportion of seagrass abundance composed of colonising species at inshore habitats in the northern Wet Tropics region, from the 2000–2001 to the 2019–20 reporting periods. The dashed line represents the overall inshore Reef average for each habitat type.

In the southern Wet Tropics, the proportion of seagrass species displaying colonising traits varied across habitats (Figure 42). In the coastal intertidal habitat there have been cycles of changing species composition since the substrate at Lugger Bay was eroded in 2011 (caused by TC Yasi). Opportunistic species appear unable to establish enduring meadows, potentially due to light limitation associated with deepening of the habitat. Colonising species become dominant following periodic decline of other species in what appears to be recalcitrant degradation. In 2019–20, the proportion of seagrass species displaying colonising traits decreased to zero at coastal intertidal habitats but based on recent historical change, is not expected to last. Colonising species remained in low proportions in all other habitats; a promising sign of recovering trajectories.

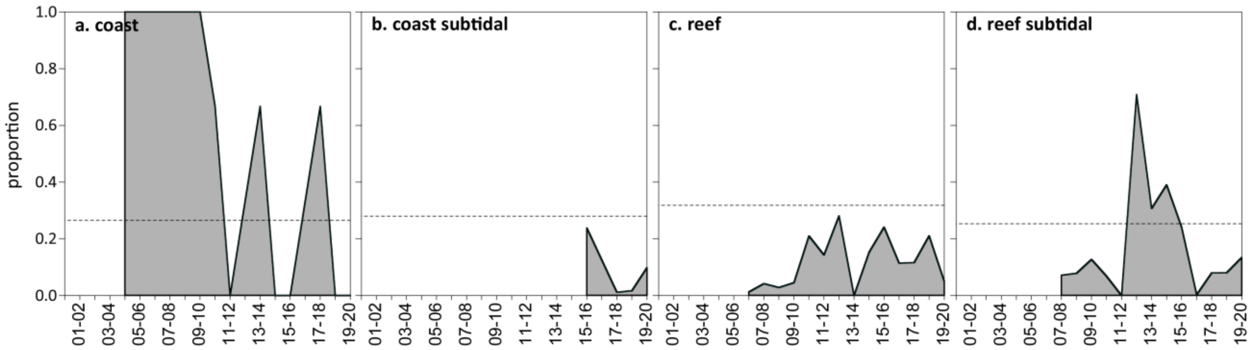


Figure 42. Proportion of seagrass abundance composed of colonising species at inshore habitats in the southern Wet Tropics region, from the 2000–2001 to the 2019–20 reporting periods. The dashed line represents the Overall inshore Reef average for each habitat type.

Seagrass meadow spatial extent within all monitoring sites has fluctuated within and between years (Figure 43). At intertidal coastal habitats in the northern Wet Tropics, meadow extent has gradually improved since 2011 and was only slightly lower than the previous highest extent. Subtidal reef meadows in the north are quite variable over seasonal and inter-annual time-scales but had peaked in extent in 2015 than earlier years. The last two reporting years have seen large variability.

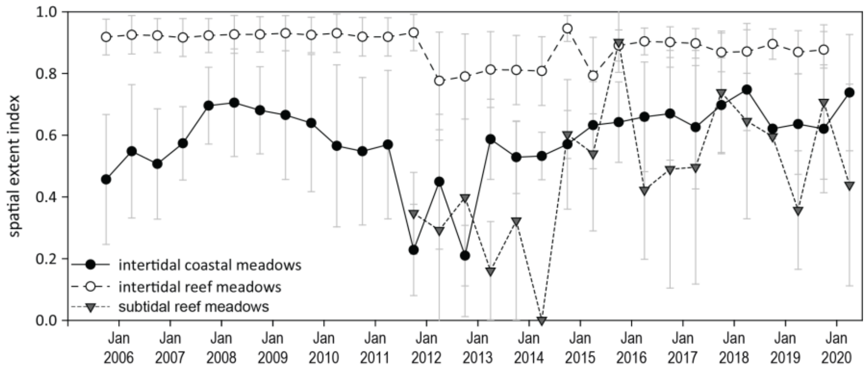


Figure 43. Change in relative spatial extent (±SE) of seagrass meadows within monitoring sites for each habitat and monitoring period across the northern Wet Tropics NRM region.

In the southern Wet Tropics, all seagrass meadows were lost in early 2011 as a consequence of cyclone Yasi (Figure 44). Since then, intertidal reef meadows have progressively improved, with the greatest extent since 2011 measured in 2019–20. At intertidal coastal habitats, the meadows have not improved greatly, but a few isolated patches which colonised in mid-2018 appear to have established. The greatest fluctuation in extent has occurred in subtidal reef meadows, which established in 2014, but after rapidly expanding have sharply declined. In 2018–19, only a few small isolated patches of seagrass remained of the subtidal reef meadows.

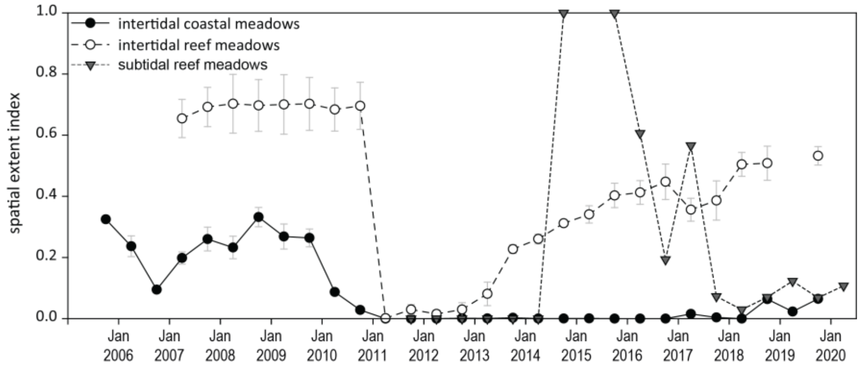


Figure 44. Change in relative spatial extent (±SE) of seagrass meadows within monitoring sites for each habitat and monitoring period across the southern Wet Tropics NRM region.

5.2.3.2 Seagrass reproductive status

Reproductive effort varies across habitats in the Wet Tropics, and is generally higher in the northern sub-region than the south. In general, reproductive effort and seed density have been buoyed in the Wet Tropics in recent years, though with some variability among habitats and regions. In the northern Wet Tropics, reproductive effort declined sharply after it peaked during 2018–19 in coastal intertidal habitats (Yule Point) (Figure 45). Reproductive effort was depressed in reef intertidal habitats, but increased to the third highest level on record in reef subtidal habitats. Seed density was the second highest on record at coastal intertidal habitats, likely a consequence of high reproductive effort in the previous year. To date, seed banks have remained very low across the region in reef habitat (Figure 45). Some possible explanations for the low seed bank include failure to set seed, particularly in low density dioecious species (Shelton 2008), or rapid loss of seeds after release from germination or grazing (Heck and Orth 2006).

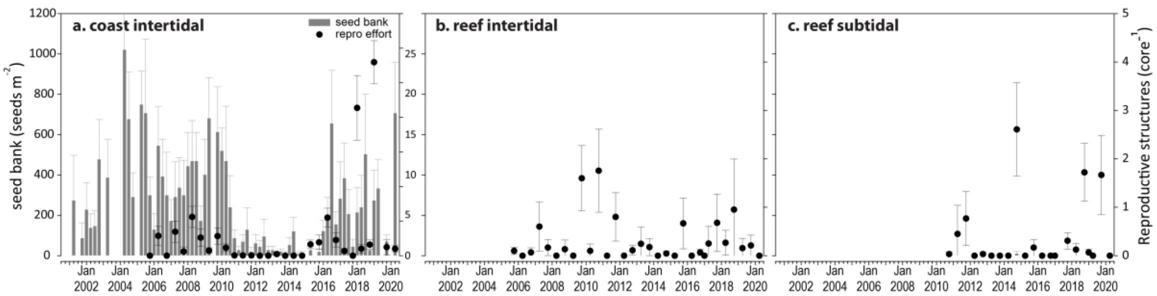


Figure 45. Reproductive effort and seed banks for inshore intertidal coast and reef habitats in the northern Wet Tropics region, 2001–2020.Seed banks presented as the total number of seeds per m^2 sediment surface (bars ±SE), and reproductive effort presented as the average number of reproductive structures per core (species and sites pooled) (dots ±SE).

In the southern Wet Tropics, sexually reproductive structures and seed banks were absent from seagrass in the coastal intertidal but occurred at third and second highest levels in reef intertidal and subtidal habitats (Figure 46). The absence of reproductive structures and seed banks may render the seagrass at risk from further disturbances, as recovery potential remains extremely low without a seed bank. However, two years of high reproductive effort recorded in reef intertidal habitats occurred in conjunction with small increases in abundance and extent and, together, indicate recovering habitats (Figure 46).

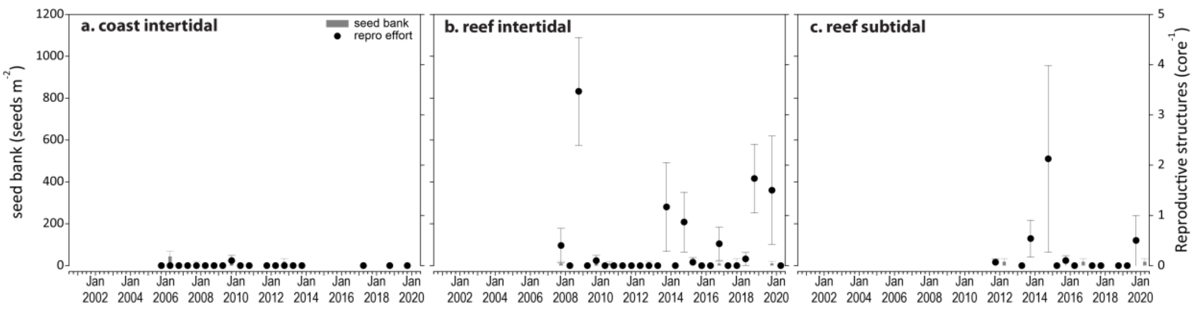


Figure 46. Reproductive effort and seed banks for inshore intertidal coast and reef habitats in the southern Wet Tropics region, 2001–20.Seed banks presented as the total number of seeds per m² sediment surface (bars ±SE), and reproductive effort presented as the average number of reproductive structures per core (species and sites pooled) (dots ±SE).

5.2.3.3 Seagrass leaf tissue nutrients

Seagrass leaf tissue molar C:N ratios of the foundation seagrass species (in the late dry season 2019) have remained relatively stable across the northern Wet Tropics over the last few years (Figure 47). However, at intertidal coastal habitats, C:N declined to levels similar to 2010–11 when extreme weather events, low light levels and elevated nutrients drove down C:N. These affect C:N because nitrogen loads are in excess of growth requirements. Record %N and N:P in leaves from the coastal habitats in 2019–20 indicate that the depressed C:N was due to nitrogen availability, while stable $\delta^{13}C$ indicate that light limitation did not cause a reduction in photosynthetic C incorporation. In the 2019–20 wet season conditions were benign, however, C:N is measured in the late dry season (around September or October), and is therefore responsive to conditions in the previous wet season. In the wet season of 2018–19, rainfall and river discharge were above average in the northern Wet Tropics. Reef habitats maintain a C:N around the guideline value (20), and appear to have been less affected by conditions in the previous season based on C:N ratios. However, in reef subtidal habitats, there was an increase in phosphorus (%P) to the second highest level, reflected in a decline in N:P and C:P. $\delta^{15}N$ values decreased at coastal habitats and increased in reef habitats, but the changes were small and suggest ongoing multiple sources of nitrogen, possibly including some anthropogenic point sources (Figure 47).

In the southern Wet Tropics, C:N ratios of the foundation seagrass species increased at reef intertidal and subtidal sites and exceeded the guideline value (20) at intertidal sites for only the third time since measurement began in 2006 (Figure 48). This appears to have been caused by a decline in nitrogen content (as %N). This occurred despite rainfall and river discharge in the southern Wet Tropics also being above average in the previous wet season (2018–19). At the coastal sites, C:N values were similar to historical values for the habitat type and unchanged from the previous year. C:N was well below guideline values, indictaing the seagrass at the sites are nitrogen replete, which is a persistent feature of the habitat type in the southern Wet Tropics. Also, lower $\delta^{13}C$ sugests some degree of light limitation, in coastal habitats and reef subtidal habitat (Figure 49). The range $\delta^{15}N$ values below 4 across all habitats suggests multiple sources of nitrogen, possibly including some anthropogenic point sources (Figure 48). However, there is currently no indication or concern that anthropogenic point sources are strongly influencing seagrass N supply overall.

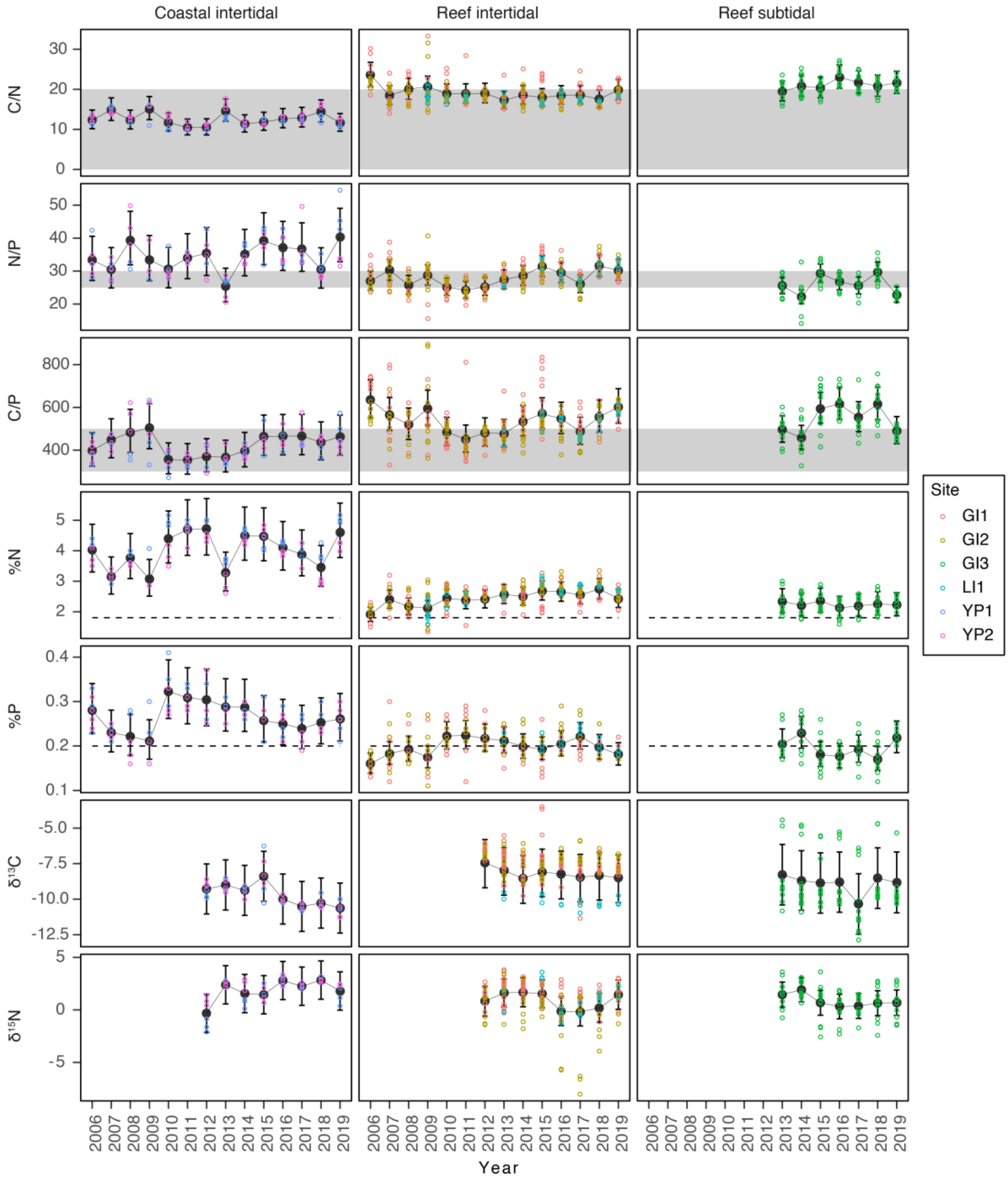


Figure 47. Seagrass leaf tissue nutrient elemental ratios (C:N:P) and concentrations (per cent N, per cent P, $\delta^{13}C$ and $\delta^{15}N$) for each habitat in the northern Wet Tropics region (± SE) (foundation species pooled). Horizontal shaded bands or dashed lines represents the accepted seagrass guideline values, where: C:N ratios within the band may indicate reduced light availability and/or N enrichment; N:P ratios above the band indicate P limitation, below indicate N limitation and within indicates replete, and; C:P ratios within the band may indicate nutrient rich habitats (large P pool). Dashed lines in per cent N and per cent P indicate global median values of 1.8 per cent and 0.2 per cent for tissue nitrogen and phosphorus, respectively (Duarte 1990).

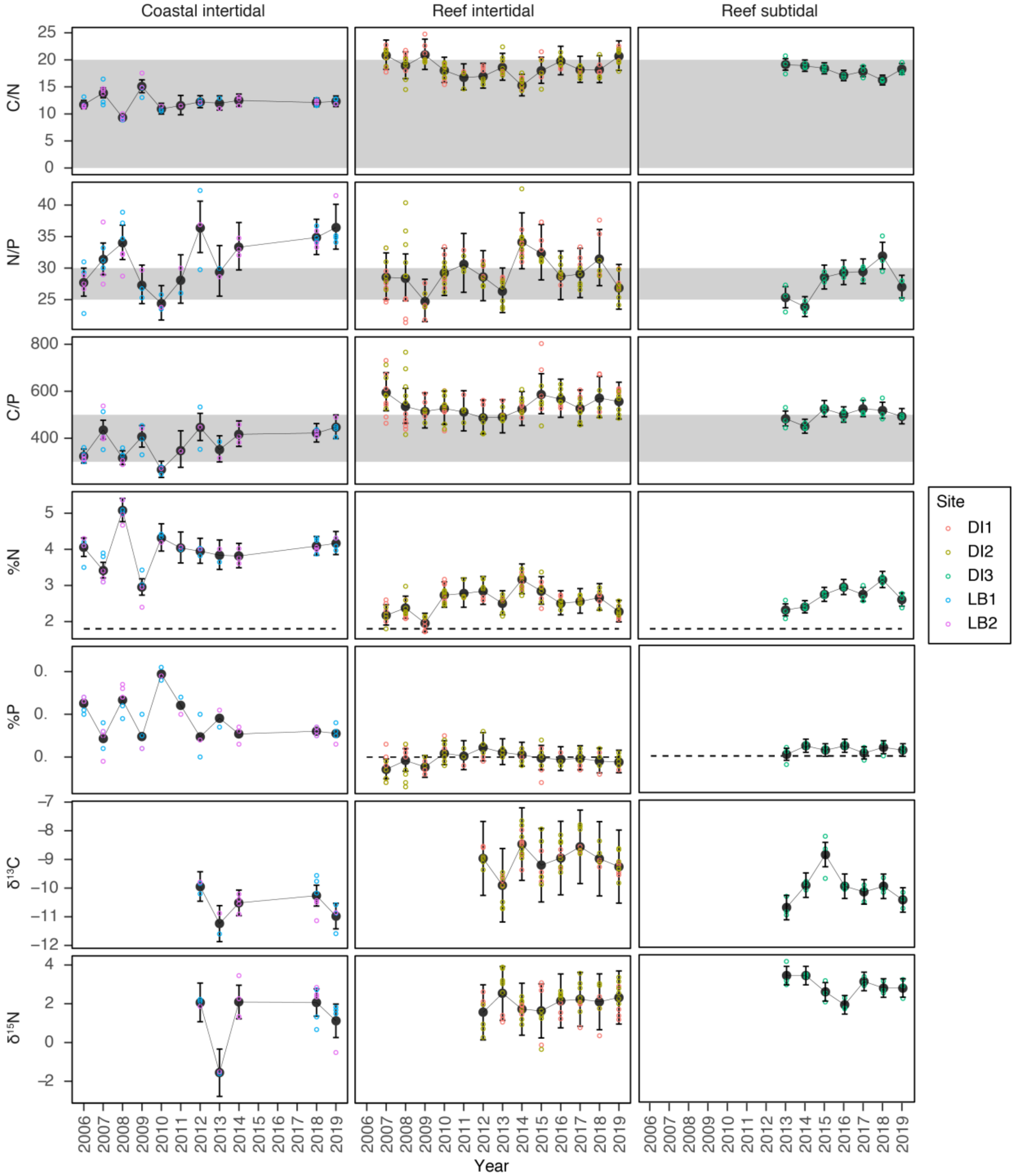


Figure 48. Seagrass leaf tissue nutrient elemental ratios (C:N:P) and concentrations (per cent N, per cent P, $\delta^{13}C$ and $\delta^{15}N$) for each habitat in the southern Wet Tropics region (± SE) (foundation species pooled). Horizontal shaded bands or dashed lines represents the accepted seagrass guideline values, where: C:N ratios within the band may indicate reduced light availability and/or N enrichment; N:P ratios above the band indicate P limitation, below indicate N limitation and within indicates replete, and; C:P ratios within the band may indicate nutrient rich habitats (large P pool). Dashed lines in per cent N and per cent P indicate global median values of 1.8 per cent and 0.2 per cent for tissue nitrogen and phosphorus, respectively (Duarte 1990).

5.2.3.4 *Epiphytes and macroalgae*

Epiphyte cover remained above the overall inshore Reef long-term average across in the wet season in all habitats in the northern Wet Tropics in 2019–20 (Figure 49), but below average in reef habitats during the dry season.

Macroalgae cover was lower than the Reef long-term average in coastal habitat and reef subtidal habitats in both the wet and dry season (Figure 49). Macroalgae cover was higher than the Reef long-term average in reef intertidal habitats, as is typical for the habitat because it attaches to coral rubble.

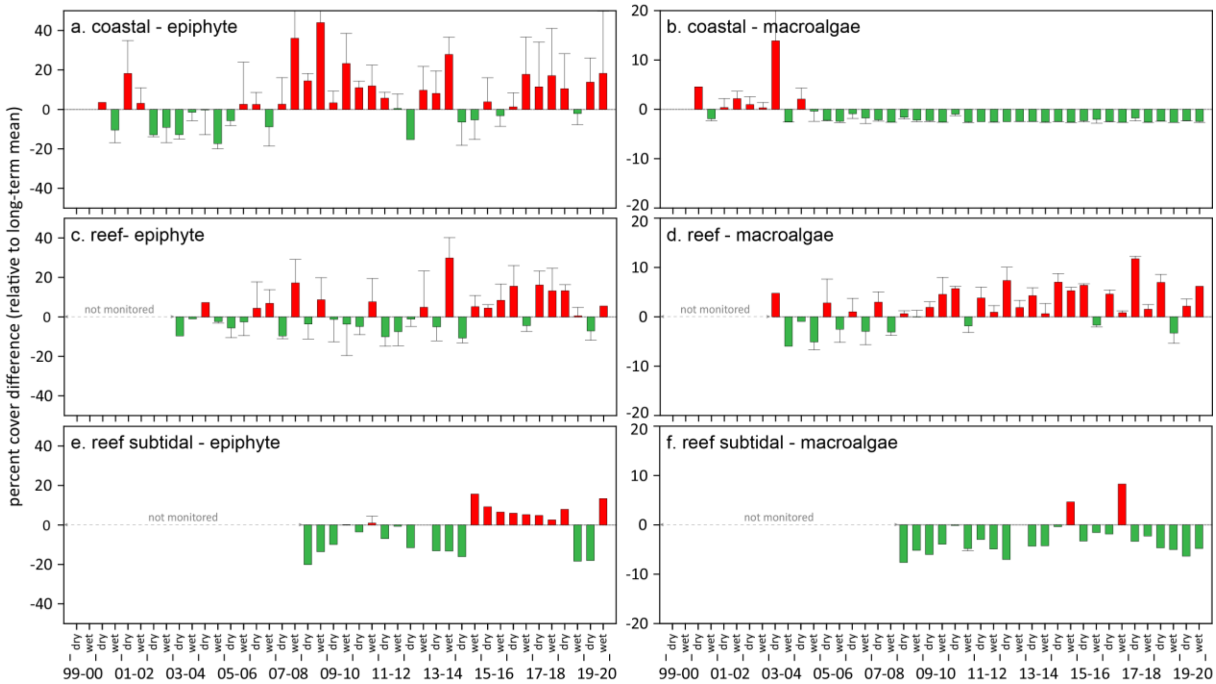


Figure 49. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term average for each inshore seagrass habitat in the northern Wet Tropics region, 2001–2020 (sites pooled, ±SE). Green bars indicate positive deviations for condition, red bars negative.

In the southern Wet Tropics, epiphyte cover in 2019–20 was around or below the Reef long-term average in the wet and dry seasons (Figure 49).

Macroalgae cover continued to remain around or below the Reef long-term average in all habitats of the southern Wet Tropics. Macroalgae cover remained near absent at coastal habitats, where a lack of consolidated substrate for attachment and elevated turbidity could prevent establishement.

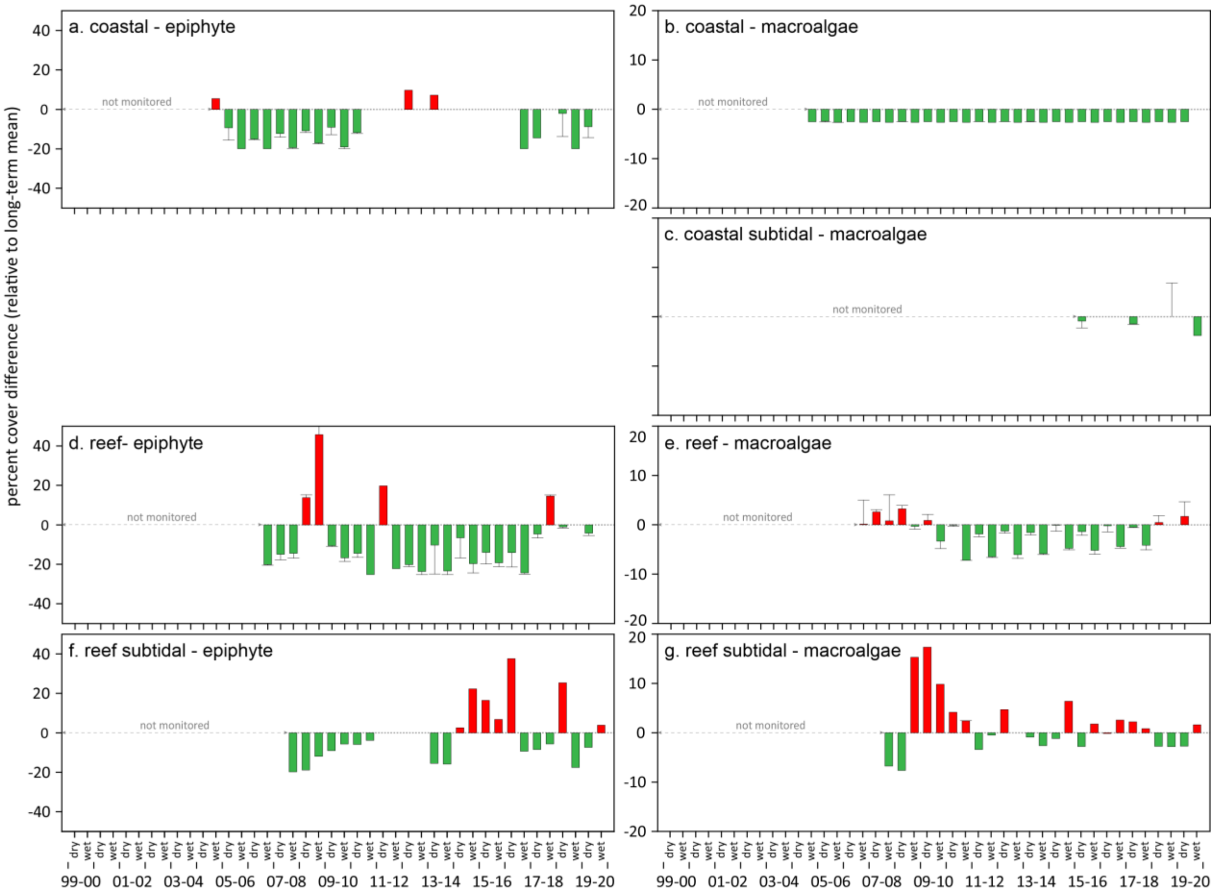


Figure 50. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term average for each inshore seagrass habitat in the southern Wet Tropics region, 2001–2020 (sites pooled, ±SE). Green bars indicate positive deviations for condition, red bars negative.

5.3 Burdekin

5.3.1 2019–20 Summary

In 2019–20, rainfall and river discharge were below the long-term average for all of the basins in the Burdekin region (Figure 52, Table 10).

Seagrass meadows across the Burdekin NRM region increased slightly in overall condition in 2019–20 but remained **poor** (Figure 51). Condition indicators contributing to this were:

- abundance score was poor
- reproductive effort score was poor
- tissue nutrient score was moderate.

Seagrass abundance decreased relative to the previous period, due to declines in per cent cover at all sites, with the largest declines occurring in reef intertidal and subtidal habitats. The declines in abundance were likely the legacy from the 2019 wet season (previous reporting year) when losses occurred due to river discharge from the Burdekin River in concert with unusually large discharges from the smaller creeks and rivers entering Cleveland Bay. Sediment loads in the discharge and wind-driven resuspension elevated turbidity and reduced benthic light during the wet season, but light levels quickly returned to seasonally-expected levels. This is because environmental conditions in 2019–20 were relatively benign, with below-average rainfall and discharge, and temperatures around the long-term average.

Reproductive effort increased on average in 2019–20 compared to the previous reporting period elevating the score from very poor to poor; however, the patterns were inconsistent among habitat types. In coastal intertidal habitat reproductive effort declined in 2019–20 and was the lowest since 2014. In addition, the seed count in seed banks was very low for the sites, but higher than typical seed densities in the Reef. Reproductive effort remianed very low in reef intertidal and subtidal habitats. In all habitats seed density was higher in the late dry, but declined in the late wet, suggesting loss to germination, which is not uncommon but was particularly clear in 2019–20. If seedlings are present, abundances are expected to increase due to vegetative growth in the next year.

The tissue nutrient indicator score has fluctuated within a moderate range since 2014–15. In 2019–20, there were small increases in C:N in all habitats. This appears primarily a consequence of nitrogen content in leaves decreasing relative to carbon at all habitats, which may be likely associated with reallocation to growth, as the plants begin to recover from previous losses.

Over the past decade, seagrass meadows of the Burdekin region have demonstrated high resilience particularly through their capacity for recovery. This may reflect a conditioning to disturbance (high seed bank, high species diversity), but also reflects the nature of the disturbances which are episodic and dominated by wind events and Burdekin River flows.

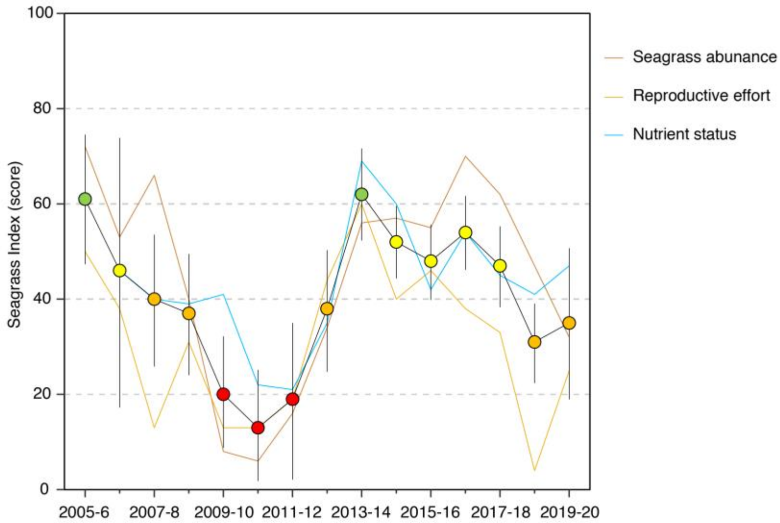


Figure 51. Report card of seagrass status indicators and index for the Burdekin NRM region (averages across habitats and sites). Values are indexed scores scaled from 0–100 (± SE) and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

5.3.2 Climate and environmental pressures

Inshore seagrass sites in the region have a very high frequency of exposure to turbid waters during the wet season and they are the highest among all regions. In 2019–20, exposure to turbid water (classes 1–5) remained at 100% of wet season weeks at all sites i.e. all sites monitored throughout the region were exposed to ‘brown’ or ‘green’ turbid water for the entire wet season. Coastal sites (BB, SB and JR) experienced the highest exposure to ‘brown’ turbid, sediment laden, waters (100 per cent of wet season weeks categories 1–4), which is slightly higher than long-term average (94–99). By contrast, reef sites at Magnetic Island were exposed predominately to ‘green’, phytoplankton rich waters for most of the wet season weeks, and there was less exposure to ‘brown’ water at reef sites compared to average (Figure 52).

Daily light levels in the Burdekin region were 10.9 mol m^{-2} d^{-1} on average in 2019–20, and therefore above the threshold thought to support optimal growth of 10 mol m^{-2} d^{-1} (Figure 52). The largest increase in daily incident light occurred at Shelley Beach, where light was 1.7 mol m^{-2} d^{-1} higher than average, owing to a large rise in light levels in the late dry season (Figure 8). The only site with lower than average light levels, was Jerona. Seasonal trends in benthic light levels vary among years in the Burdekin region. In 2019–20, the regional trend in light followed what is typically observed in other regions: benthic light levels are high throughout the winter months and late dry season, and sharply decline in the wet season (Figure 52), however the maximum and minimum light levels, vary considerably among sites with the lowest at the Magnetic Island subtidal site, followed by Bushland Beach (Figure 8Figure 102).

This year intertidal and subtidal within-canopy temperatures were similar to the previous period and the long-term average (Figure 52). Maximum intertidal within-canopy temperatures exceeded 35°C for a total of 47 days during 2019–20, with the highest temperature recorded at 39.8°C (JR1, 3pm 07Mar20). Maximum subtidal temperature during 2019–20 was 33.8°C (5pm, 15Feb20). Daily tide exposure was similar to the long-term average but below the long-term median at all sites (Figure 52, Figure 94, Figure 95), which may have provided some respite from the elevated temperatures.

The proportion of mud at Jerona (Barratta Creek) coastal meadows was much higher than Townsville meadows (Bushland Beach and Shelley Beach) and has remained well above the Reef long-term average (Figure 111). Post 2011, Townsville coastal meadows have been dominated by fine sediments, although the proportion of mud has periodically increased at Bushland Beach over the last five years (Figure 111). Conversely, reef habitats remain dominated by sand sediments, although the composition of fine sediments and mud has persisted at Cockle Bay (MI2) in the last few years (Figure 112, Figure 113).

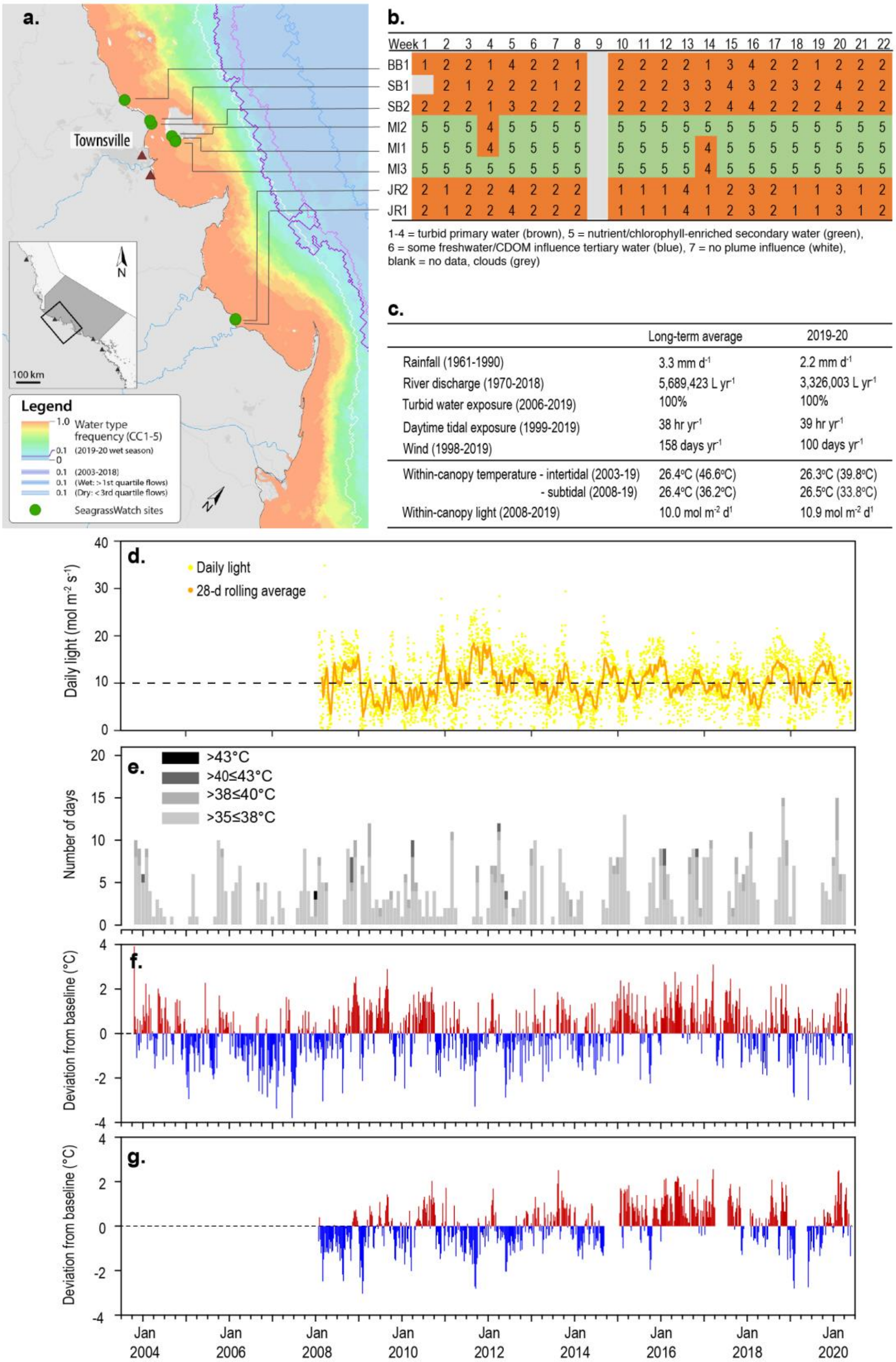


Figure 52. Environmental pressures in the Burdekin region including: a. frequency of exposure to turbid water (colour classes 1–5) (from Waterhouse et al. 2021); b. wet season water type at each site; c. average conditions over the long-term and in 2019–20; d. daily light and the 28-day rolling mean of daily light for all intertidal sites; e. number of days intertidal site temperature exceeded 35°C, 38°C, 40°C and 43°C, and; f. deviations from 14-year mean weekly temperature records.

5.3.3 Inshore seagrass and habitat condition

Three seagrass habitat types were assessed across the Burdekin region in 2019–20, with data from 10 sites (Table 14, Table 19). An additional coastal location, Bowen, was included in 2019–20. This location was previously monitored as part of the Seagrass-Watch global seagrass observing network from 2007 to 2012, but resumed in 2019 due to returned capacity and is planned to continue for the forseable future.

Table 14. List of data sources of seagrass and environmental condition indicators for each seagrass habitat type in the Burdekin NRM region. *Seagrass-Watch. For site details see Table 3 and Table 4.

Habitat	Site code and location		seagrass abundance	seagrass composition	seagrass distribution	reproductive effort	seed banks	leaf tissue nutrients	meadow sediments	epiphytes & macroalgae
coastal intertidal	BB1	Bushland Beach (Townsville)	■	■	■	■	■	■	■	■
	BW1*	Front Beach (Bowen)	■	■			■		■	■
	BW2*	Front Beach (Bowen)	■	■			■		■	■
	JR1	Jerona (Barratta CK, Bowling Green Bay)	■	■	■	■	■	■	■	■
	JR2	Jerona (Barratta CK, Bowling Green Bay)	■	■	■	■	■	■	■	■
	SB1	Shelley Beach (Townsville)	■	■	■	■	■	■	■	■
	SB2*	Shelley Beach (Townsville)	■	■			■		■	■
reef intertidal	MI1	Picnic Bay (Magnetic Island)	■	■	■	■	■	■	■	■
	MI2	Cockle Bay (Magnetic Island)	■	■	■	■	■	■	■	■
reef subtidal	MI3	Picnic Bay (Magnetic Island)	■	■	■	■	■	■	■	■

5.3.3.1 Seagrass index and indicator scores

In the 2019–20 monitoring period, the seagrass condition index for the Burdekin region increased slightly, but remained **poor** (Figure 53). The grade appears a legacy of the previous monitoring periods, which, as a result of the influence of region-wide above average wet season rainfall and river discharge, have carried over into the 2019–20 reporting period. Conversely, the reproductive effort and tissue nutrient status increased in 2019–20.

Examination of indicators contributing to seagrass condition over the long-term, show declines from 2009–2011 as a consequence of the years of above-average rainfall and severe weather, proceeded by rapid recovery. Based on those previous trends, the seagrass meadows in 2019–20 would appear to be in a vulnerable state and at risk of further decline, but the presence of reproductive structures (albeit at low numbers) and a seed bank, indicates some capacity to recover depending on conditions (Figure 53).

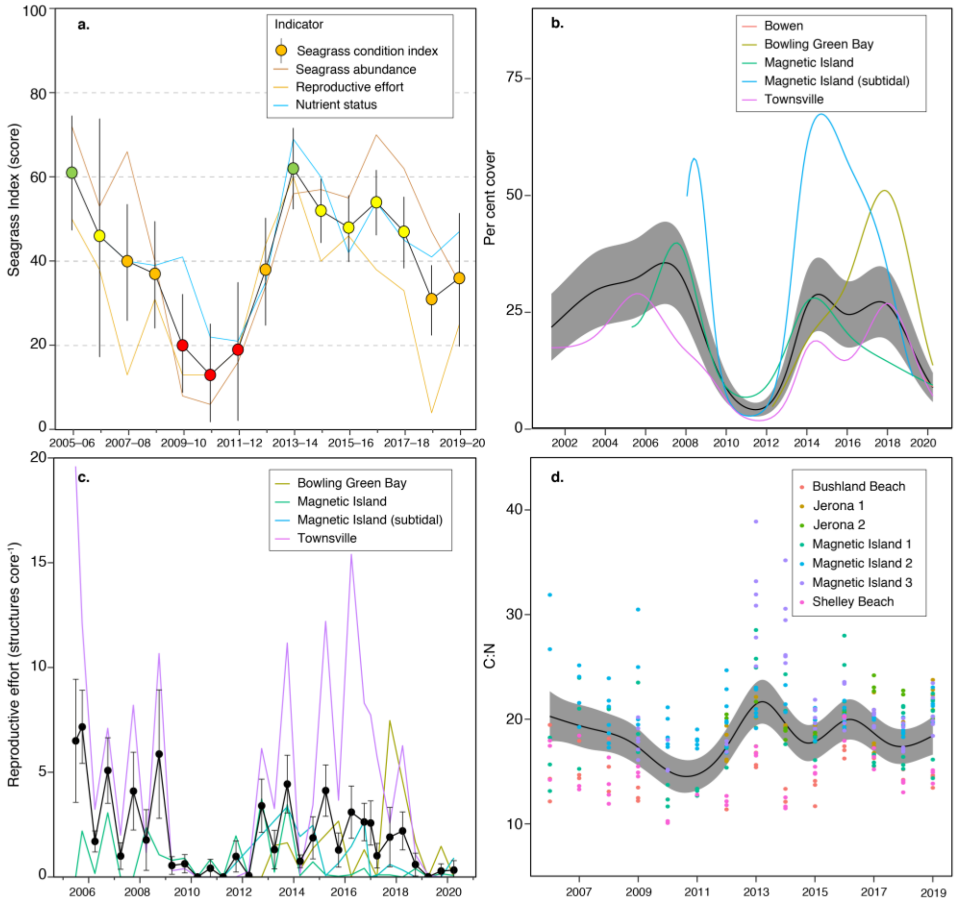


Figure 53. Temporal trends in the Burdekin seagrass condition index and the indicators used to calculate the index: a. seagrass condition index (circles, ± SE) and indicator trends (lines); b. GAM plots of seagrass abundance (per cent cover) trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); c. average number of reproductive structures (± SE) (GAM not possible due to high count of zero values); and d. elemental ratios (atomic) of leaf tissue C:N nutrient content at each site (coloured circles) and regional trend represented by a GAM plot as dark line with shaded areas defining 95 per cent confidence intervals of the trend

5.3.3.2 Seagrass abundance, composition and extent

Over the duration of the MMP, seagrass abundance in the Burdekin region has shown a pattern of loss and recovery. Between 2008–09 and 2010–11, losses occurred as a result of multiple consecutive years of above-average rainfall (river discharge) and severe weather (cyclone Yasi). From 2011, seagrass rapidly recovered, however since 2014, seagrass abundance has progressively declined at reef (intertidal and subtidal) habitats. In 2018–19, the largest declines occurred in reef subtidal and coastal intertidal habitats, while in 2019–20 all of the Burdekin region sites declined in abundance with largest declines at reef intertidal and subtidal sites.

An examination of the long-term abundances across the Burdekin region indicates no significant trend (from first measure to 2019–20), although significant trends were detected at two of the five coastal sites. One site (SB2), which has been monitored for nearly two decades (since 2001), showed a decreasing trend (Table 21). The other site (JR2), near Jerona (Barratta Ck, Bowling Green Bay), has only been monitored since 2012, and not surprisingly showed a significant increasing trend in abundance, as this coincides with the main recovery period after the regional losses. A significant long-term decline occurred at Cockle Bay, Magnetic Island (reef intertidal, MI2) since monitoring began in 2005 (Table 21).

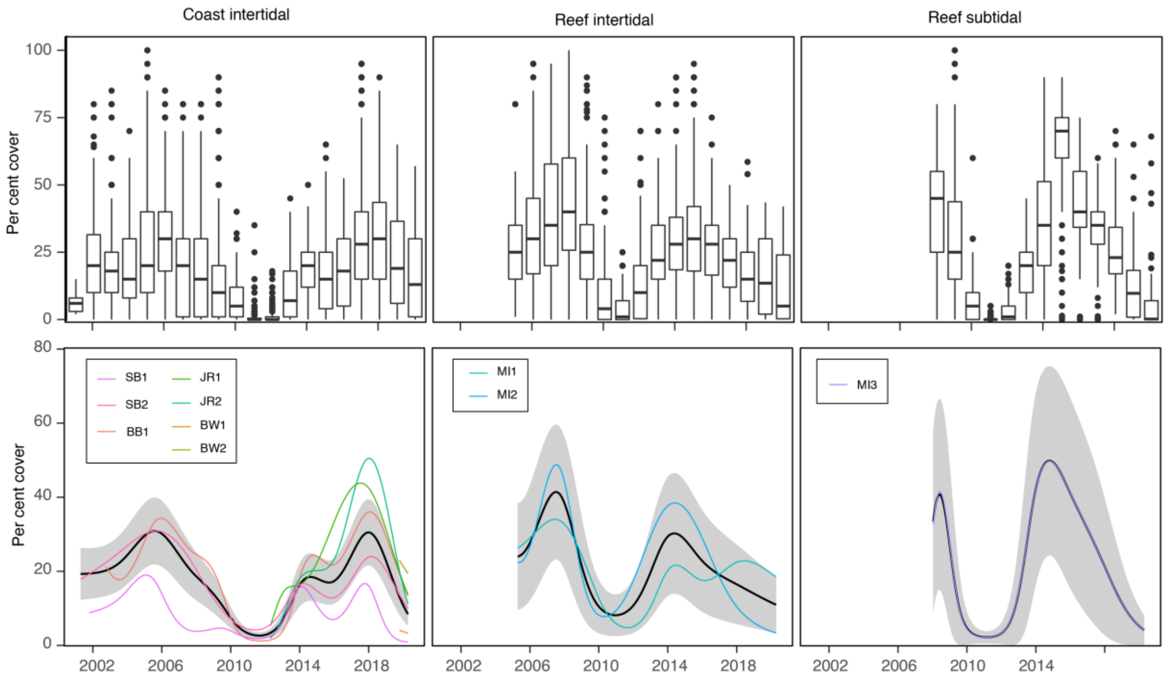


Figure 54. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the Burdekin NRM region from 2001 to 2020. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero indicates 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, and the dots represent outlying points. GAMM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

This year, as it has been since 2014–2015, a low proportion of species displaying colonising traits are present in all habitats (e.g. *Halophila ovalis*). Instead these habitats are dominated by opportunistic species (*H. uninervis, Z. muelleri, C. serrulata*) in coastal and reef sites or persistent species in intertidal reef habitat (*T. hemprichii*). Opportunistic and persistent foundation species also have a capacity to resist stress (survive, through reallocation of resources) caused by acute disturbances (Collier *et al.* 2012b), and therefore, current species composition provides greater overall resilience in Burdekin meadows. However, the presence of colonising species is important for recovery following loss (Kilminster et al 2015). Given the declines in seagrass abundance over the past few years, there may be an increase in the proportion of colonising species during future surveys.

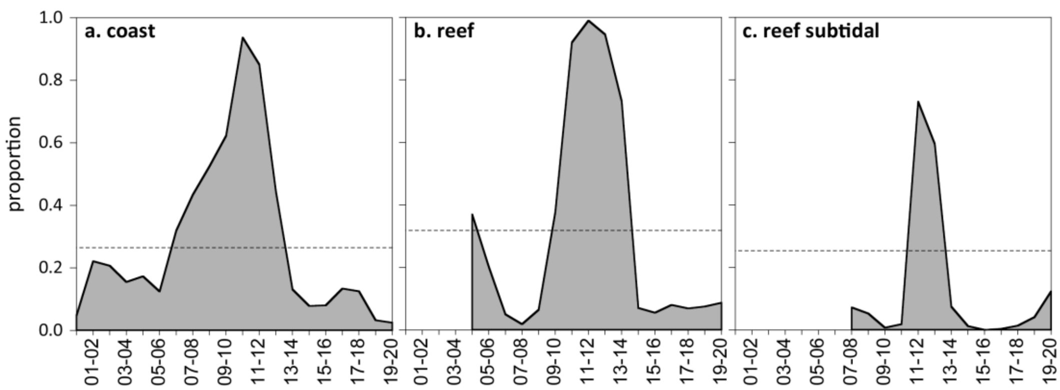


Figure 55. Proportion of seagrass abundance composed of colonising species at inshore habitats in the Burdekin region, 2001–2020. Grey area represents Reef long-term average proportion of colonising species for each habitat type.

Meadow spatial extent declined to the lowest level recorded in reef subtidal habitats, in what appears to have been an ongoing legacy of the flood events in early 2019 (Figure 56). By contrast, intertidal reef meadows increased in extent in 2019–20, following declines experienced in the last reporting period due to a proliferation of scarring and fragmentation. Meadow extent similarly increased in intertidal coastal meadows in 2019–20 after a period of slight decline but with a large variation in this response among sites as shown through the large standard errors.

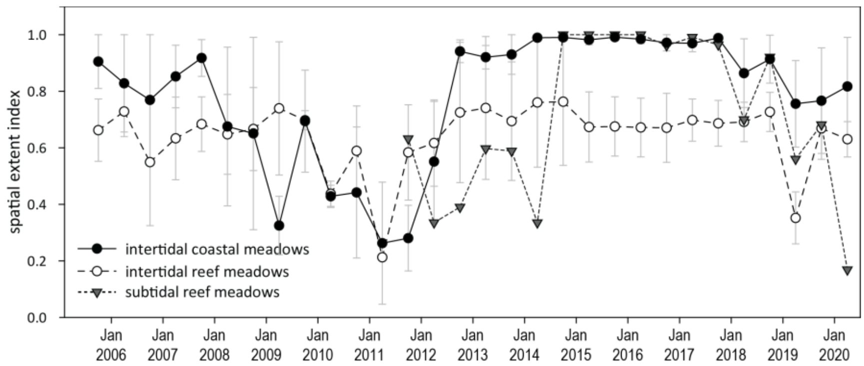


Figure 56. Change in spatial extent (± SE) of seagrass meadows within monitoring sites for each inshore intertidal habitat and monitoring period across the Burdekin region, 2005–2020.

5.3.3.3 Seagrass reproductive status

Reproductive effort is highly variable across Burdekin region habitats, particularly in coastal habitats where very high and anomalous levels of reproductive effort can occur, usually at times when abundance is also very high (Figure 57). In 2019–20, reproductive effort remained very low in coastal and reef intertidal habitats, in what appears to be a lag effect of the 2019 floods. Seed density in the seed banks of these habitats is also declining, likely due to seed germination following disturbances and declines in abundance, as well reduced replenishment. At reef subtidal habitats there was an increase in reproductive effort in 2019–20 from zero in the previous year. Seed densities sharply declined in the post-wet season presumably due to germination, but will hopefull be replenished through sexual reproduction.

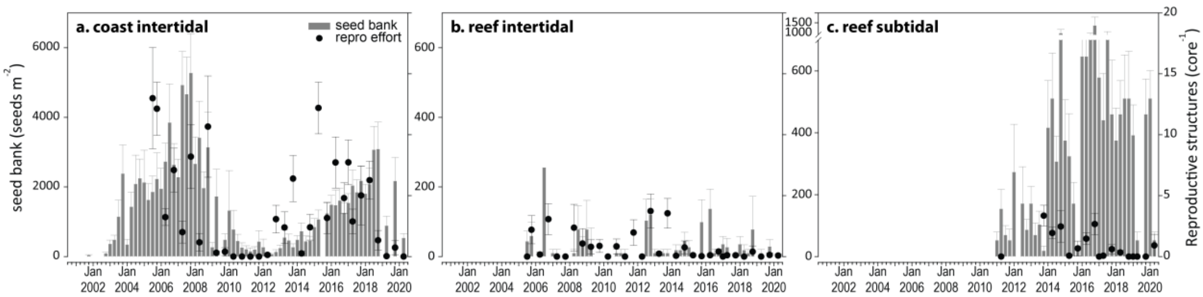


Figure 57. Reproductive effort at inshore intertidal coast and reef and subtidal reef habitats in the Burdekin region. Seed bank presented as the total number of seeds per m^2 sediment surface (bars ±SE), and late dry season reproductive effort presented as the average number of reproductive structures per core (species and sites pooled) (dots ±SE). NB: Y-axis scale for seed banks differs between habitats.

5.3.3.4 Seagrass leaf tissue nutrients

Seagrass leaf tissue molar C:N ratios increased slightly in 2019–20, and increased above the threshold of 20 at reef subtidal habitats (Figure 58). At coastal intertidal and reef intertidal habitats C:N varies slightly, but usually in a manner that reflects local processes, in particular nitrogen loads and light levels (see Case Study 1 McKenzie et al 2020). The C:N ratios declined to a low in 2010–11 following extreme weather events, then recovered to a maxima in 2016–17 followed by small changes since then including two years of decline, and then an increase in 2019–20. The increase in C:N was associated with reductions in per cent N (Figure 58). This is a surprising result, given the large riverine discharge levels (3 times greater than median) in the 2019 wet season, just prior to tissue nutrient levels being measured.

N:P and C:P increased at reef intertidal habitat and indicated P limitation due to reduced per cent P levels. N:P and C:P remained relatively unchanged in other habitats(Figure 58). *$\delta^{13}C$* declined in all habitats, and there was a significant decline in coastal habitats. This is indicative of light limitation, and greater discrimination against the heavier C isotope (^{13}C) because of lower rates of photosynthetic C incorportion.

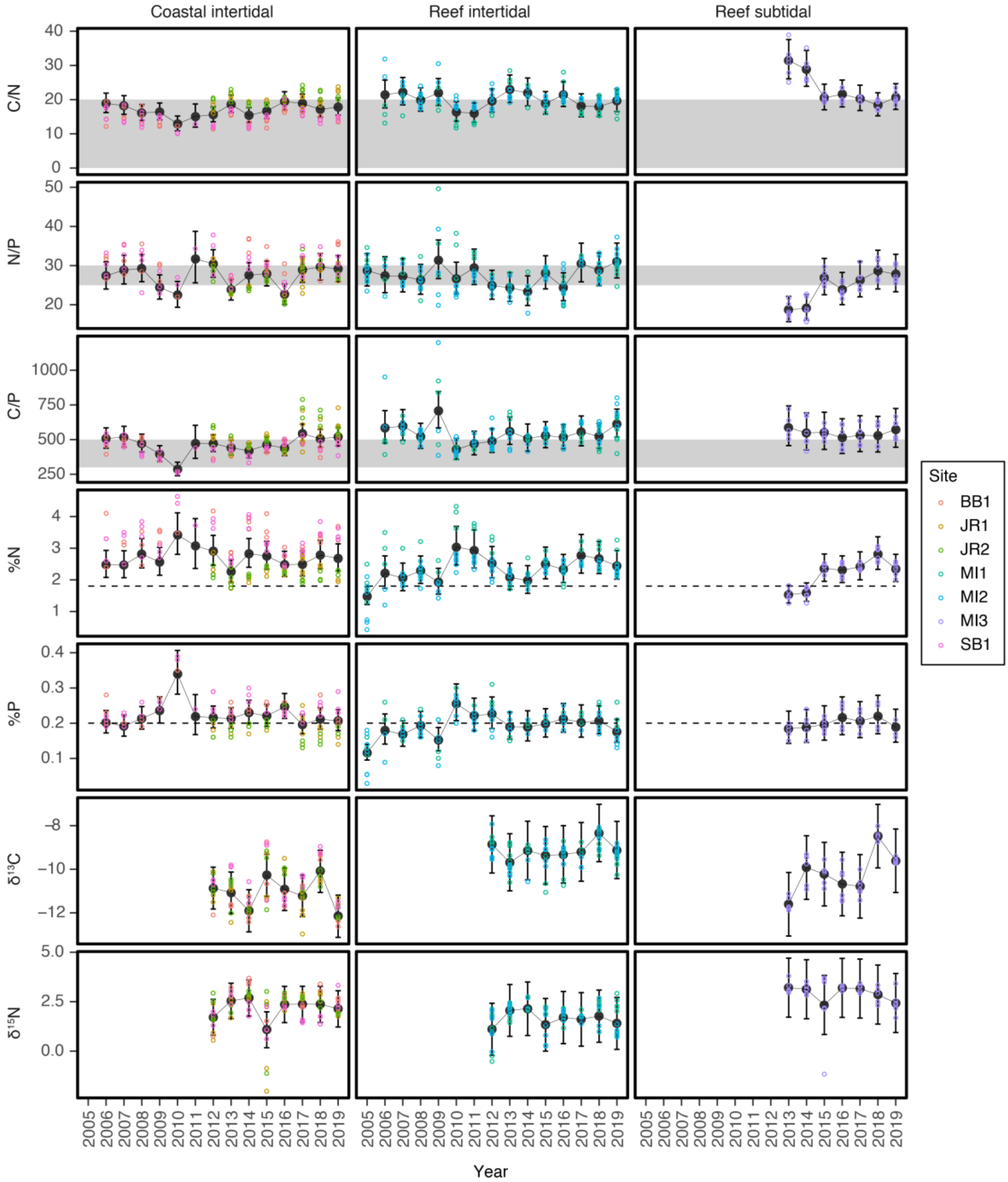


Figure 58. Seagrass leaf tissue nutrient elemental ratios (C:N:P) and concentrations (per cent N, per cent P, $\delta^{13}C$ and $\delta^{15}N$) for each habitat in the Burdekin region (± SE) (foundation species pooled). Horizontal shaded bands or dashed lines represents the accepted seagrass guideline values, where: C:N ratios within the band may indicate reduced light availability and/or N enrichment; N:P ratios above the band indicate P limitation, below indicate N limitation and within indicates replete, and; C:P ratios within the band may indicate nutrient rich habitats (large P pool). Dashed lines in per cent N and per cent P indicate global median values of 1.8 per cent and 0.2 per cent for tissue nitrogen and phosphorus, respectively (Duarte 1990).

5.3.3.5 *Epiphytes and macroalgae*

Epiphyte cover on seagrass leaf blades usually differs between the wet and dry season at coastal sites, but in 2019–20, it was above the overall inshore Reef average in both seasons and at the highest level since 2004. Both epiphytes and macroalgae cover can increase following nutrient enrichment (Cabaço *et al.* 2013; Nelson 2017); however, due to complex ecological and biological factors (e.g. grazing Heck and Valentine 2006), their abundance may not necessarily correlate to nutrient loading. Epiphytes are lost as new leaves replace older leaves, which have high epiphyte loads. The increase in epiphytes in this reporting year may be associated with lower rates of leaf turnover, as the meadows underwent senescence rather than growth. However, in reef intertidal habitat, epiphyte loads were lower than the overall inshore Reef average, and in reef subtidal habitats epiphytes were seasonally variable, being higher in the wet season.

Macroalgae abundance has remained low and below the long-term average at coastal habitats, where there is limited substrate for establishement. Macroalage was high and reached record levels in reef intertidal habitats, but remained low in subtidal habitats.

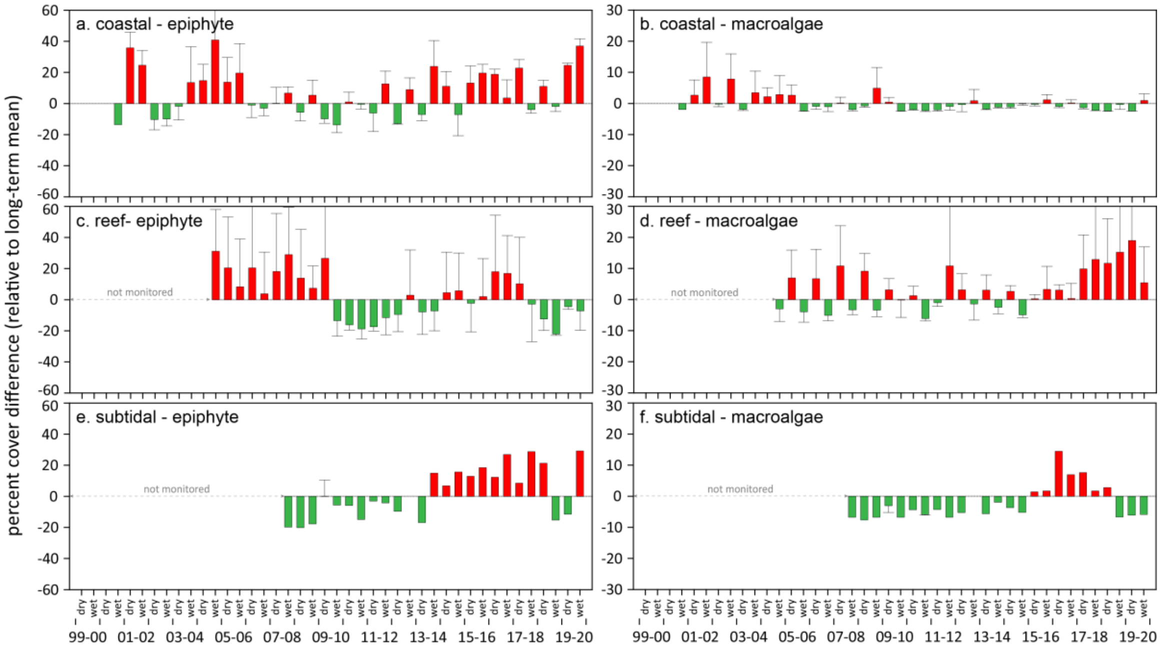


Figure 59. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term Reef average for each inshore seagrass habitat in the Burdekin region (sites pooled, ±SE). Green bars indicate positive deviations for condition, red bars negative.

5.4 Mackay–Whitsunday

5.4.1 2019–20 Summary

The 2019–20 monitoring period in the Mackay–Whitsunday region was relatively benign with environmental pressures around or below the long-term averages. It was characterised by rainfall and discharge that was below the long-term average (Figure 7, Table 10, Figure 52).

Inshore seagrass meadows across the Mackay–Whitsunday NRM region increased in overall condition in 2019–20, but the condition grade remained **poor** (Figure 60). There was a small increase in all indicators. Indicators for the overall condition score were:

- abundance score was poor
- reproductive effort score was poor
- tissue nutrient score was poor.

Nearly three quarters of sites either increased or remained unchanged in abundance in 2019–20 relative to the previous period. The greatest losses occurred in the coastal subtidal habitat, although only a single location in the region is assessed. Overall, the long-term trend indicates a declining trajectory, however improvements over the last two years indicate a region nearly recovered to 2016-17 levels, following the losses experienced in early 2017.

Seagrass reproductive effort declined slightly at coastal habitats, and improved in all other habitats. Reproductive effort at the estuarine site is highly variable both inter-annually and seasonally, but there are usually some reproductive structures observed in the dry season. Seeds are persisting within the seed bank of all habitats, which provides some capacity to recover from future impacts.

The leaf tissue nutrient score increased in 2019–20 and reached an equal highest score for the region. The increase was observed at all locations and habitats. This may reflect the consistently low rainfall since 2012–13, resulting in most years having average river discharge, and two years in which it was 1.5 to 2 times greater than the long-term median. Despite this, the score remains below the threshold of 20, indicating that nitrogen occurs in excess of growth requirements at the Mackay–Whitsunday sites.

The Mackay–Whitsunday regional seagrass condition had been improving from 2010–2011, when it reached its lowest level since monitoring commenced to 2016–2017. After this time, the recovery trend abated as a consequence of cyclone Debbie. In 2019–20, the score returned to the 2015–16 level, but remained poor. Moderate rainfall and discharge, as well as near average water temperatures in 2019–20 are conditions that likely supported this recovery. Continued improvement and return to a moderate or good state will depend of favourable conditions and alleviated pressures in future.

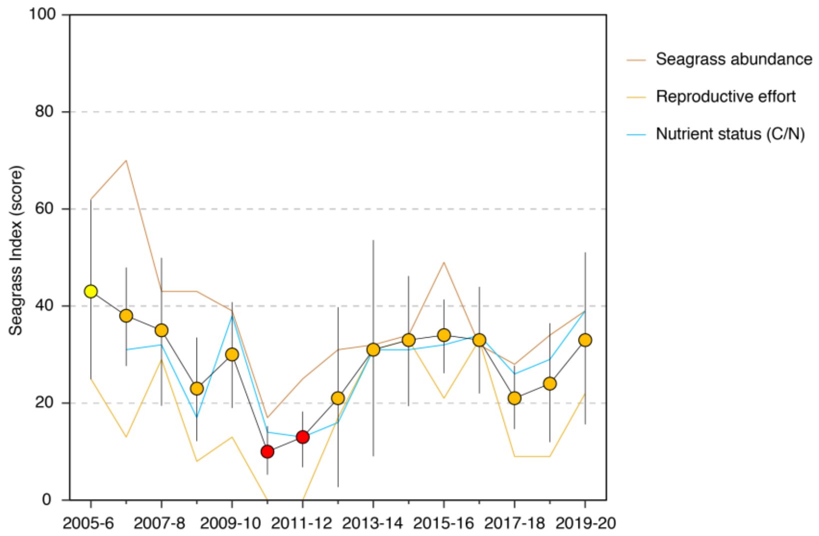


Figure 60. Report card of seagrass status indicators and index for the Mackay–Whitsunday NRM region (averages across habitats and sites). Values are indexed scores scaled from 0–100 (± SE) and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

5.4.2 Climate and environmental pressures

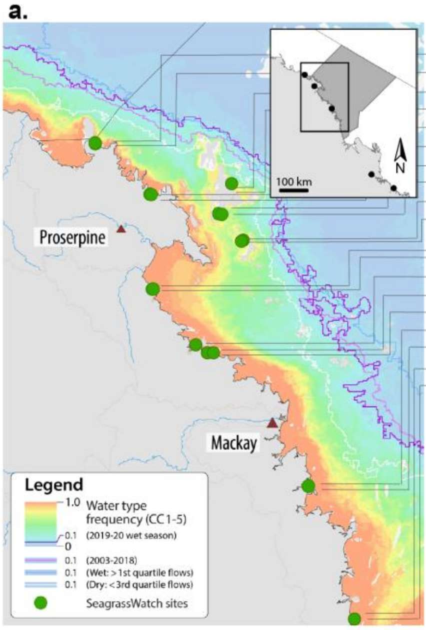
Exposure of inshore seagrass to turbid waters during the wet season above the long-term average (Figure 61). Exposure to either ‘brown’ or ‘green’ turbid water was variable among seagrass habitats (Figure 61). Estuarine and coastal sites were not only exposed to turbid waters for the entire wet season, but were the only habitats exposed to ‘brown’ sediment laden waters. Estuarine sites in Sarina Inlet (SI1 and SI2), were exposed to ‘brown’ turbid water for 100 per cent of the wet season (Figure 9, Figure 61). Reef habitats fringing the mainland (HB1 and HB2) and located on offshore islands (HM1 and HM2, LN1 and LN2) were exposed primarily to ‘green’ water though with some ‘brown’ water at coastal reef sites, and sometimes neither ‘brown’ or ‘green’ at the reef sites on reef tops (Figure 9, Figure 61).

Within-canopy light was slightly higher (12.4 mol m^{-2} d^{-1}) than the long-term average (11.9 mol m^{-2} d^{-1}) for all sites combined within the region (Figure 9, Figure 61, Figure 103). At a site level, benthic light was higher than average at all sites. The single biggest increase was at the estuarine site at Sarina Inlet where light was 3 mol m^{-2} d^{-1} higher than the long-term average for the site caused by an extended dry season increase in light, and a high maximum light level (Figure 103).

2019–20 was the seventh consecutive year intertidal within-canopy temperatures were above the long-term average, but the difference was marginal (Figure 61). Maximum intertidal within-canopy temperatures exceeded 35°C for a total of 68 days during 2019–20, with the highest temperature recorded at 41.1°C (MP2, 10Feb20). 2018–19 was the third full year of subtidal monitoring with an annual average temperature of 25.5°C, and maximum of 31.1°C (2pm 20Feb20). Daily tide exposure was above the long-term average in 2018–19 for the second consecutive year (Figure 61, Figure 96), which may have exacerbated the stresses from the marginally higher water temperatures experienced at intertidal sites.

The proportion of fine grain sizes decreases in the sediments of the seagrass monitoring sites/meadows with distance from the coast/river mouths in the Mackay–Whitsunday region. The proportion of mud in estuarine sediments increased in 2019–20 relative to the previous period but remained below the overall inshore Reef long-term average (Figure 114). Coastal habitat meadows had less mud than estuarine habitats over the long term, but fluctuate within and between both meadows and years. In 2018–19 some sites/meadows continued to contain a higher proportion of mud (e.g. PI2 and MP2) than the Reef long-term average (Figure 115). Reef habitats were composed predominately of fine to medium sand, with the proportion of mud decreasing in 2019–20 relative to the previous period (Figure 116).

a.



Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
HB2	5	5	5	4	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5		5	5
HB1	5	5	5	4	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5		5	5
TO1	6	6	5	5	5	5	5	6	5	6	5	5	5	5	5	5	5	5	5	5	5	5
TO2	6	6	5	5	5	5	5	6	5	6	5	5	5	5	5	5	5	5	5	5	5	5
PI2	1	2	2	2	4	2	4	2		4	2	4	4	4	4	3	4	1	4	4	2	1
PI3	1	2	1	2	1	4	4	1		3	2	1	4	2	4	3	4	2	4		1	4
HM1	6	6	5	5	5	5	5	6	5	6	5	5	5	5	5	5	5	5	5	5	5	5
HM2	6	6	5	5	5	5	5	6	5	6	5	5	5	5	5	5	5	5	5	5	5	5
LN2	6	6	6	5	5	5	5	6	5	6	5	5	5	5	5	5	5	5	5	5	5	5
LN1	6	6	6	5	5	5	5	6	5	6	5	5	5	5	5	5	5	5	5	5	5	5
MP3	5	1	2	4	4	4	4	4	5	3	5	1	4	1	4	1	2	3	3	2	4	4
MP2	1	2	2	2	4	3	4	4	4	3	4	1	4	3	4	3	3	3	3	4	4	4
SH1	2	3	2	2	4	4	4	3	3	4	5	3	5	3	4	1	3	2	2	4	3	5
NB1	5	4	4	4	5	4	5	4	4	4	5	4	5	4	4	4	4	5	4	5	5	5
NB2	5	4	4	4	5	4	5	4	4	4	5	4	5	3	4	4	4	4	4	5	5	5
SI2	1	2	1	1	4	4	4	1	4	1	4	2	4	1		1	4	1	3	2	2	4
SI1	1	2	1	1	4	4	4	1	4	1	4	2	4	1		1	4	1	3	2	2	4
CV1	1	2	2	2	2	2	2	2	4	1	5	2	5	2	2	2	4	2	2	1	2	4
CV2	5	2	2	3	4	4	5	2	5	4	5	2	5	2	3	2	4	2	2	2	3	5

1-4 = turbid primary water (brown), 5 = nutrient/chlorophyll-enriched secondary water (green), 6 = some freshwater/CDOM influence tertiary water (blue), 7 = no plume influence (white), blank = no data, clouds (grey)

c.

	Long-term average	2019-20
Rainfall (1961-1990)	7.7 mm d^{-1}	6.6 mm d^{-1}
River discharge (1970-2016)	1,833,088 L yr^{-1}	1,168,274 L yr^{-1}
Turbid water exposure (2006-2018)	91%	94%
Daytime tidal exposure (1999-2019)	50 hr yr^{-1}	56 hr yr^{-1}
Wind (1998-2019)	159 days yr^{-1}	155 days yr^{-1}
Within-canopy temperature - intertidal (2003-2019)	25.3°C (42.7°C)	25.5°C (41.1°C)
- subtidal (2008-2019)		26.5°C (31.0°C)
Within-canopy light (2010-2019)	11.9 mol m^{-2} d^{-1}	12.4 mol m^{-2} d^{-1}

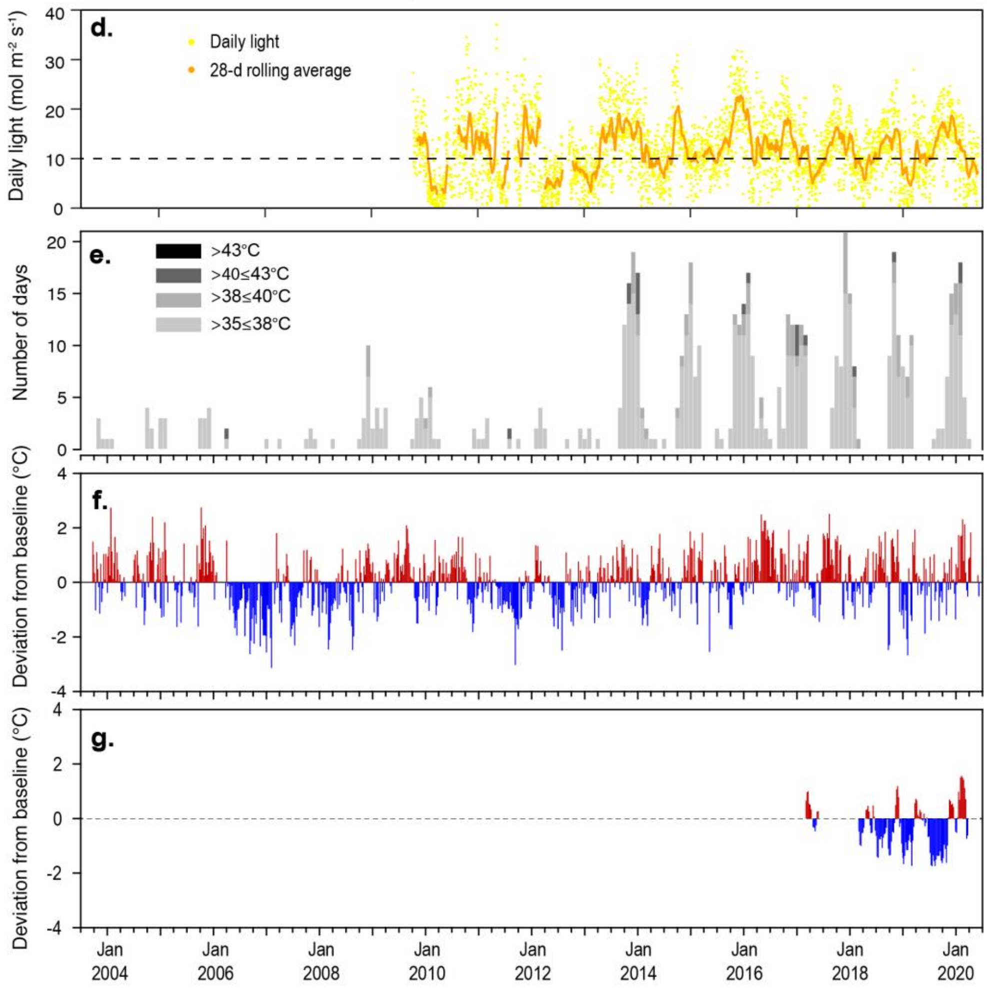


Figure 61. Environmental pressures in the Mackay–Whitsunday NRM region including: a. frequency of exposure to turbid water (colour classes 1–5) (from Waterhouse et al. 2021); b. wet season water type at each site; c. average conditions over the long-term and in 2018–20; d. daily light and the 28-day rolling mean of daily light for all sites; e. number of day temperature exceeded 35°C, 38°C, 40°C and 43°C, and; f. deviations from 15-year mean weekly temperature records.

5.4.3 Inshore seagrass and habitat condition

Five seagrass habitat types were assessed across the Mackay–Whitsunday region this year, with data from 19 sites (Table 15, Table 19).

Table 15. List of data sources of seagrass and environmental condition indicators for each seagrass habitat type in the Mackay–Whitsunday NRM region. † drop camera sampling (QPWS), *Seagrass-Watch. For site details see Table 3 and Table 4.

Habitat	Site		abundance	composition	distribution	reproductive effort	seed banks	leaf tissue nutrients	meadow sediments	epiphytes	macroalgae
estuary intertidal	SI1	Sarina Inlet	■	■	■	■	■	■	■	■	■
	SI2	Sarina Inlet	■	■	■	■	■	■	■	■	■
coastal intertidal	MP2	Midge Point	■	■	■	■	■	■	■	■	■
	MP3	Midge Point	■	■	■	■	■	■	■	■	■
	PI2*	Pioneer Bay	■	■			■		■	■	■
	PI3*	Pioneer Bay	■	■			■		■	■	■
	SH1*	St Helens	■	■			■		■	■	■
	CV1*	Clairview	■	■			■		■	■	■
	CV2*	Clairview	■	■			■		■	■	■
coastal subtidal	NB1†	Newry Bay	■	■							■
	NB2†	Newry Bay	■	■							■
reef intertidal	HM1	Hamilton Island	■	■	■	■	■	■	■	■	■
	HM2	Hamilton Island	■	■	■	■	■	■	■	■	■
	HB1*	Hydeaway Bay	■	■			■		■	■	■
	HB2*	Hydeaway Bay	■	■			■		■	■	■
reef subtidal	LN1	Lindeman Is	■	■	■	■	■	■	■	■	■
	LN2	Lindeman Is	■	■	■	■	■	■	■	■	■
	TO1†	Tongue Bay	■	■							■
	TO2†	Tongue Bay	■	■							■

5.4.3.1 Seagrass index and indicator scores

In the 2019–20 monitoring period, the Mackay–Whitsunday region seagrass condition index increased from the previous year, but remained graded as **poor** (Figure 62).

Overall, the Mackay–Whitsunday seagrass index had been improving since 2010–11, when it reached its lowest level since monitoring commenced. In 2016–17 the improving trend abated and abundance and reproductive effort declined as a consequence of cyclone Debbie (Figure 62). Over the following two years, the index gradually improved, recovering to the 2016-17 level by 2019–20.

Abundance declined after 2017–18 but has increased across the region over the past two reporting periods remained rated as poor. Abundance has been assessed at a number of additional sites since 2016–17. The overall trend for the region follows those observed at long-term monitoring locations with decline and recovery observed after 2017–18, but remaining below historical levels due to a lack of recovery at some locations.

Reproductive effort remained low in 2019–20 but increased relative to the previous monitoring period from very poor to poor (Figure 62). This appears a legacy of losses experienced from the impacts of cyclone Debbie and associated flooding.

The tissue nutrient status has remained relatively stable since 2012–13, but increased slightly in 2019–20 to the equal highest level observed into the region, matching that in 2009–10. The tissue nutrient indicator was rated as poor.

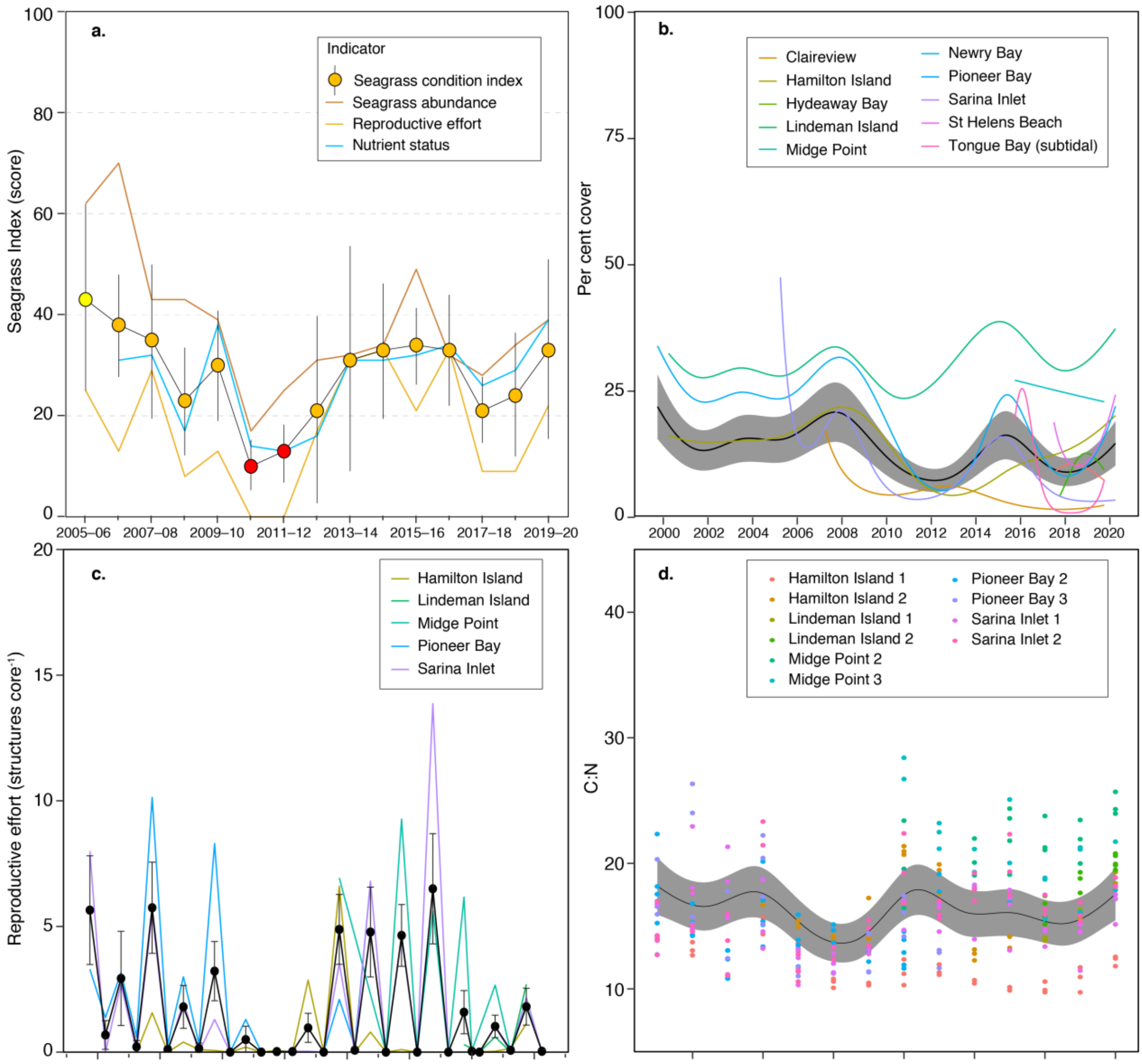


Figure 62. Temporal trends in the Mackay–Whitsunday seagrass condition index and the indicators used to calculate the index: a. seagrass condition index (circles, ± SE) and indicator trends (lines); b. GAM plots of seagrass abundance (per cent cover) trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); c. average number of reproductive structures (±SE) (GAM not possible due to high count of zero values); and d. elemental ratios (atomic) of leaf tissue C:N nutrient content at each site (coloured circles) and regional trend represented by a GAM plot as dark line with shaded areas defining 95 per cent confidence intervals of the trend.

5.4.3.2 Seagrass abundance, community and extent

Seagrass abundance increased in 2019–20 at nearly 60% of sites across the region, relative to the previous period; continuing the improvemnets over the previous two periods (Figure 63). Losses were observed at nearly a quarter of sites, across all habitats, with the exception of estuarine habitats. Abundance has been assessed at a number of additional sites since 2016–17, particularly at coastal intertidal and coastal and reef subtidal sites.

Seagrass abundance (per cent cover) in the Mackay–Whitsunday region in 2019–20 was higher in coastal habitats (intertidal = 13.4 ±1.3 per cent, subtidal = 19.8 ±1.8 per cent) than reef habitats (intertidal = 11.4 ±1.4 per cent, subtidal = 7.6 ±0.9 per cent) or estuarine (3.4 ±1.2 per cent), respectively. As a consequence of the recovering abundances, seagrass per cent covers increased between seasons throughout 2019–20 at intertidal coastal (late dry = 14.5 ±1.4 per cent, late monsoon = 21.5 ±1.9 per cent) and reef habitats (late dry = 9.4 ±1.4 per cent, late monsoon = 13.5 ±1.4 per cent). Little or no change was detected at subtidal or estuarine sites between seasons within 2019–20 (Figure 63).

Seagrass abundance at estuary and coastal intertidal habitats has fluctuated greatly between and within years over the long-term, with some sites experiencing total or near total loss followed by recovery (Figure 63). The long-term trend indicates a declining trajectory (Table 21) with a region struggling to recover from losses in the years leading up to 2010–11 and in early 2017.

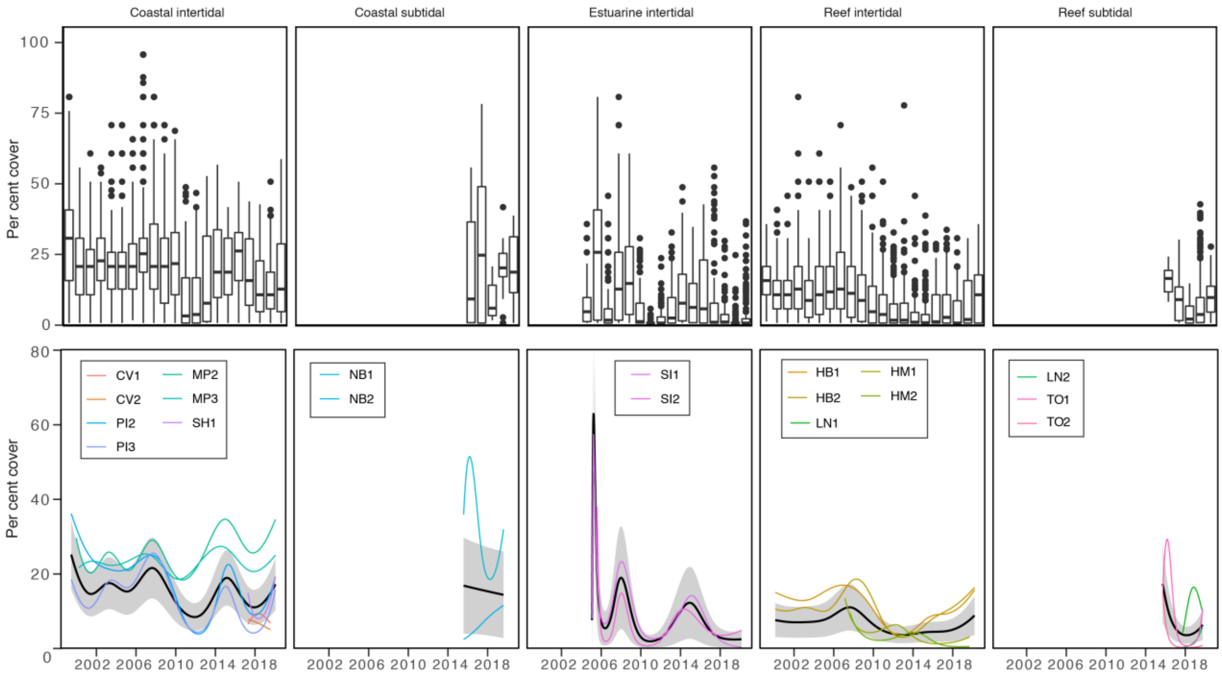


Figure 63. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the Mackay–Whitsunday NRM region from 1999 to 2020. Whisker plots (top) show thee box representing the interquartile range of values, where the boundary of the box closest to zero 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, and the dots represent outlying points. GAMM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

The most common seagrass species across all habitats in the Mackay–Whitsunday NRM region were *Halodule uninervis* and *Zostera muelleri*, mixed with the colonising species *Halophila ovalis*.

Colonising species dominated intertidal meadows across the Mackay–Whitsunday region in the first few years following the extreme weather in 2011. In the last three years, there has been a reduction in colonising species in estuarine and coastal intertidal habitats. In all habitats except reef, opportunistic foundational species (*H. uninervis* and *Z. muelleri*) now dominate (Figure 64), suggesting meadows may have an improved ecosystem resistance to tolerate disturbances (Figure 64). In contrast, colonising species in intertidal reef habitats

(Hamilton Island), have remained above the Reef long-term average since 2006, while at subtidal reef habitats the increase above the Reef long-term average in 2018-19 was maintained in 2019–20 (Figure 64).

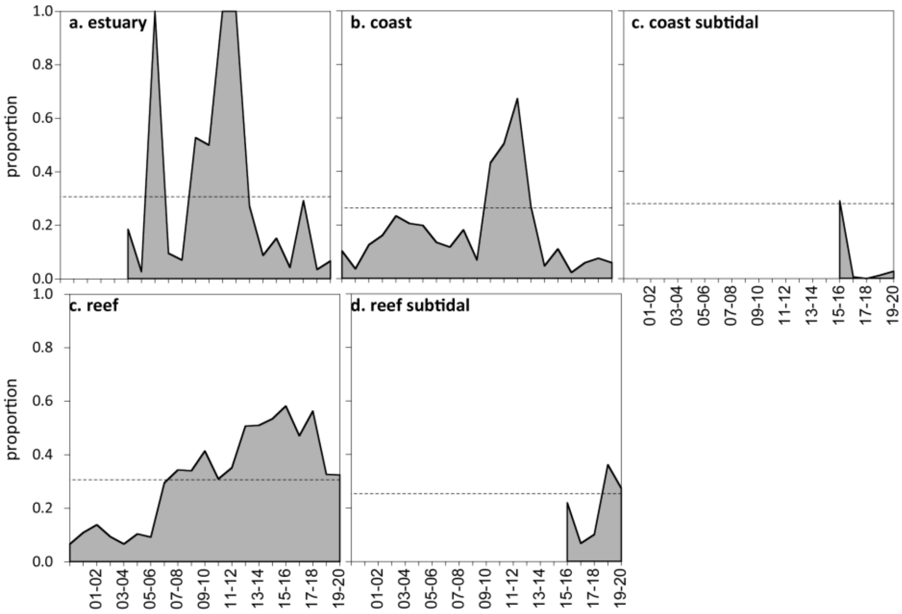


Figure 64. Proportion of seagrass abundance composed of colonising species at inshore intertidal habitats in the Mackay–Whitsunday region, 1999–2020. Grey area represents Reef long-term average proportion of colonising species for each habitat type.

Seagrass meadow landscape mapping was conducted within all sentinel monitoring sites in October 2019 and April 2020 to determine if changes in abundance were a consequence of the meadow landscape changing (e.g. expansion or fragmentation) and to indicate if plants were allocating resources to colonisation (asexual reproduction). Over the past 12 months, spatial extent improved slightly at reef intertidal meadows following the declines experienced in 2016–2017 as a consequence of the destructive effects of cyclone Debbie. At coastal meadows, extent remained steady, but at estuarine meadows extent declined slightly in early 2020 after recovering in late 2019 from delines experienced earlier in the year (Figure 65).

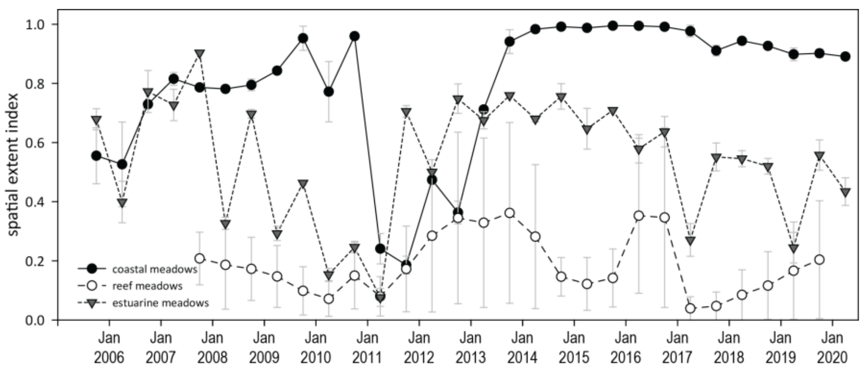


Figure 65. Change in spatial extent (± SE) of seagrass meadows within monitoring sites for each inshore intertidal habitat and monitoring period across the Mackay–Whitsunday NRM region.

5.4.3.3 Seagrass reproductive status

Reproductive effort was highly variable and highly seasonal in the Mackay–Whitsunday region (Figure 66). Reproductive effort and seed banks declined slightly in coastal habitats, relative to the previous period. At the estuary meadow (Sarina Inlet), reproductive effort increased slightly but seed banks near doubled relative to the previous year. In contrast, reproductive effort and the seeds density continued to remain very low at reef sites in 2019–20, which appears typical for reef habitat meadows (Figure 66).

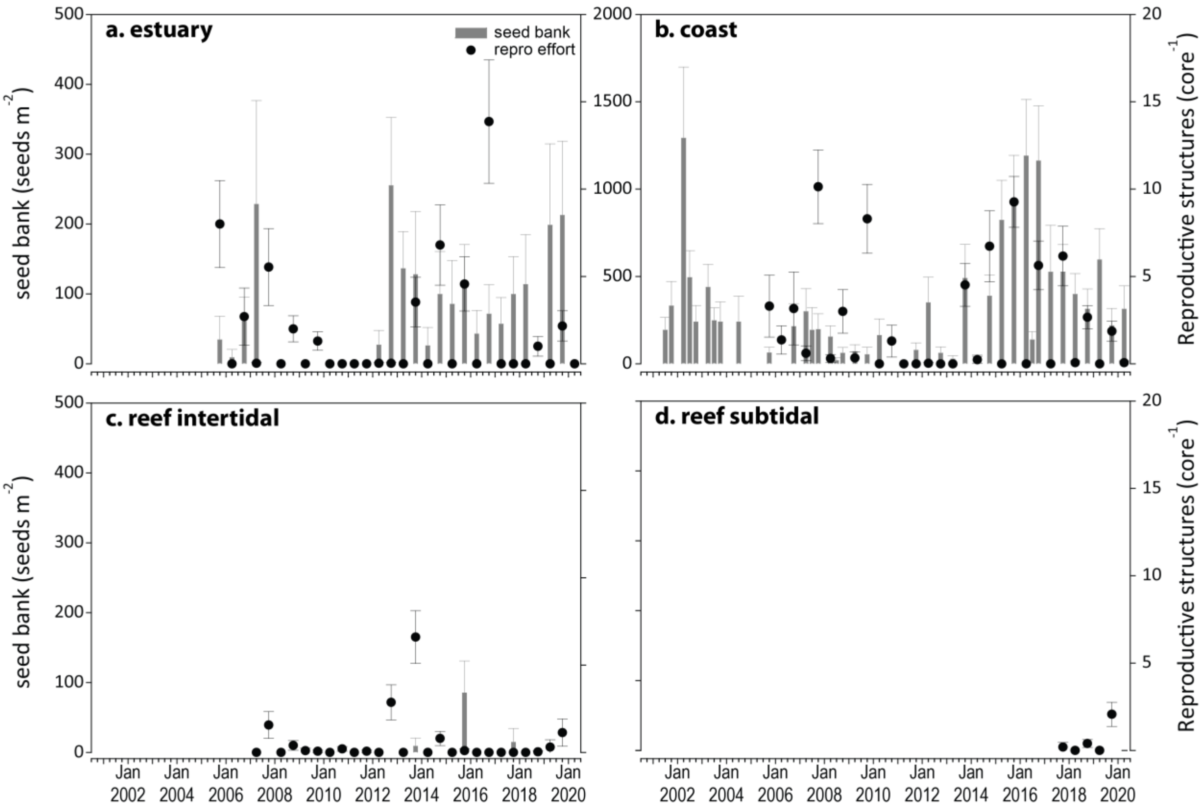


Figure 66. Seed bank and reproductive effort at inshore intertidal coast, estuary, and reef habitats in the Mackay–Whitsunday region, 2001–2020. Seed bank presented as the total number of seeds per m^2 sediment surface (bars ±SE), and late dry season reproductive effort presented as the average number of reproductive structures per core (species and sites pooled) (dots ±SE). NB: Y-axis scale for seed banks differs between habitats.

5.4.3.4 Seagrass leaf tissue nutrients

Seagrass leaf molar C:N ratios show little inter-annual variability into the Mackay–Whitsundays, but increased slightly in 2019–20 compared to the previous year in all habitats, but remained below 20 (Figure 67). This indicates an ongoing surplus of N relative to photosynthetic C incorporation.

N:P ratios decreased in reef habitats due to a reduction in per cent N and an increase in per cent P. N:P remained slightly above the threshold indicating P limitation in reef habitat, but within the nutrient replete band (neither nutrient limiting) at coastal and estuarine sites. C:P ratios increased at estuarine intertidal sites as per cent P declined, and C:P decreased at reef sites as per cent P increased.

The moderate and fluctuating $\delta^{15}N$ (e.g. increasing at reef habitats), suggests some influence of an anthropogenic source of N at some sites (e.g., Hamilton Island) (Figure 67).

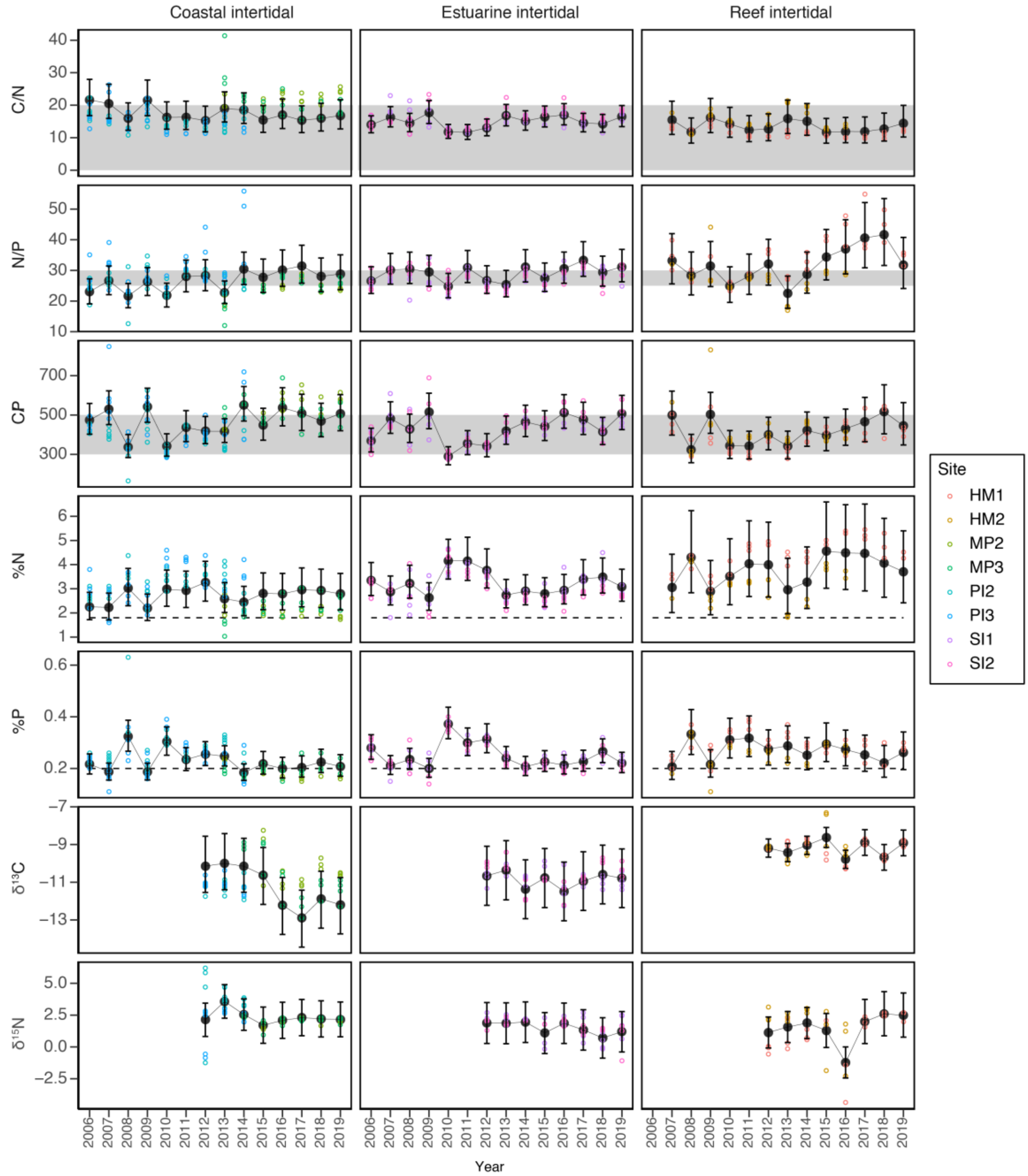


Figure 67. Seagrass leaf tissue nutrient elemental ratios (C:N:P) and concentrations (per cent N, per cent P, $\delta^{13}C$ and $\delta^{15}N$) for each habitat in the Mackay–Whitsunday region (± SE) (foundation species pooled). Horizontal shaded bands or dashed lines represents the accepted seagrass guideline values, where: C:N ratios within the band may indicate reduced light availability and/or N enrichment; N:P ratios above the band indicate P limitation, below indicate N limitation and within indicates replete, and; C:P ratios within the band may indicate nutrient rich habitats (large P pool). Dashed lines in per cent N and per cent P indicate global median values of 1.8 per cent and 0.2 per cent for tissue nitrogen and phosphorus, respectively (Duarte 1990).

5.4.3.5 Epiphytes and macroalgae

Epiphyte cover on seagrass leaf blades in 2019–20 has remained below the overall inshore Reef long-term average at estuarine and reef habitats since early 2017, and increased slightly at coastal habitats relative to the previous reporting year (Figure 68).

Percentage cover of macroalgae remained unchanged, at or below the overall inshore Reef long-term average for estuarine and coastal habitats throughout 2019–20 (Figure 68). At intertidal reef meadows, macroalgae cover decreased to below the overall inshore Reef long-term average in 2019–20, but remained above and increased slightly at subtidal reef meadows (Figure 68).

Figure 68. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term average for each inshore intertidal habitat in the Mackay–Whitsunday region, 1999–2020 (sites pooled, ±SE). Green bars indicate positive deviations for condition, red bars negative.

5.5 Fitzroy

5.5.1 2019–20 Summary

Environmental conditions were relatively benign in 2019–20, and similar to the long-term average levels for the region. River discharge was below average, and benthic light levels were slightly higher than average. Average annual water temperature was around the average, but there were a number of high temperature days, including three days when temperature exceeded 40°C, a threshold likely to impart stress on all species, and in particular on *Zostera muelleri*.

Overall, the Fitzroy regional seagrass condition score remained graded as **poor** in 2019–20 (Figure 69). There were no substantial changes from the previous year in any of the indicators, where the:

- abundance score was poor
- reproductive effort score was very poor
- tissue nutrient score was poor.

All sites, except in the estuarine habitat, reduced in abundance in 2019–20. Abundances at the coastal intertidal sites in Shoalwater Bay declined in 2019–20 after a period of near record high levels. Estuarine habitat abundance remains very low, after a wave of mud and burrowing shrimp activity moved through the area, but is showing signs of recovery. Abundances remain very low at the reef intertidal sites, with little variability among years except in the degree of fragmentation as shown by the seagrass extent. However, a reduction in the proportion of colonising species in 2018–19 indicates that the reef meadows have been relatively stable. The long-term trend in the seagrass abundance score across the region is largely unchanged over the past few years.

Reproductive effort remains well below historical peaks for all habitats in the region. However, the consistent presence of some reproductive structures and a persistent seed bank in both coastal and estuarine habitats indicates some resilience and capacity to recover from any future events. Of concern is that reproductive effort at reef sites remains very low to absent, and there is no seed bank despite an increase in the proportion of *H. uninervis*, a species that can contribute to the seed bank.

The seagrass leaf nutrient status increased in 2019–20, due to a slight increase at all sites, and C:N exceeding the threshold of 20 at estuarine sites. Seagrass leaf molar C:N ratios continue to indicate a surplus of N relative to photosynthetic C incorporation (i.e. C:N is less than 20) at most sites; however, there is no indication of elevated N across the region. This is supported by continuing low epiphyte and macroalgae cover.

Inshore seagrass meadows across the region remain in the early stages of recovering from multiple years of climate related impacts which, similar to Mackay–Whitsunday, are more recent than in other regions. The estuarine habitats have been improving, while other habitats demonstrate a legacy of reduced resilience.

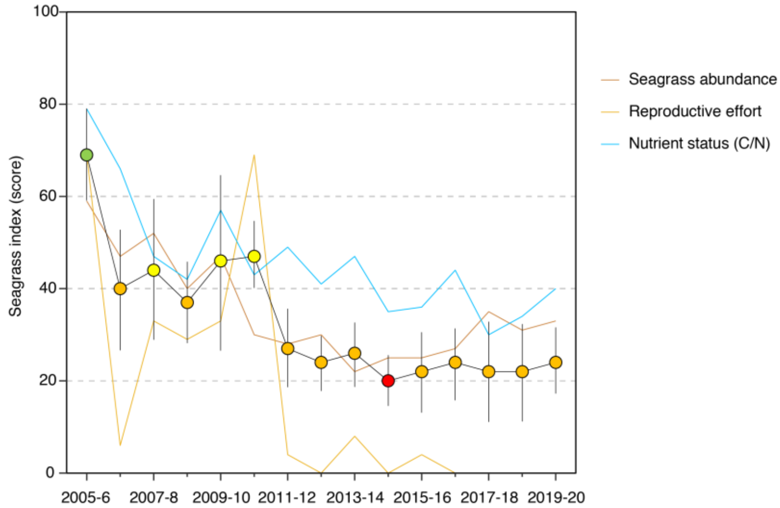


Figure 69. Report card of seagrass status index and indicators for the Fitzroy NRM region (averages across habitats and sites). Values are indexed scores scaled from 0–100 (± SE) and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

5.5.2 Climate and environmental pressures

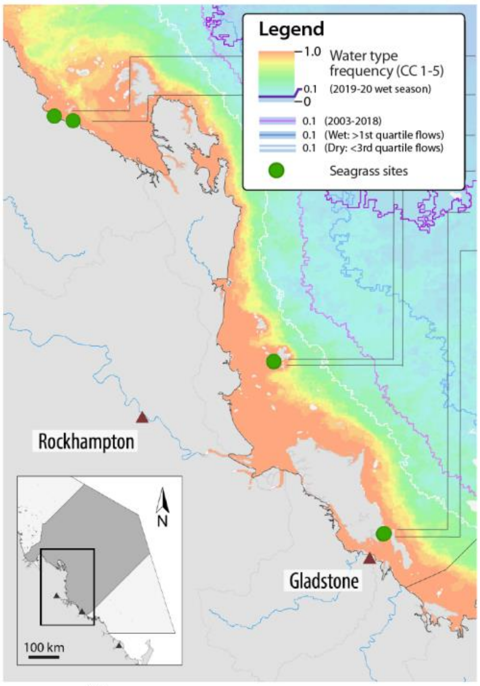
Rainfall and river discharge in 2019–20 were below the long-term average for the Fitzroy region (Figure 70). Exposure of inshore seagrass to turbid waters during the wet season was similar, albiet slighty higher, than the long-term average, with the coastal and estuarine sites exposed to highly turbid 'brown' water in most weeks. By contrast, the reef sites were exposed to predominately 'green' water which has lower light attenuation.

Annual within-canopy light availability was higher in 2019–20 than both the previous period and the long-term average for the region (Figure 9, Figure 70). The most notable change in benthic light levels occurred at Shoalwater Bay, where benthic light levels (15.5 mol m^{-2} d^{-1}) were below the long-term average (18.4 mol m^{-2} d^{-1}). But despite this, light levels at Shoalwater Bay were the highest among all sites in the region because they are very shallow and frequently expose to full sunlight (Figure 104). Daytime tidal exposure was less than the previous period but remained above the long-term average for the region, which increases the risk of desiccation stress, but in the turbid shallow waters can provide windows of light for photosynthesis (Figure 97).

2019–20 within-canopy temperatures were similar to the previous period and the long-term average (Figure 70). Maximum intertidal within-canopy temperatures exceeded 35°C for a total of 63 days during 2019–20, with the highest temperature recorded in the region at 40.5°C (RC1, 3pm 06Feb20). Daily tidal exposure was above the long-term average in 2019–20 for the second period in four years (Figure 61, Figure 96), which may have exacerbated stresses experienced at intertidal sites.

The proportion of fine grains in meadow sediments generally decreases with distance from the coast/river mouths. Estuarine sediments were composed primarily of finer sediments, with the mud portion fluctuating around the overall inshore Reef long-term average. The mud wave, which had impacted one estuary site (GH1) in the previous period, dissipated in 2019–20, and there was an instance of elevated mud at the other site (GH2) in the late dry of 2019 (Figure 117). Coastal and reef habitat sediments are dominated by fine sand/sand, with the proportion of mud in coastal habitats decreased in 2019–20 (Figure 118, Figure 119).

a.



b.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
RC1	2	1	2	1	2	1	5	1	5	1	4	1	4	1	4	1	2	1	4	1	1	2
WH1	2	1	1	1	3	1	4	1	5	1	4	1	5	2	5	2	2	1	1	1	2	4
GK2	5	5	5	5	5	5	5	5	5	5	5	5	5	4	5	5	5	5	5	5	5	5
GK1	5	5	5	5	5	5	5	5	5	5	5	5	5	4	5	5	5	5	5	5	5	5
GH2	4	2	4	3	5	3	4	2	5	4	4	2	4	4	3	2	4	2	1	2	2	4
GH1	4	2	4	3	5	3	4	2	5	4	4	2	4	4	3	2	4	2	1	2	2	4

1-4 = turbid primary water (brown), 5 = nutrient/chlorophyll-enriched secondary water (green), 6 = some freshwater/CDOM influence tertiary water (blue), 7 = no plume influence (white), blank = no data, clouds (grey)

c.

	Long-term average	2019-20
Rainfall (1961-1990)	2.9 mm d^{-1}	2.4 mm d^{-1}
River discharge (1970-2016)	3,515,873 L yr^{-1}	3,189,235 L yr^{-1}
Turbid water exposure (2006-2018)	98%	100%
Daytime tidal exposure (1999-2018)	110 hr yr^{-1}	125 hr yr^{-1}
Wind (1998-2017)	80 days yr^{-1}	62 days yr^{-1}
Within-canopy temperature - intertidal (2003-19)	24.2°C (42.7°C)	24.3°C (40.5°C)
Within-canopy light (2009-2019)	15.0 mol m^{-2} d^{1}	15.9mol m^{-2} d^{1}

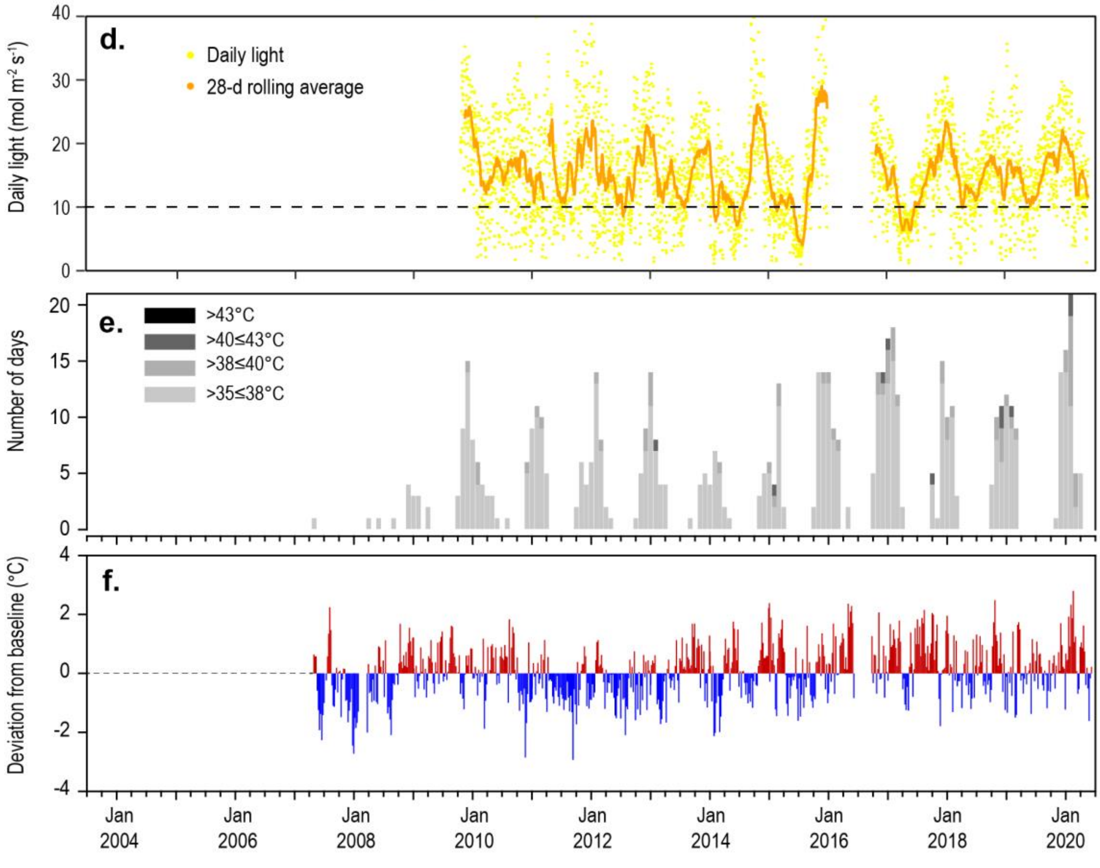


Figure 70. Environmental pressures in the Fitzroy region including: a. frequency of exposure to turbid water (colour classes 1–5) (from Waterhouse et al. 2021); b. wet season water type at each site; c. average conditions over the long-term and in 2019–20; d. daily light and the 28-day rolling mean of daily light for all sites; e. number of day temperature exceeded 35°C, 38°C, 40°C and; 43°C, and f. deviations from 13-year mean weekly temperature records.

5.5.3 Inshore seagrass and habitat condition

Three seagrass habitat types were assessed across the Fitzroy region in 2018–19, with data from 6 sites (Table 16).

Table 16. *List of data sources of seagrass and environmental condition indicators for each seagrass habitat type in the Fitzroy NRM region. For site details see* Table 3 *and* Table 4*.*

Habitat	Site		abundance	composition	distribution	reproductive effort	seed banks	leaf tissue nutrients	meadow sediments	epiphytes	macroalgae
estuary intertidal	GH1	Gladstone Hbr	■	■	■	■	■	■	■	■	■
	GH2	Gladstone Hbr	■	■	■	■	■	■	■	■	■
coastal subtidal	RC1	Ross Creek (Shoalwater Bay)	■	■	■	■	■	■	■	■	■
	WH1	Wheelans Hut (Shoalwater Bay)	■	■	■	■	■	■	■	■	■
reef intertidal	GK1	Great Keppel Is.	■	■	■	■	■	■	■	■	■
	GK2	Great Keppel Is.	■	■	■	■	■	■	■	■	■

5.5.3.1 Seagrass index and indicator scores

In the 2019–20 monitoring period, the seagrass condition index remained relatively stable and was graded as **poor** (Figure 71).

The abundance score increased marginally on average, but remained poor (Figure 71).

Reproductive effort has remained low since 2011–2012 and scored very poor in 2019–20 for the seventh year in a row. Therefore, fluctuations in the seagrass condition index over the last seven monitoring periods have been primarily driven by fluctuations in abundance and tissue nutrient status.

Tissue nutrient elemental C:N increased slightly in 2019–20, but remained on the grade threshold of poor (Figure 71).

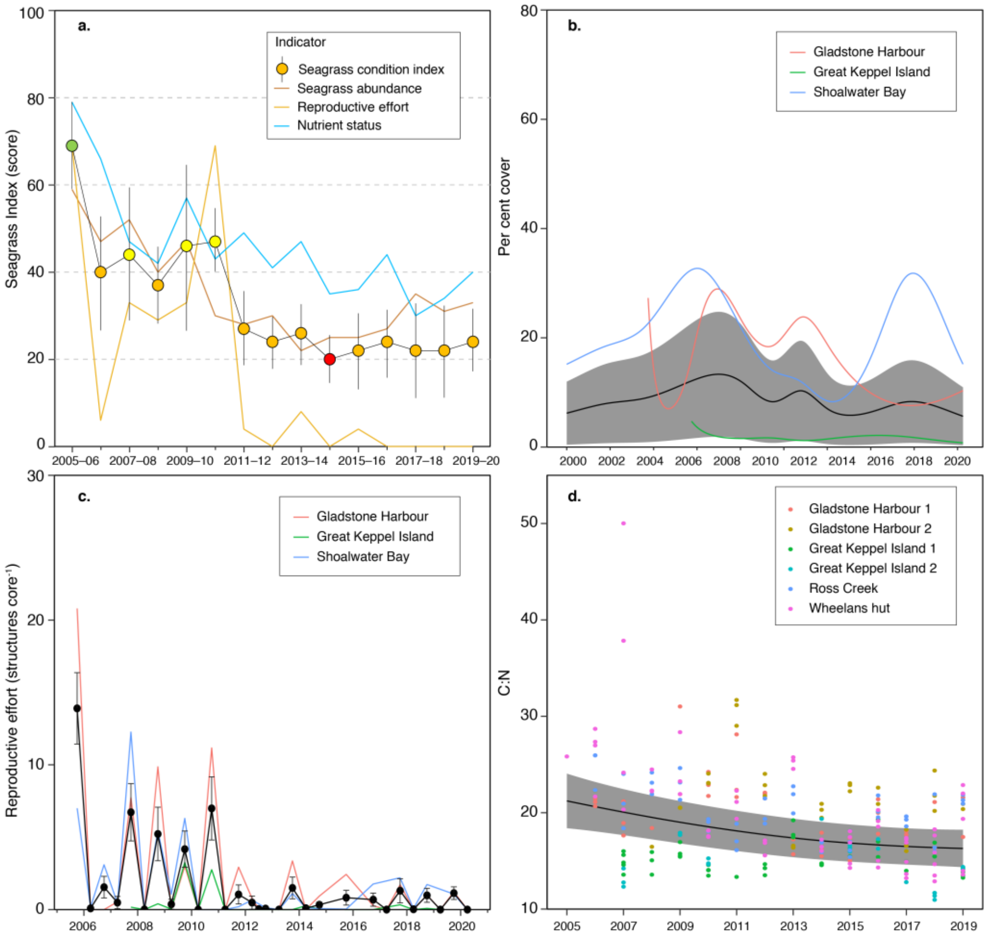


Figure 71. Temporal trends in the Fitzroy seagrass condition index and the indicators used to calculate the index: a. seagrass condition index (circles, ± SE) and indicator trends (lines); b. GAM plots of seagrass abundance (per cent cover) trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); c. average number of reproductive structures (±SE) (GAM not possible due to high count of zero values); and d. elemental ratios (atomic) of leaf tissue C:N nutrient content at each site (coloured circles) and regional trend represented by a GAM plot as dark line with shaded areas defining 95 per cent confidence intervals of the trend

5.5.3.2 Seagrass abundance, composition and extent

In 2019–20, coastal and reef sites declined in abundance relative to the previous period, however, this was offset by the estuary sites where one site (GH1) doubled in abundance and the other site remained stable. Seagrass abundances (per cent cover) in the Fitzroy region in 2019–20 were significantly higher in coastal (18.2 ±0.7 per cent) and estuarine (11.2 ±1.8 per cent) habitats, than reef (0.5 ±0.3 per cent) (Figure 72). Seagrass abundances across all habitats were higher in the late dry than the late wet season (e.g. coastal 25.2 ±0.7 per cent and 11.2 ±0.7 per cent, respectively).

Seagrass abundance at estuary and coastal intertidal habitats has fluctuated greatly between years over the life of the monitoring, with some sites experiencing total or near total loss followed by recovery (Figure 72). In 2019–20, all but one of the coastal sites decreased in abundance relative to the previous period, but the increase at GH2 was enough to slightly elevate the score for the region (Figure 72).

Examination of the long-term trend in seagrass abundance (per cent cover) across the region reveals a significant decrease (Figure 71, Table 21). These decreases have primarily occurred in the estuary and reef habitats, although two thirds of all monitoring sites in the region (including coastal) show no significant trend (Table 21).

Seagrass abundance in the estuarine habitat — believed to be low due to a legacy of a mud wave traversing across the meadow — is showing signs of recovery at GH2, leading to a general increase in abundance for the habitat type. As the mud wave dissipated in 2018–19, meadow integrity (e.g. reduced scarring) improved.

In the north of the region, coastal sites receive low river discharge, however, the meadows were still exposed to turbid ‘brown’ sediment laden waters for much of the year. There turbid waters could be partly the result of wind-driven resuspension, but appear mainly the consequence of the extreme tidal movement in Shoalwater Bay (some of the highest along the Queensland coast).

Seagrasses in Shoalwater Bay are able to persist on the large intertidal banks, where periods of shallowing water provide some respite from the highly turbid waters. However, these periods of shallowing water and carbon limitation (when exposure to air coincides with low spring tides) not only stress plants with desiccation, but also fluctuating water temperatures.

Maximum water temperatures exceeded 35°C for a total of 57 days in Shoalwater Bay during 2019–20, with a highest temperature of 40.5°C. The high temperatures are particularly stressful for *Z. muelleri* communities which dominate the coastal habitats as it has a thermal optima for overall net primary productivity of 24°C and above 35°C net productivity goes into deficit, i.e. it loses energy (Collier *et al.* 2017). This is in stark contrast to other tropical species (*H. uninervis* and *C. serrulata*), which must exceed 40°C for respiration rates and photoinhibition to cause the plants to lose energy for pulsed exposure (Collier *et al.* 2017). Similarly, water temperature exceeded 35°C (max 38.3) on 22 days at Pelican banks in Gladstone Harbour and this was likely to have placed a substantial stress on these *Z. muelleri* dominated communities.

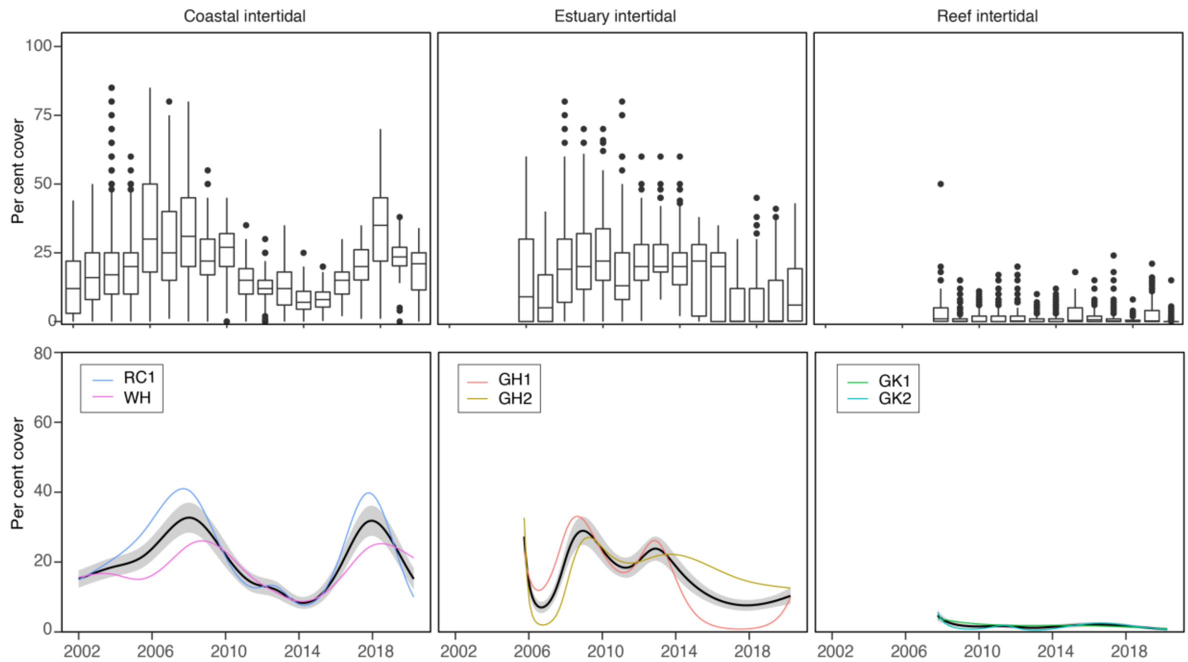


Figure 72. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the Fitzroy NRM region from 2002 to 2019. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero indicates 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, and the dots represent outlying points. GAMM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

Coastal meadows in Shoalwater Bay (Ross Creek and Wheelans Hut) had an increased proportion of colonising species (*H. ovalis*) after 2011 but remained dominated (>0.5) by the opportunistic species *Z. muelleri* and *H. uninervis* (Figure 73). In 2019–20, the proportion of these opportunistic species increased at both the coastal and estuarine sites (Figure 73) which continued to be dominated by *Zostera muelleri*. Colonising species, however, continued to dominate the reef habitat sites (well above the overall inshore Reef long-term average), which appears a direct relationship with decreased abundances over the last few years (Figure 73).

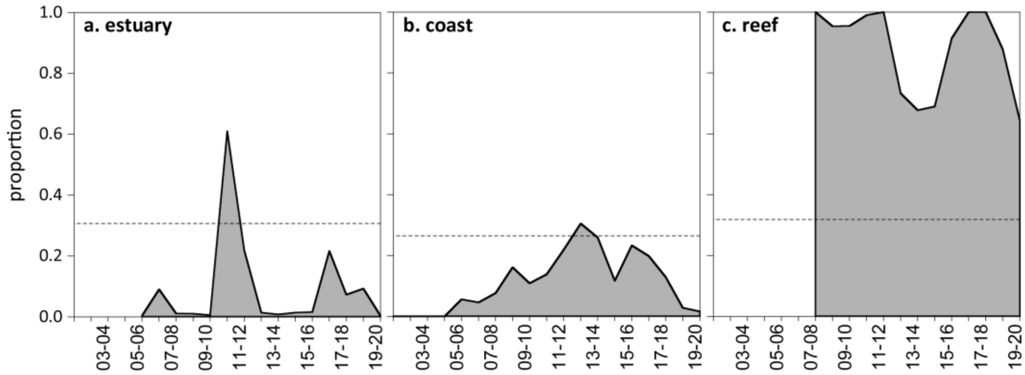


Figure 73. Proportion of seagrass abundance composed of colonising species in inshore intertidal habitats of the Fitzroy region, 2001–2020. Grey area represents Reef long-term average proportion of colonising species for each habitat type.

The extent of the coastal meadows within monitoring sites in Shoalwater Bay has changed little since monitoring commenced in 2005. The extent of the estuarine meadows has fluctuated since 2016 when there was a large reduction in one of the sites due to extensive scarring and sediment deposition. This year the sediment deposition abated and the meadow was showing signs of recovering, e.g. shoot extension and improved meadow cohesion. Conversely, meadows on the reef flat at Great Keppel Island remained highly fragmented after the 2016 losses and show little sign of recovery, e.g. unstable sediments.

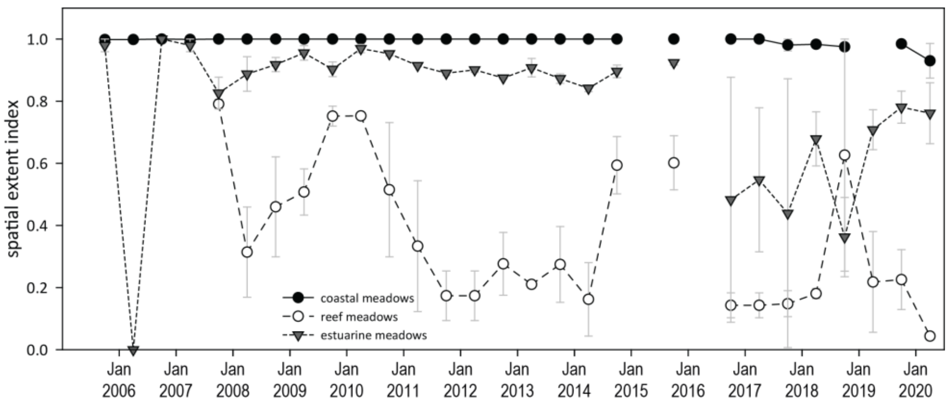


Figure 74. Change in spatial extent (± SE) of seagrass meadows within monitoring sites for each inshore intertidal habitat across the Fitzroy NRM region, 2005–2020.

5.5.3.3 Seagrass reproductive status

Reproductive effort has varied inconsistently among habitats in the Fitzroy region over the life of the MMP (Figure 75). Reproductive effort is higher in the late dry season and remained steady at coastal and estuary sites in 2019–20 (Figure 75). A seed bank has also persisted at coastal and estuary sites since 2012. Reproductive effort has remained very low at reef sites and were absent in 2019–20 together with the seed bank (Figure 75). This limits the meadow capacity to recover following further disturbance.

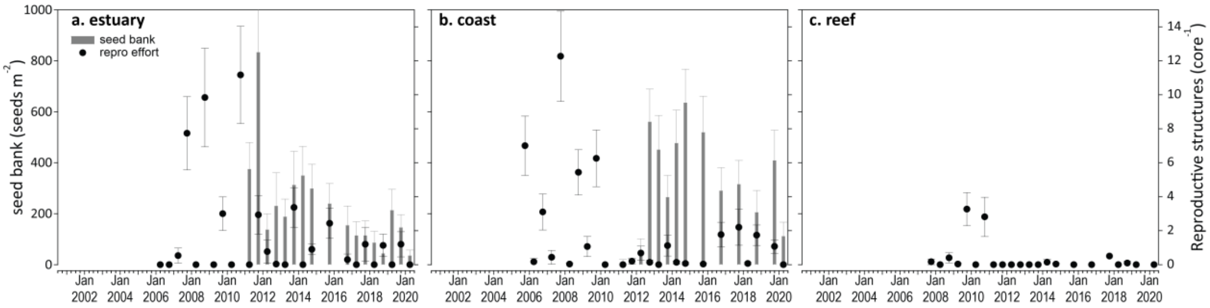


Figure 75. Reproductive effort for inshore intertidal coastal, estuary and reef habitats in the Fitzroy region, 2005–2020. Seed bank presented as the total number of seeds per m^2 sediment surface (bars ±SE), and late dry season reproductive effort presented as the average number of reproductive structures per core (species and sites pooled) (dots ±SE).

5.5.3.4 *Seagrass leaf tissue nutrients*

Seagrass leaf molar C:N ratios marginally increased across all habitats in 2019–20 relative to the previous year. C:N remained at or below 20 at coastal and reef sites (Figure 67), indicating a surplus of N relative to photosynthetic C incorporation. By contrast, C:N increased to over 20 at estuarine sites for the second year out of the previous seven. N:P ratios decreased across estuarine and coastal habitats, due to a large reduction in leaf tissue %P, which has been declining after 2016–17 when large discharges from the rivers and creeks of the region occurred. There is no indication of elevated N, despite per cent N remaining above the global median. The low $\delta^{15}N$ (e.g. decreasing at reef habitats), suggests negligible influence of an anthropogenic source of N (Figure 67).

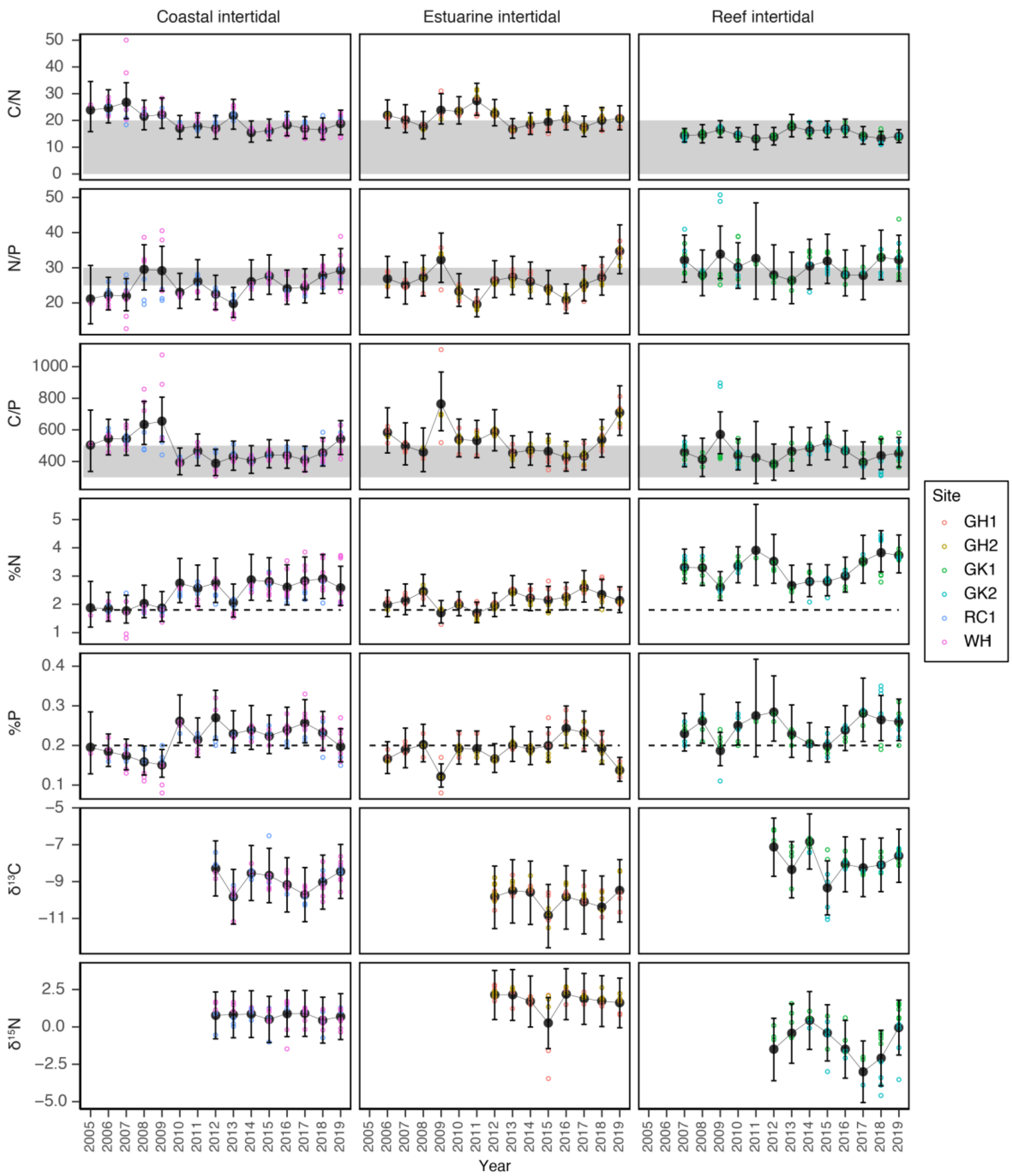


Figure 76. Seagrass leaf tissue nutrient elemental ratios (C:N:P) and concentrations (per cent N, per cent P, $\delta^{13}C$ and $\delta^{15}N$) for each habitat in the Fitzroy region (± SE) (foundation species pooled). Horizontal shaded bands or dashed lines represents the accepted seagrass guideline values, where: C:N ratios within the band may indicate reduced light availability and/or N enrichment; N:P ratios above the band indicate P limitation, below indicate N limitation and within indicates replete, and; C:P ratios within the band may indicate nutrient rich habitats (large P pool). Dashed lines in per cent N and per cent P indicate global median values of 1.8 per cent and 0.2 per cent for tissue nitrogen and phosphorus, respectively (Duarte 1990).

5.5.3.5 Epiphytes and Macroalgae

Epiphyte cover on the leaves of seagrass in estuarine habitats of the Fitzroy region increased in 2019–20 to above the overall inshore Reef long-term average for the first time in four years. At coastal habitats, however, epiphyte abundances continued to fluctuate and at reef habitats remain below the overall inshore Reef long-term average for the seventh consecutive year (Figure 77).

Macroalgae cover remained very low and below the overall inshore Reef long-term average at all habitats in the Fitzroy region, with a minor deccrease at the reef habitat (Figure 77).

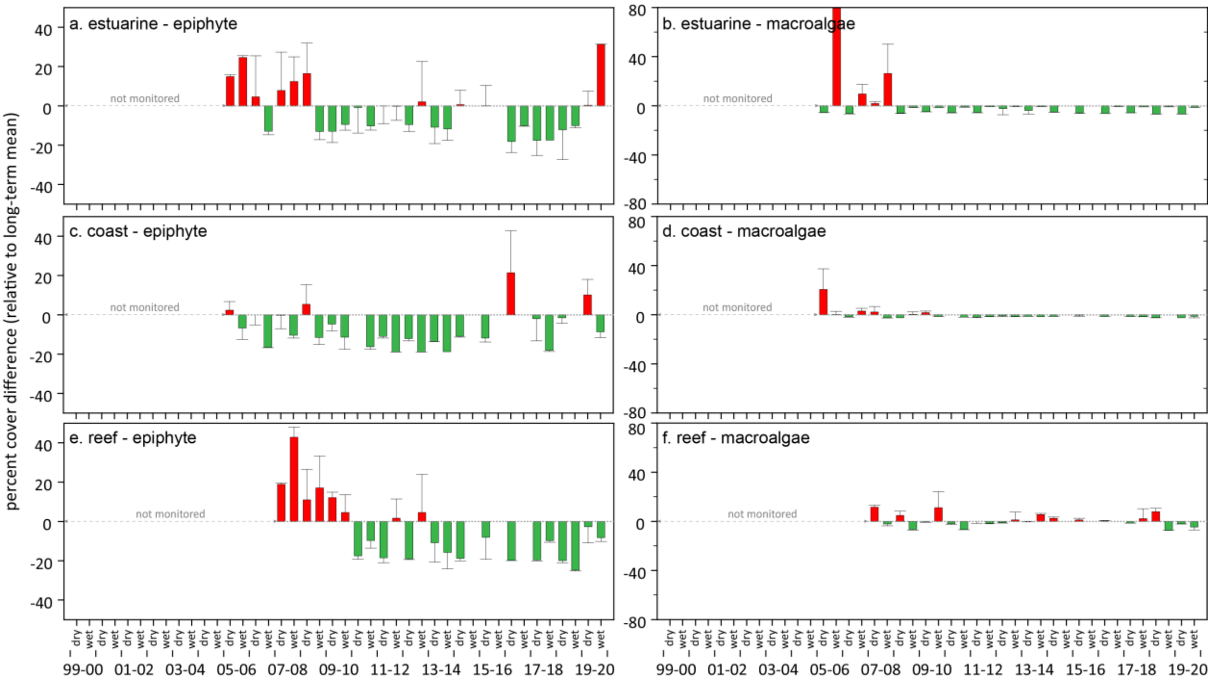


Figure 77. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term average (2005-2018) for each inshore intertidal seagrass habitat in the Fitzroy region, 2005–2020 (sites pooled, ±SE). Green bars indicate positive deviations for condition, red bars negative.

5.6 Burnett–Mary

5.6.1 2019–20 Summary

Environmental conditions were generally moderate in 2019–20, with rainfall and river discharge below average, and yet all sites continued to be exposed to high levels of turbidity, predominantly 'brown' water, for all weeks (100 per cent) during the wet season. Within-canopy temperatures in 2018–19 were slightly above the long-term average for the seventh consecutive year.

Inshore seagrass meadows across the Burnett–Mary NRM region changed little in overall condition in 2019–20, with the index score remaining in a **poor** grade (Figure 78). The scores of abundance and reproductive effort decreased marginally, nutrient status increased but the grades for each remained unchanged. Contributing indicators to the overall score were:

- abundance score was poor
- reproductive effort score was very poor
- tissue nutrient score was poor.

Seagrass abundance decreased mariginally overall, but there are location-specific variations in the trends in the region. Abundances increased at Rodds Bay and Burrum Heads, but abundance and meadow extent declined futher at Urangan.

The persistent seed banks coupled with improved abundances in meadows in the estuarine habitats in the north of the region may indicate an improved resilience; however reproductive effort continues to remain very low across estuarine habitats, possibly limiting replenishment of seed bank.

In late 2019, seagrass leaf tissue nutrient concentrations and ratios continue to indicate surplus availability of N to photosynthetic C incorporation in estuarine and coastal meadows; from natural N-fixation rather than anthropogenic sources. Although N availability may be high, it does not appear to have influenced epiphyte and macroalgae abundances which remain low across the region.

The marginal increase in Burnett–Mary region seagrass condition index in the 2019–20 continues from increases in 2018–19, following the declines in 2016–17 and 2017–18, from the highest score in 10 years, and was driven by increases in the nutrient status indicator.

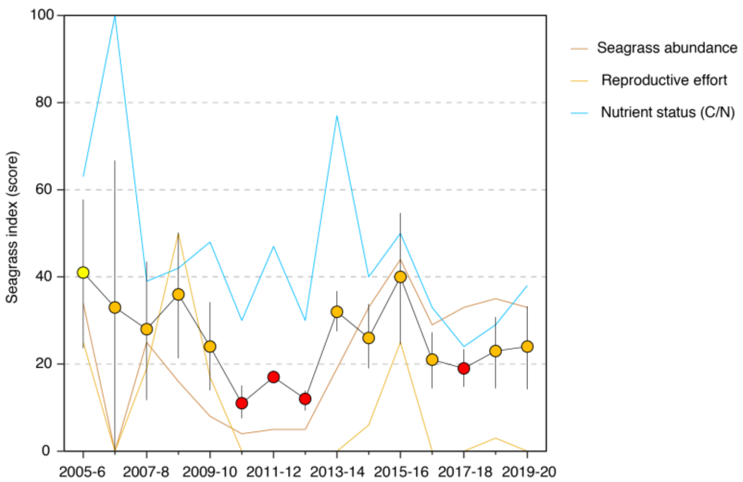


Figure 78. Report card of seagrass index and indicators for the Burnett–Mary region (averages across habitats and sites). Values are indexed scores scaled from 0–100 (± SE) and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

5.6.2 Climate and environmental pressures

During 2019–20, rainfall and river discharge in the Burnett–Mary region were below average (Figure 79, Table 9). But despite this, monitoring sites were exposed to turbid water, predominantly ‘brown’ turbid water for 100 per cent of the wet season (Figure 79).

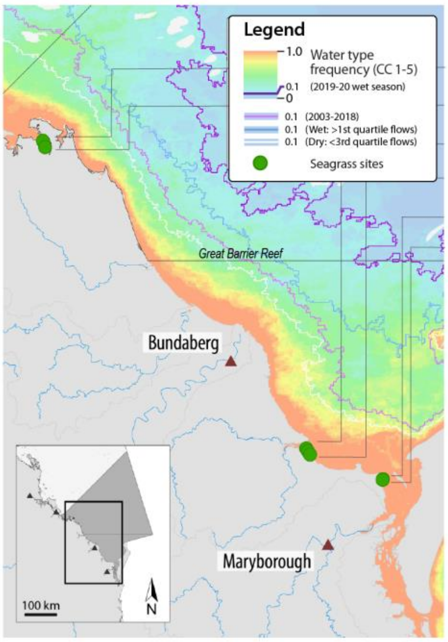
Within-canopy light was lower than the long-term average for the region as a whole (Figure 79, Figure 98). However, due to relocation of RD2 to RD3 and the recent addition of light monitoring to the Burrum Heads sites, it is difficult to assess trends in light levels at this time.

Within-canopy temperatures in 2019–20 were warmer than the previous year and slightly above the long-term average (Figure 79). Maximum intertidal within-canopy temperatures exceeded 35°C for a total of 13 days during 2019–20, with the highest temperature recorded at 40.9°C (UG2, 2pm 07Mar20).

Although daily tidal exposure was well below the long-term average for the region (Figure 79), levels of exposure differed with meadows in the north exposed for longer than those in the south (Figure 98). The less than long-term average exposure may have reduced the risk of temperature and desiccation stress in the south, but may also increase the risk of light limitation in the turbid water areas.

Sediments in the estuary seagrass habitats of the Burnett–Mary region are generally dominated by mud. In 2019–20, the proportion of mud increased in the meadows in the south of the region, after experiencing a period of increased sands in 2018–19. Meadows in the north remained relatively stable, albeit with seasonal variability (Figure 120). Coastal meadows in 2019–20 continued to be dominated by fine sand with little change from the previous year (Figure 121).

a.



b.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
RD1	4	4	4	3	4	2	4	4	4	4	2	1	4	4	3	1	3	4	2	4	1	4
RD2	3	2	3	1	2	1	4	1	4	3	1	1	4	4	3	2	1	2	2	2	3	4
BH1	1	1	4	1	4	1	5	1	4	4	3	1	4	1	4	1	1	4	2	4	1	4
BH3	1	1	2	1	1	1	2	1	2	2	1	1	2	2	4	2	1	2	1	1	1	2
UG1	1	3	4	4	4	2	5	2	5	4	3	1	4	1	4	1	4	4	2	4	1	4
UG2	1	3	4	4	4	2	5	2	5	4	3	1	4	1	4	1	4	4	2	4	1	4

1-4 = turbid primary water (brown), 5 = nutrient/chlorophyll-enriched secondary water (green), 6 = some freshwater/CDOM influence tertiary water (blue), 7 = no plume influence (white), blank = no data, clouds (grey)

c.

	Long-term average	2019-20
Rainfall (1961-1990)	3.3 mm d^{-1}	2.6 mm d^{-1}
River discharge (1970-2016)	1,596,593 L yr^{-1}	928,321 L yr^{-1}
Turbid water exposure (2006-2018)	100%	100%
Daytime tidal exposure (1999-2019)	112 hr yr^{-1}	77 hr yr^{-1}
Wind (1998-2019)	83 days yr^{-1}	67 days yr^{-1}
Within-canopy temperature - intertidal (2003-19)	23.5°C (40.9°C)	23.8°C (40.9°C)
Within-canopy light (2009-2019)	12.2 mol m^{-2} d^{1}	10.9 mol m^{-2} d^{1}

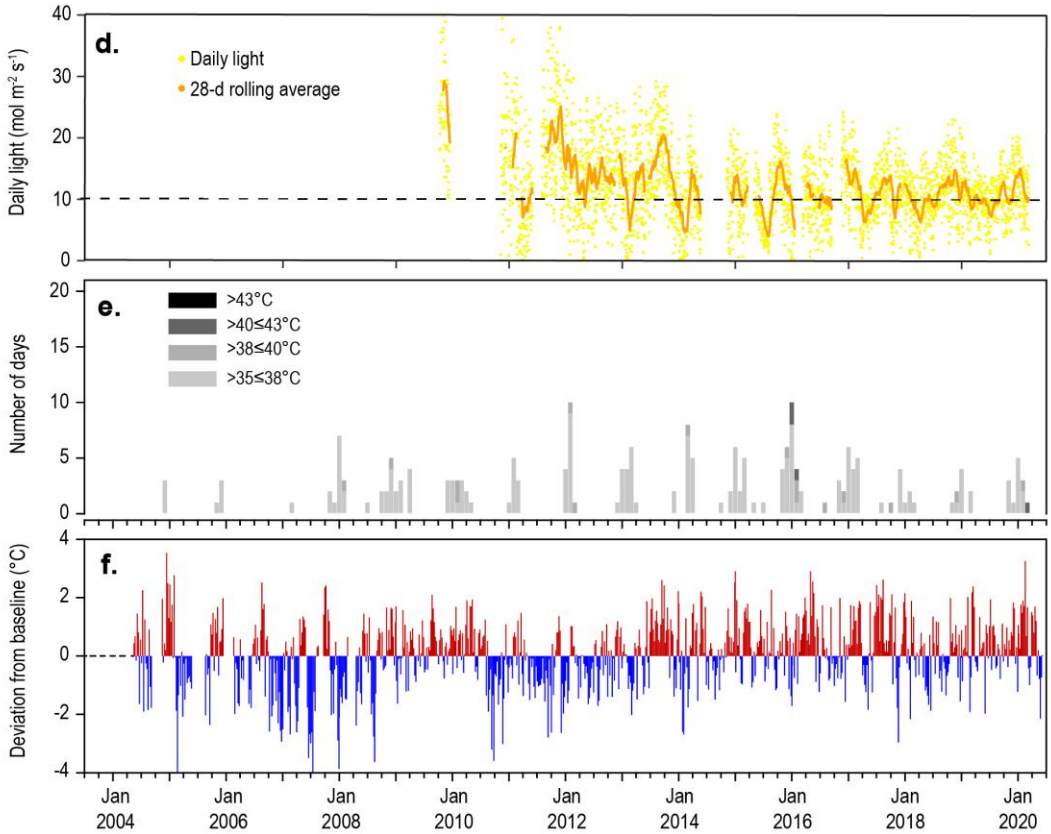


Figure 79. Environmental pressures in the Burnett–Mary region including: a. frequency of exposure to turbid water (colour classes 1–5) (from Waterhouse et al. 2021); b. wet season water type at each site; c. average conditions over the long-term and in 2019–20; d. daily light and the 28-day rolling mean of daily light for all sites; e. number of day temperature exceeded 35°C, 38°C, 40°C and 43°C, and; f. deviations from 14-year mean weekly temperature records.

5.6.3 Inshore seagrass and habitat condition

Only estuarine and coastal habitats were assessed across the Burnett–Mary region in 2019–20, with data from 6 sites (Table 17).

Table 17. List of data sources of seagrass and environmental condition indicators for each seagrass habitat type in the Burnett–Mary NRM region. For site details see Table 3 and Table 4.

Habitat	Site		abundance	composition	distribution	reproductive effort	seed banks	leaf tissue nutrients	meadow sediments	epiphytes & macroalgae
estuary intertidal	RD1	Rodds Bay	■	■	■	■	■	■	■	■
	RD3	Rodds Bay	■	■	■	■	■	■	■	■
	UG1	Urangan	■	■	■	■	■	■	■	■
	UG2	Urangan	■	■	■	■	■	■	■	■
coastal intertidal	BH1	Burrum Heads	■	■	■	■	■	■	■	■
	BH3	Burrum Heads	■	■	■	■	■	■	■	■

5.6.3.1 Seagrass index and indicator scores

In the 2019–20 monitoring period, the Burnett–Mary region seagrass condition index remained largely unchanged and rated as a poor grade (Figure 80). The index remains well below the 2015–2016 level (which was the second highest on record) due to trends in all of the indicators (Figure 80).

Over the long term, seagrass abundance regionally has fluctuated greatly (e.g. periods of loss and subsequent recovery). Increases between 2012 and 2016 were largely due to large increases at Urangan, which have since declined, while abundances at other locations have steadily increased. The long-term trend suggests that where losses have been observed, they are not part of a declining trend (Table 21).

Reproductive effort remained low and rated as very poor in 2019–20. Reproductive effort is generally low in the region, but occasional large increases have occurred in 2008–9 and 2015–16 (Figure 80).

Seagrass leaf tissue nutrient status (C:N), increased slightly in 2019–20. The long term trends of C:N across the Burnett–Mary region using GAM plots suggests there has been no discernible trend since 2005 (Figure 80).

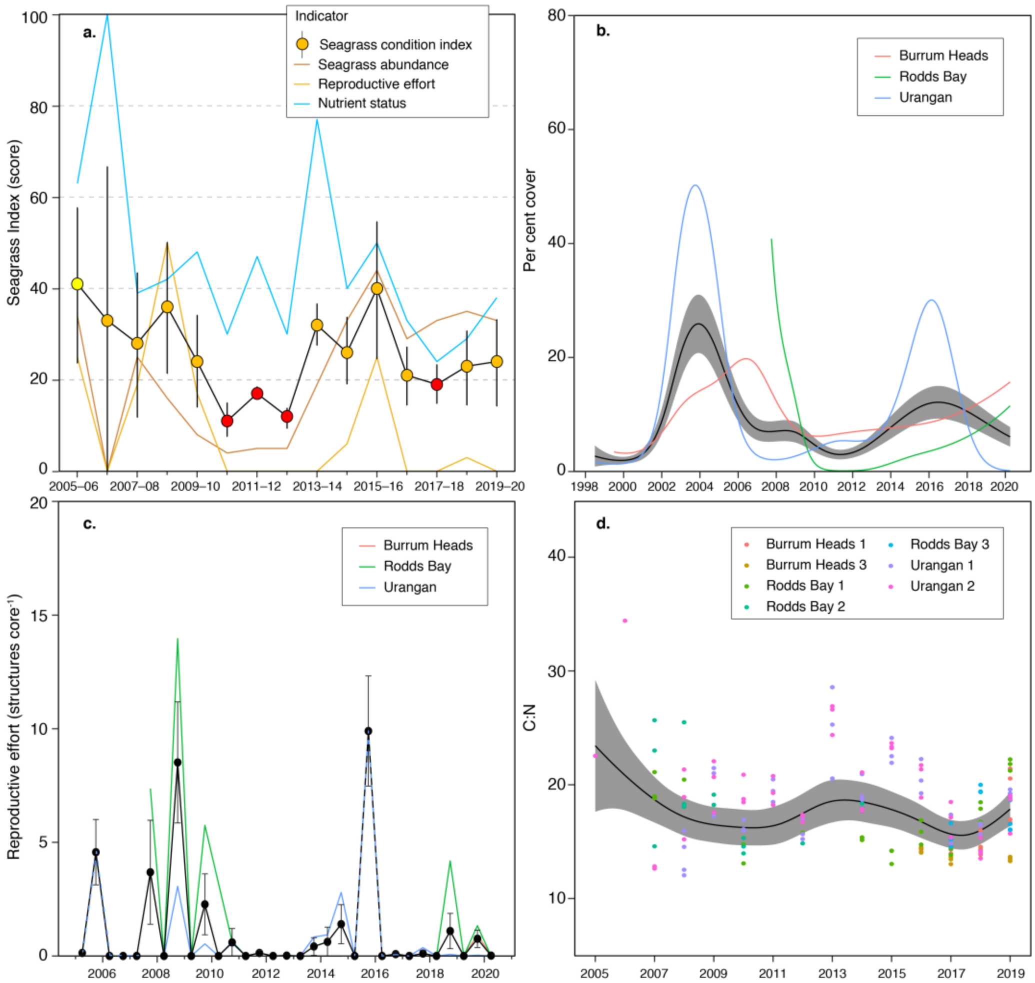


Figure 80. Temporal trends in the Burnett–Mary seagrass condition index and the indicators used to calculate the index: a. seagrass condition index (circles, ± SE) and indicator trends (lines); b. GAM plots of seagrass abundance (per cent cover) trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); c. average number of reproductive structures (±SE) (GAM not possible due to high count of zero values); and d. elemental ratios (atomic) of leaf tissue C:N nutrient content at each site (coloured circles) and regional trend represented by a GAM plot as dark line with shaded areas defining 95 per cent confidence intervals of the trend.

5.6.3.2 Seagrass abundance, composition and extent

Seagrass abundances (per cent cover) across the Burnett–Mary region in 2019–20 were greater in coastal than estuarine habitats (15.2 ±0.6 per cent and 5.8 ±1.5 per cent, respectively), however estuarine abundances were higher in the late dry than the late wet season (10.2 ±2.0 per cent and 1.4 ±0.3 per cent, respectively). Half of the monitoring sites decreased in abundance in 2019–20 relative to the previous period, while only a third increased. Only one of the estuarine meadows in Rodds Bay remained stable in 2019–20.

Since monitoring was established, the estuarine meadows have come and gone on an irregular basis. The only site to significantly decline over the long-term, was in the north of the region in the Rodds Bay estuary (RD2), however this decline was due to changes in the intertidal bank topography which rendered the site no longer suitable for ongoing monitoring, and the site has been discontinued. In the south, despite recent declines, both an estuary and a coastal site have significantly increased over the long-term, while no trend is apparent at the remaining monitoring sites (Table 21).

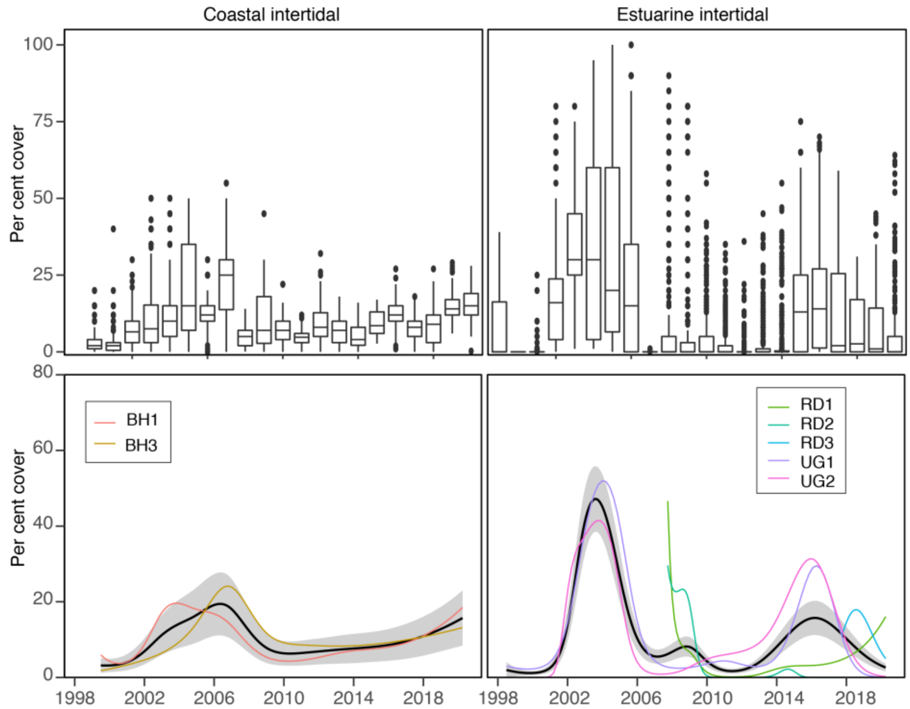


Figure 81. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the Burnett–Mary NRM region from 1999 to 2020. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero indicates 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, and the dots represent outlying points. GAMM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

The estuarine and coastal seagrass habitats have remained dominated by *Zostera muelleri* with varying components of *Halophila ovalis*. In 2019–20, the proportion of colonising species increased at estuarine meadows compared to the previous monitoring year, but conversely continued to decline well below the Reef long-term average in coastal meadows (Figure 82). An increase in the proportion of colonising species in the meadows suggests some level of physical disturbance which may reduce ability to tolerate/resist major disturbances in future.

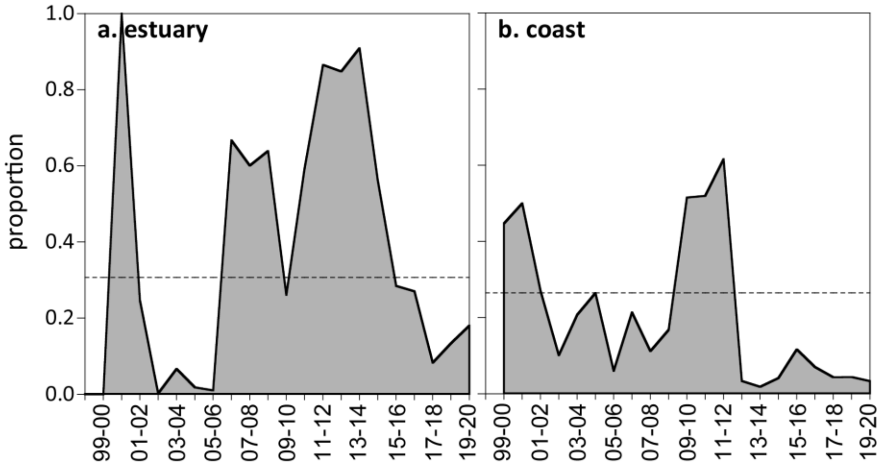


Figure 82. Proportion of seagrass abundance composed of colonising species at: a. estuary and b. coastal habitats in the Burnett–Mary region, 1998–2020. Dashed line represents Reef long-term average proportion of colonising species for each habitat type.

Over the last 12 months, meadow spatial extent has remained stable at coastal meadows relative to the previous year (Figure 83). Estuarine meadows, however, continued to decline slightly in extent. This decline was restricted to meadows in the south (Urangan) which have fluctuated greatly with periods of decline, absence and recovery over the life of the MMP.

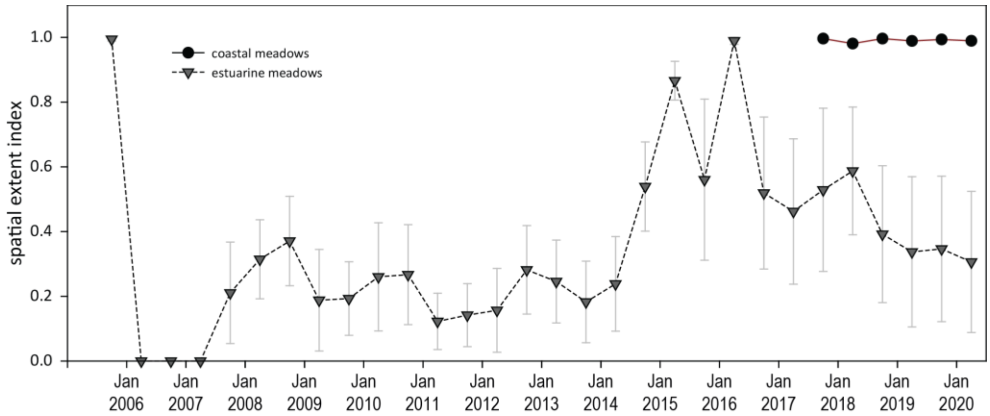


Figure 83. Change in spatial extent (± SE) of estuary seagrass meadows within monitoring sites for each habitat and monitoring period across the Burnett–Mary NRM region.

5.6.3.3 Seagrass reproductive status

Seagrass reproductive effort in the dry season increased for the first time this year at coastal habitats since assessments commenced, but were not as high at estuarine sites compared to the previous monitoring period (Figure 84). A seed bank persists at all meadows monitored across the region, which was slightly greater at estuary sites in 2019–20 than the previous period (Figure 84). This may indicate the meadows have a greater capacity to recover from the declining abundances, provided conditions are favourable.

The apparent disconnect between reproductive effort and seed densities may be an artefact of the sampling frequency and the somewhat stochastic triggers and possibly short flowering period.

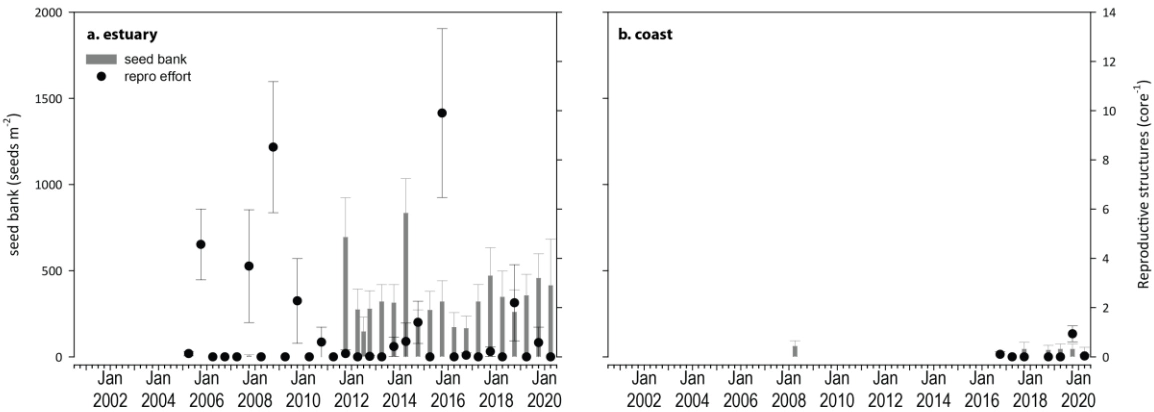


Figure 84. Burnett–Mary estuary seed bank and reproductive effort. Seed bank presented as the total number of seeds per m^2 sediment surface (bars ±SE), and late dry season reproductive effort presented as the average number of reproductive structures per core (species and sites pooled) (dots ±SE).

5.6.3.4 Seagrass leaf tissue nutrients

In 2019, *Zostera muelleri* leaf tissue molar C:N, C:P and N:P ratios increased at the coastal and estuary sites compared to the previous year, but C:N remained below the threshold value of 20 (Figure 85). This indicates a surplus of N relative to photosynthetic C incorporation. Leaf tissue N:P and C:P remained above the threshold (shaded band) in both estuary and coastal habitats, which is indicative of P-limitation and also of surplus N availability (for N:P). The marginally less negative $\delta^{13}C$ and $\delta^{15}N$ remained relatively stable.

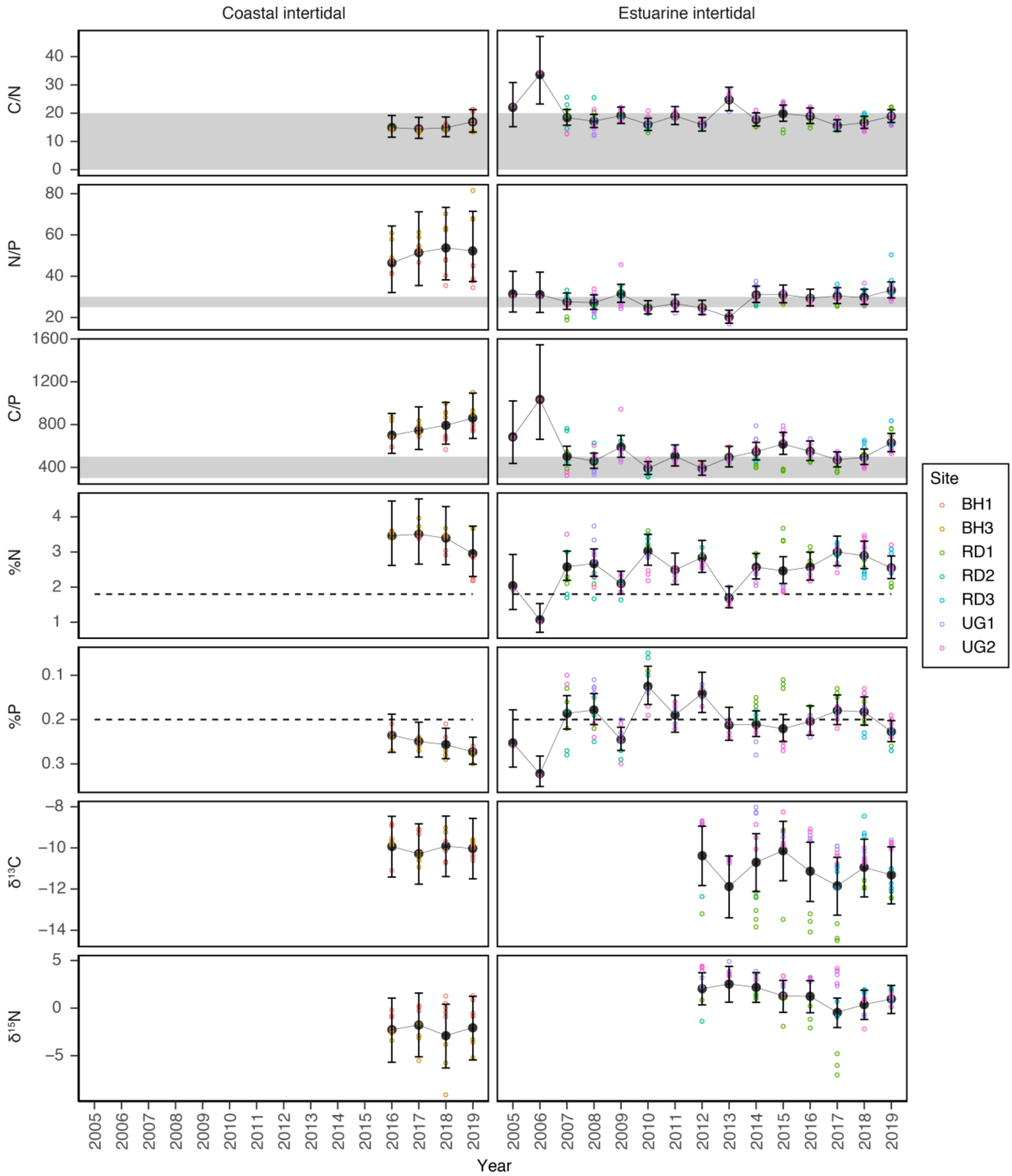


Figure 85. Seagrass leaf tissue nutrient elemental ratios (C:N:P) and concentrations (per cent N, per cent P, $\delta^{13}C$ and $\delta^{15}N$) for each habitat in the Burnett–Mary region (± SE) (foundation species pooled). Horizontal shaded bands or dashed lines represents the accepted seagrass guideline values, where: C:N ratios within the band may indicate reduced light availability and/or N enrichment; N:P ratios above the band indicate P limitation, below indicate N limitation and within indicates replete, and; C:P ratios within the band may indicate nutrient rich habitats (large P pool). Dashed lines in per cent N and per cent P indicate global median values of 1.8 per cent and 0.2 per cent for tissue nitrogen and phosphorus, respectively (Duarte 1990).

5.6.3.5 Epiphytes and macroalgae

Epiphyte cover on seagrass leaf blades in 2019–20 remained higher than the long-term average for the sixth consecutive year at estuarine habitats (Figure 86). Alternatively, at coastal habitats, the epiphyte abundance has remained below the long-term average for the fourth consecutive year (Figure 86).

Per cent cover of macroalgae has remained low and below the long-term average at across the habitats monitored (Figure 86), with the exception of a slight increase in estuarine habitats in the late wet of 2019.

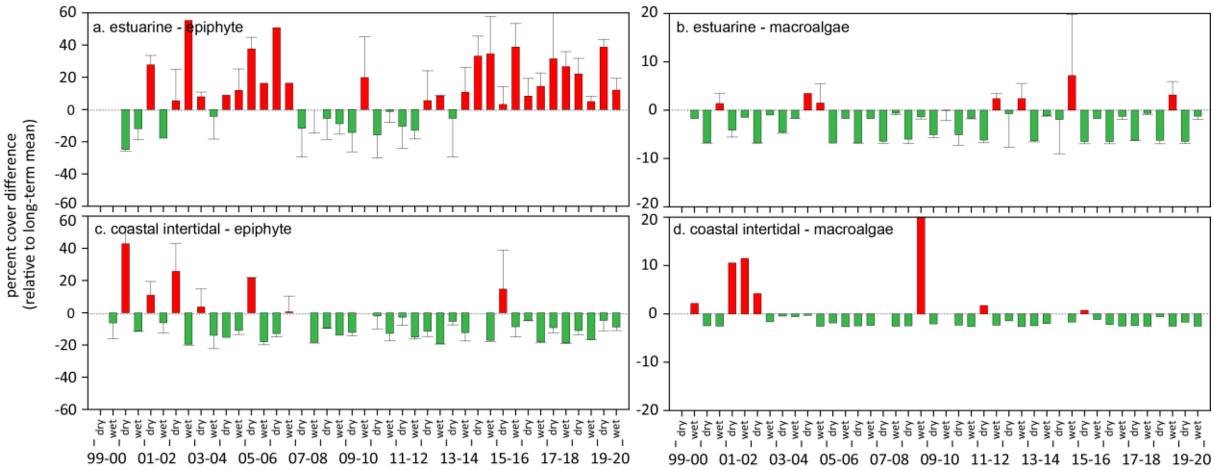


Figure 86. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term average for each seagrass habitat in the Burnett–Mary NRM region (sites pooled, ±SE). Green bars indicate positive deviations for condition, red bars negative.

6 Discussion

Although 2019–20 was a relatively benign year in terms of environmental pressures, some seagrass habitats of the Reef are failing to recover to abundances observed during the first few years of the MMP (2005–2008).

Following the declines experienced between 2009 and 2011, there had been some recovery, however this trend has recently reversed and abundance is on a declining trend. This appears to be associated with low overall resilience (especially reproductive effort and capacity to recover) and cumulative pressures.

Taking a longer historical view using all available data (Figure 17) abundances at estuarine interidal habitats remain well below historical records. This finding is supported by a recent analysis of above-ground biomass (Carter *et al.* 2021).

Abundances at coastal intertidal habitats are in reasonable condition and near historical levels (1998-2005). The coastal subtidal monitoring within this program is relatively recent, and long-term trends cannot be assessed yet, but the recent analysis by Carter et al (2021) also identified that abundance of some subtidal coastal communities was below levels previously reached.

Both estuarine and subtidal coastal habitats generally have periods of low light availability associated with high turbidity or coloured water. Seagrasses in those habitats are likely to be near their minimum light requirements for most of the time. This makes them vulnerable to additional incursions below light thresholds and may be one of the reasons they have not recovered.

Abundances at reef habitats have remained below historical levels for the last decade (Figure 18), which coupled with the persistently low levels of reproductive effort and low numbers of seeds, suggests an ecological system that is strained, and vulnerable to further impacts. In the following sections resilience and cumulative pressures are discussed.

6.1 Seagrass resilience

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), which is essentially the capacity of an ecosystem to cope with stress (Connolly *et al.* 2018). Seasonal and inter-annual variability in pressures on the Reef drive dynamic changes in seagrass meadows, such that state is dependent on being able to recover following events, particularly in the dynamic estuarine and coastal habitats where the impacts are greatest. In short, recovery capacity is very important for seagrass meadows of the Reef.

Throughout the inshore Reef, the rate of seagrass recovery since 2011 has been slow in some locations compared to earlier documented recovery rates (e.g. Birch and Birch 1984; Campbell and McKenzie 2004). The resilience of the meadows of the Reef appears to be suppressed, partly due to low reproductive effort and seed density. This, coupled with ongoing disturbances continues to present a concerning outlook.

Sexual reproduction facilitates adaptation through genetic diversity, and the presence of viable seeds and their germination increases the recovery aspect of resilience (Randall Hughes and Stachowicz 2011). At some of the reef sites reproductive structures are never observed for some species, while at others there is some reproductive effort but seed banks are not forming or persisting either because no seeds are being produced, or seeds are lost through other processes, such as predation (Orth *et al.* 2006). The absence of a seed bank and poor reproductive effort has left many of the inshore meadows across the Reef vulnerable.

Resilient seagrass meadows are able to resist pressures to some degree and recover following decline, and these are linked to the life-history strategies of the species present. Measuring resilience is challenging, however, characteristics that exemplify a seagrass meadows' resistance and recovery mechanisms have been identified (Udy *et al.* 2018). A subset of those have been used to develop a resilience metric, which is based around reproductive effort but is scored according to species-specific flowering and resistance strategies (Collier *et al.* 2021).

Meadows that have a high proportion of persistent species, such as *Thalassia hemprichii*, are recognised as having some measure of resilience because they are able to resist disturbances, even though they rarely flower. By contrast, a meadow with a high proportion of colonising species, such as *Halophila ovalis*, may not be 'resilient', even if flowering prolifically, because they have low capacity to resist disturbances and are therefore scored accordingly low.

In 2019–20 the resilience metric declined across the Reef on average for the fourth year in a row (Collier *et al.* 2021), supporting that resilience is compromised and the inshore seagrass meadows are vulnerable to impacts.

Natural recovery requires environmental conditions that enable expansion following loss, and subsequent sexual reproduction and seed bank formation. Our monitoring reveals that it can take more than five years for foundational seagrass species of the Reef to recover following loss. However, multiple, cumulative and consecutive pressures over the past 15 years have likely hampered recovery.

6.2 Pressures on seagrass meadows

Chronic declines in inshore water quality of the Reef since European settlement have contributed to major ecological shifts in a few Reef marine ecosystems (De'ath and Fabricius 2010; Roff *et al.* 2013).

This has been caused in part by intensive use of the catchments for agriculture and grazing, which have led to an increase in the anthropogenic sediment, organic matter and nutrient load to the Reef (Lewis *et al.* 2021). Flood waters deliver these terrestrially sourced pollutants dispersing them over the sensitive inshore ecosystems, including seagrass meadows (summarised in Schaffelke *et al.* 2013). These in turn reduce water clarity and the amount of light able to penetrate to benthic habitats (Bainbridge *et al.* 2018).

Concerns over the health of inshore water quality underpin the Reef 2050 Water Quality Improvement Plan, and the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program; of which the MMP and inshore seagrass monitoring is a component. But multiple pressures are the cause of ecological decline, including cyclone damage and coastal development for urban centres and commercial ports (Schaffelke *et al.* 2017; De'ath *et al.* 2012), while climate change and rising temperature has left the Reef less resilient, and more challenging to manage (GBRMPA, 2019).

Cumulative pressures appear to have slowed and abated inshore seagrass recovery across the Reef, which in turn may reduce capacity of the plants to produce viable seed banks in some locations (van Katwijk *et al.* 2010). There were frequent and repeated disturbances over the past decade and a half, and some of these pressures are summarised in Figure 87.

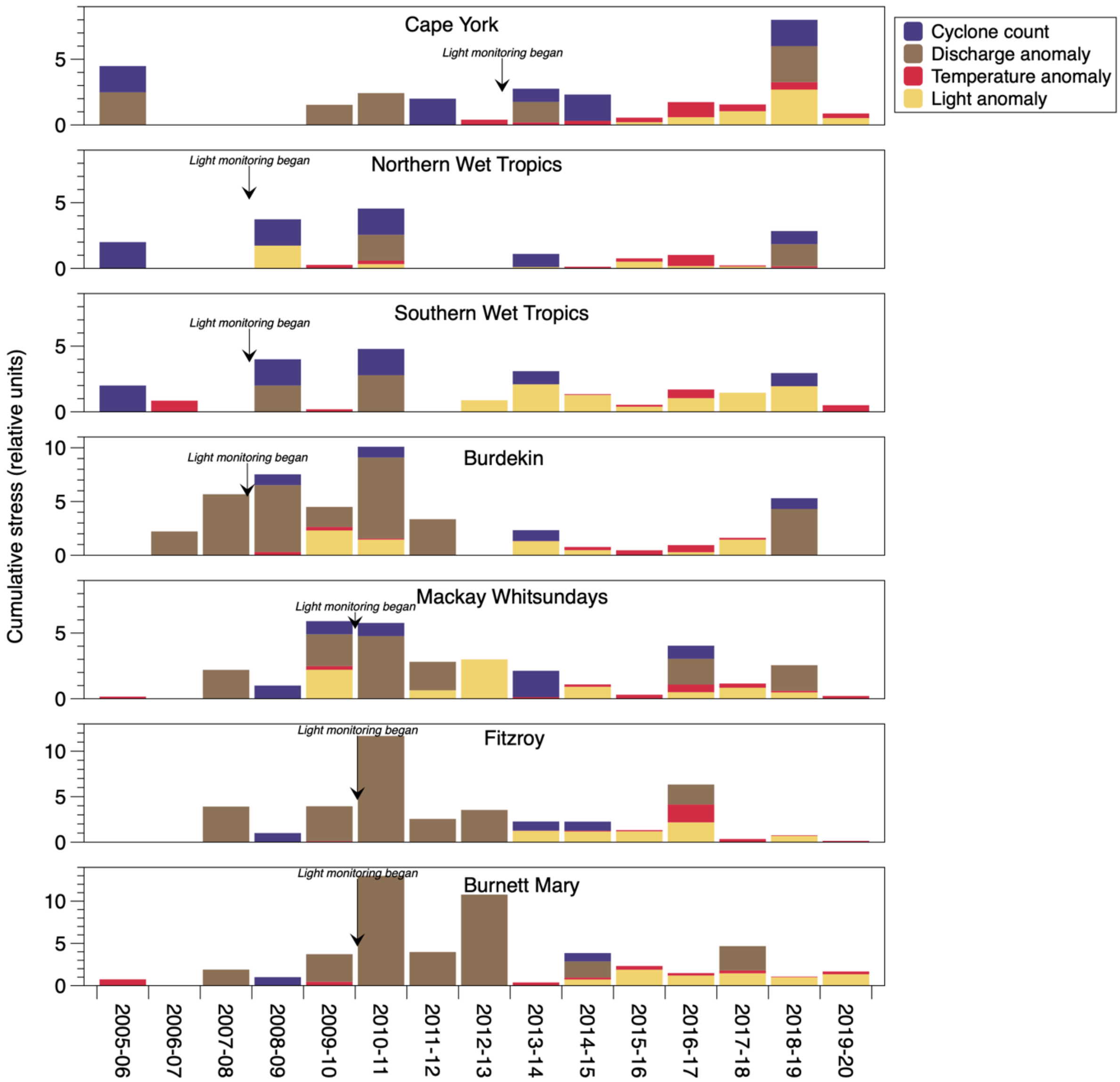


Figure 87. Cumulative pressures on seagrass habitats of the inshore regions of Reef, by NRM region from 2005 to 2020. This includes count of cyclones to affect each region, discharge anomaly as the magnitude of discharge volume greater than 1.5 times the median value, annual average within-canopy temperature above the long-term annual average, and the annual average above-canopy daily light less than the long-term average. Initiation of light monitoring is also indicated.

Cyclones de-stablise sediments and physically remove seagrass plants and seed banks. Though these impacts tend to be localised, they can be very severe and recovery can be difficult if the substrate is altered and propagules (including plants and seeds) are lost.

Cyclones are more common in the northern region of the Reef (Figure 87). While Cape York is generally less affected by anthropogenic activities than the southern regions, frequent cyclone disturbances occur. Both Cape York and the Wet Tropics have been affected by cyclones in 5 of the past 15 years. Cyclones are one of the principal causes of loss and low recovery in the southern Wet Tropics which was affected by severe cyclones Larry in 2006 and Yasi in 2011. The Mackay–Whitsunday region has also been affected by cyclones in five of the previous 15 years with lasting impacts in some locations, e.g. Whitsunday Islands.

The more widespread impacts of cyclones arise from heavy rainfall and elevated river discharge. Large discharges can be caused by rainfall associated with the cyclone itself, or by generally unstable wet season conditions and rainfall associated with the monsoon trough, when cyclones are also more likely to occur. There were consecutive years of above average discharge before and after 2011, particularly in the central and southern regions.

One of the principal pathways through which discharge affects seagrass ecosystems is the reduction in light associated with high concentrations of suspended sediments, nutrients and organic matter of discharges (Bainbridge *et al.* 2018; Lewis *et al.* 2021). Resuspension of this material prolongs the impact of discharge for months or even longer in inshore regions (Fabricius *et al.* 2016). Indeed seagrass monitoring sites are exposed to a very high frequency of coloured or turbid water even in low discharge years (Figure 26, Figure 35, Figure 36, Figure 52, Figure 61, Figure 70, Figure 79).

Benthic light levels were also below average for a number of years in all regions since light monitoring began, even when discharge levels were lower than average (Figure 10). There were low and variable light levels across the Reef habitats from 2014–15 to 2018–19 in most regions, but this trend appeared to reverse in 2019–20 (Figure 8, Figure 87). Additionally, the effects of low light can take some time to manifest, as seagrasses are able to tolerate low light by drawing on carbohydrate reserves. As these deplete, morphological change and shoot loss occurs (Collier *et al.* 2012b; Collier *et al.* 2016a; O'Brien *et al.* 2018). As an example, declines in abundance in the Burdekin region, which are a legacy of floods and low light conditions in 2019, are the main contributor to low overall abundance in 2019–20. This is of high significance in a region which contains the second highest area of inshore seagrass in the Reef and where declining seagrass condition can severely impact "downstream" species of conservation concern which are dependent on seagrass e.g. dugongs and turtles (Wooldridge 2017).

These periods of low light have coincided with years of elevated water temperature. Climate change is the most significant threat to the Reef's long-term outlook (GBRMPA, 2019), and thermal anomalies are emerging in seagrass habitats as well. It has become more common for within-canopy water temperature in any week to be above average than below average since 2013 (Figure 11).

Annual temperature was above average in most years in most regions since 2013 (Figure 87). Extreme temperatures that cause photoinhibition and 'burning' (>40ºC) occur when heatwaves coincide with low tides are still relatively rare, but increasing in some regions such as the Fitzroy (Figure 70). The chronic effect of rising water temperature may be taking a physiological toll by increasing respiration rates and seagrass light requirements (Collier *et al.* 2012a; Collier *et al.* 2016a). These high temperatures have been occurring in years when light levels were also low, and have likely been acting in concert to hamper recovery rates.

There are numerous other potential stressors including changes to herbivory, habitat fragmentation, acidification, competition with macroalgae, infection and increased desiccation.

Except for extreme events (very large discharge and cyclones), it is difficult to ascribe cause to any one pressure when there are many occurring successively or concurrently. However, through targeted research, cumulative pressures can be quantified and cumulative indices of pressure developed (Uthicke *et al.* 2016; Lawrence 2019; Uthicke *et al.* 2020).

6.3 Emerging priorities for management

Practicable conservation opportunities exist, which can make substantial and quantifiable improvements to seagrass condition. Management initiatives that target reversing wider-scale catchment degradation and poor water quality (i.e. Paddock 2 Reef), are expected to benefit inshore seagrass by improving resilience to other stressors. Minimising localised pressures from coastal and urban runoff, and the direct effects of coastal development (e.g. dredging) will also reduce cumulative stress.

In addition to direct action, improving the accuracy of indicators, and refining thresholds and indices of pressures, including cumulative stress, will improve our understanding of seagrass status and resilience and options for management.

Some of these management options were outlined in the previous report (McKenzie *et al.* 2021), and are summarized and updated here:

1. Accurate models of seagrass recovery to identify when recovery is on track or when intervention may be required.
2. Risk assessments updated to ensure that the most relevant pressures are being measured (in the most relevant manner), and methods for assessing cumulative impacts need to be developed.
3. Site-level monitoring undertaken in this program scaled to broader-levels (e.g. RIMReP) to fully capture the extent of habitat decline and recovery so that the potential ecological consequences can be inferred. For example, continuous improvements in earth observing imagery of the Reef, Remote Automated Vehicles (ROVs), along with advances in machine- and deep-learning to process images, offer opportunities for broad-scale assessment of seagrass condition and health in some habitat types that were not available in the past.
4. Indicators reviewed and revised as needed. For example, a resilience indicator has been developed as a replacement for the reproductive metric and will be applied in future reports (Collier *et al.* 2021). However, resilience is complex and the indicator includes quantitative measures of only a few elements of resilience (Udy *et al.* 2018). Further exploration of practicable ways to assess resilience that inform current status and future risk would be informative.
5. Active environmental engineering may be considered in localised areas to improve habitat suitability, by mitigating limiting factors (e.g. wave energy, erosion) or creating new habitat.
6. Active seagrass restoration or enhancement of resilience may be of benefit, but significant research is required before techniques can be operationalised (see also Tan *et al.* 2020). The basis of poor and variable reproductive effort could be investigated, as reproduction underpins the capacity for meadows to recover naturally, and seeding offers a potential restoration strategy.

7 Conclusion

This year inshore seagrass meadows across the Reef were relatively stable in overall condition, with the seagrass Index remaining **poor**. The abundance score declined from moderate to poor, but the reproductive effort and tissue nutrient scores increased slightly. Environmental conditions were relatively benign across the Reef in 2019–20, but there were legacy effects of pressures from the previous year.

In 2019–20, the inshore seagrass of the Reef was in a **poor** condition in all NRM regions. Slight improvements in seagrass condition in the Burdekin and Mackay–Whitsunday regions were offset by continuing (albeit slight) declines in the northern NRMs, while the most southern NRMs remained relatively unchanged. The largest improvement was in the Mackay–Whitsunday region. Improvements overall were driven mostly by increases in the tissue nutrient indicator. The Index has been poor or very poor for an extended period in all regions (at least since 2011-12), except the Burdekin region, which displayed recovery and subsequent decline since 2011.

Seagrass abundance had been increasing at most locations since 2010–11, but declined in condition in the past three reporting years, including in the northern NRMs in 2019–20. The decline was driven predominantly by seagrass loss in the Burdekin region, but there were also declines in abundance at more than a third of sites in Cape York, Fitzroy and Burnett–Mary regions.

Climatic conditions in 2019–20 were benign with no cyclones, low discharges from rivers, average or above average benthic light levels and moderate temperatures. But the Reef occurs in a climate belt where variable rainfall patterns and cyclones, and increasingly in recent years - marine heatwaves - creates frequent disturbances moving up and down the 2,300 kilometre coastline creating complex and varied environmental conditions (Figure 88)(Babcock *et al.* 2019). These appear to have placed seagrass habitats of the Reef under strain and prevented recovery even in a year without notable impacts. The Burdekin region also experienced the legacy effects of very high discharges in 2019 through declines in seagrass abundance.

There were some positive signs including increasing or stable abundances at over half of sites, nearly a third of meadows continuing to expand, declining epiphyte loads and increasing reproductive effort at a third of sites.

Tropical seagrasses of the Reef are a mosaic of different habitat types with multiple seagrass species assemblages. At a habitat level, those in poorest condition were estuarine habitats which have very low abundances. Reef habitats also have consistently very poor reproductive effort and low or no seeds in the seed banks.

Trends

Seagrass meadows of the Reef are dynamic, with large changes in abundance being seemingly typical in some regions (e.g. Birch and Birch 1984; Preen *et al.* 1995; Campbell and McKenzie 2004; Waycott *et al.* 2007), but the timing and mechanisms that cause it (i.e. declines and subsequent recovery) are complex.

In late 2008, locations in the northern Wet Tropics and Burdekin regions were in a moderate state of health with abundant seagrass and seed banks. In contrast, locations in the southern Mackay–Whitsunday and Burnett–Mary regions were in a poor state, with low abundance, reduced reproductive effort and small or absent seed banks (Figure 88).

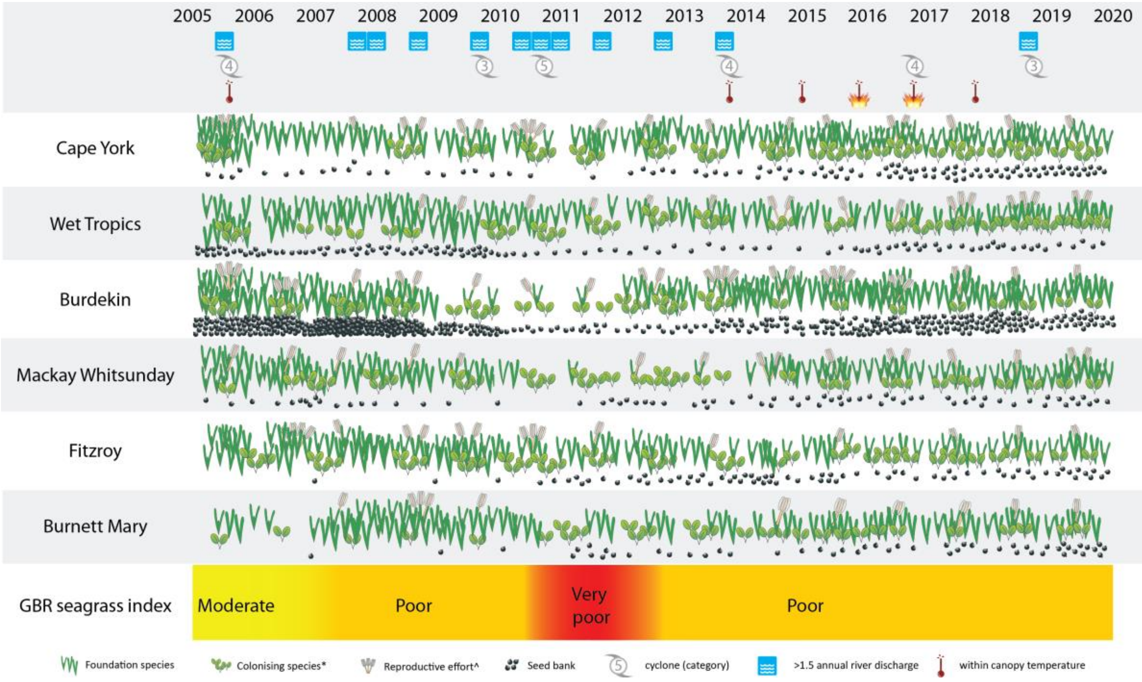


Figure 88. Summary of inshore seagrass state illustrating pressures, abundance of foundation / colonising species, seed banks and reproductive effort from 2005 to 2020. * colonising species are represented by the genus *Halophila*, however, *Zostera* and *Halodule* can be both colonising and foundational species depending on meadow state. ^ not conducted in 2005.

In 2009 with the onset of the La Niña, the decline in seagrass state steadily spread across the Burdekin region and to locations within the Fitzroy and Wet Tropics where discharges from large rivers and associated catchments occurred (McKenzie *et al.* 2010a; McKenzie *et al.* 2012). The only locations of better seagrass state were those with relatively little catchment input, such as Gladstone Harbour and Shoalwater Bay (Fitzroy region), Green Island (northern Wet Tropics), and Archer Point (Cape York) (McKenzie *et al.* 2012).

By 2010, seagrasses of the Reef were in a poor state with declining trajectories in seagrass abundance, reduced meadow extent, limited or absent seed production and increased epiphyte loads at most locations. These factors would have made the seagrass populations particularly vulnerable to large episodic disturbances, as demonstrated by the widespread and substantial losses documented after the floods and cyclones of early 2011.

Following the extreme weather events of early 2011, seagrass habitats across the Reef further declined, with severe losses reported from the Wet Tropics, Burdekin, Mackay–Whitsunday and Burnett–Mary regions. By 2011–12, the onset of seagrass recovery was observed across some regions, however a change had occurred where colonising species dominated many habitats.

The majority of meadows appeared to allocate resources to vegetative growth rather than reproduction, indicated by the lower reproductive effort and seed banks. In 2016–17, recovery had slowed or stalled across most of the regions, and seagrass condition had been gradually declining. It appears cumulative pressures continue to undermine the resilience of inshore seagrass meadows of the Reef. Frequent and repeated disturbances seem to be maintaining lower seagrass abundance at some locations, perpetuated by feedbacks, which in turn may be reducing capacity of the plants to expand and produce viable seed banks.

The Wet Tropics and Fitzroy regions have shown the slowest recovery rates since 2012, although there have been recent declines in all regions except the Mackay–Whitsundays as well. The causes differ between the regions.

In the Fitzroy region declines up to early 2011 were more moderate than in other regions, but the estuarine intertidal and coastal intertidal habitats declined further in 2013–2015, and recovery had since been slow except in coastal habitats.

In the southern Wet Tropics, severe impacts to the substrate from scouring and subsequent deposition of fine sediments in 2011, signficantly delayed the onset of recovery. From 2018, the substrate appeared to be stabilizing and was more conducive for seagrass growth (increasing and less mobile fine sands), however, expansion of the meadows has not occurred as fast as previously experienced (e.g. following cyclone Larry in 2006). It is likely the low seagrass cover is continuing sediment resuspension, i.e. feedbacks are maintaining a disturbed state under average conditions. In such a state, seagrass may require lower environmental thresholds, such as below average temperatures and higher light availablility, before recovery rates improve.

The long-term data sets, dating back to 1998 in some locations, provide valuable insight into the magnitude and periodicity of changes to inshore seagrass meadows. The Burdekin region, for example, has undergone two cycles of extreme recovery and loss, corresponding to periods of above-average discharges from the local rivers and creeks, which are pressures that will continue to influence the region. By contrast some locations in the Wet Tropics and Burdekin regions experienced declines in early 2006 as a consequence of cyclone Larry, but most sites recovered within 1–2 years.

For the Reef's inshore seagrass meadows to improve from their current vulnerable state will require a return to conducive conditions for seagrass growth and reduced environmental pressures in the immediate future.

While climatic conditions cannot be controlled, the scale of effect they have on seagrasses can be lessened through initiative such as the Paddock to Reef Program. It is imperative that resilience, including ability to recover following loss, remains at the forefront of research and management priorities. Thermal anomalies are one of the largest challenges for managing the Reef (GBRMPA, 2019), and there are signs that seagrass habitats are experiencing increasing temperatures, which heightens the need for resilient inshore meadows.

To secure the future of the Reef's seagrass ecosystems, improved ecosystem science on resilience and recovery would be worthwhile. In conjunction with over-arching research, it is important to continue to improve monitoring.

Research and development priorities remain: 1. recovery models, 2. risk assessment and scaling of pressures data, 3. scaling of seagrass condition data, 4. re-assessment of metrics; 5. an assessment of what affects seagrass reproductive effort to inform points 1 to 4; and 6. assessing restoration or enhancement activities, including habitat modifications using engineering approaches to remove limiting factors or create new habitat.

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Appendix 1 Seagrass condition indicator guidelines

A1.1 Seagrass abundance

The status of seagrass abundance (per cent cover) was determined using the seagrass abundance guidelines developed by McKenzie (2009). The seagrass abundance measure in the MMP is the average per cent cover of seagrass per monitoring site. Individual site and subregional (habitat type within each NRM region) seagrass abundance guidelines were developed based on per cent cover data collected from individual sites and/or reference sites (McKenzie 2009). Guidelines for individual sites were only applied if the conditions of the site aligned with reference site conditions.

A reference site is a site whose condition is considered to be a suitable baseline or benchmark for assessment and management of sites in similar habitats. Ideally, seagrass meadows in near pristine condition with a long-term abundance database would have priority as reference sites. However, as near-pristine meadows are not available, sites which have received less intense impacts can justifiably be used. In such situations, reference sites are those where the condition of the site has 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).

There is no set/established protocol for the selection of reference sites and the process is ultimately iterative. The criteria for defining a minimally/least disturbed seagrass reference site is based on Monitoring River Health Initiative (1994) and includes some or all of the following:

- beyond 10 km of a major river: as most suspended solids and particulate nutrients are deposited within a few kilometres of river mouths (McCulloch *et al.* 2003; Webster and Ford 2010; Bainbridge *et al.* 2012; Brodie *et al.* 2012)
- no major urban area/development (>5000 population) within 10 km upstream (prevailing current)
- no significant point source wastewater discharge within the estuary
- has not been impacted by an event (anthropogenic or extreme climate) in the last 3-5 years
- where the species composition is dominated by the foundation species expected for the habitats (Carruthers *et al.* 2002)
- does not suggest the meadow is in recovery (i.e. dominated by early colonising).

The 80th, 50th and 20th percentiles were used to define the guideline values as these are recommended for water quality guidelines (Department of Environment and Resource Management 2009), and there is no evidence that this approach would not be appropriate for seagrass meadows in the Reef. At the request of the Paddock to Reef Integration Team, the 80th percentile was changed to 75th to align with other Paddock to Reef report card components. By plotting the percentile estimates with increasing sample size, the reduction in error becomes apparent as it moves towards the true value (e.g. Figure 89).

Across the majority of reference sites, variance for the 50th and 20th percentiles levelled 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 (2000) Guidelines recommendation of 24 data values. If the variance had not plateud, the percentile values at 24 sampling events was selected to best represent the variance as being captured. This conforms with Kiliminster *et al.* (2015) definition where a enduring meadow is present for 5 years.

Nonlinear regressions (exponential rise to maximum, two parameter) were then fitted to per cent cover percentile values at each number of sampling events using the following model:

$$y = a\left(1 - e^{-bx}\right)$$

where y is the seagrass cover percentile at each number of sampling events (x), a is the asymptotic average of the seagrass cover percentile, and b is the rate coefficient that determines how quickly (or slowly) the maximum is attained (i.e. the slope). The asymptotic average was then used as the guideline value for each percentile (Table 18).

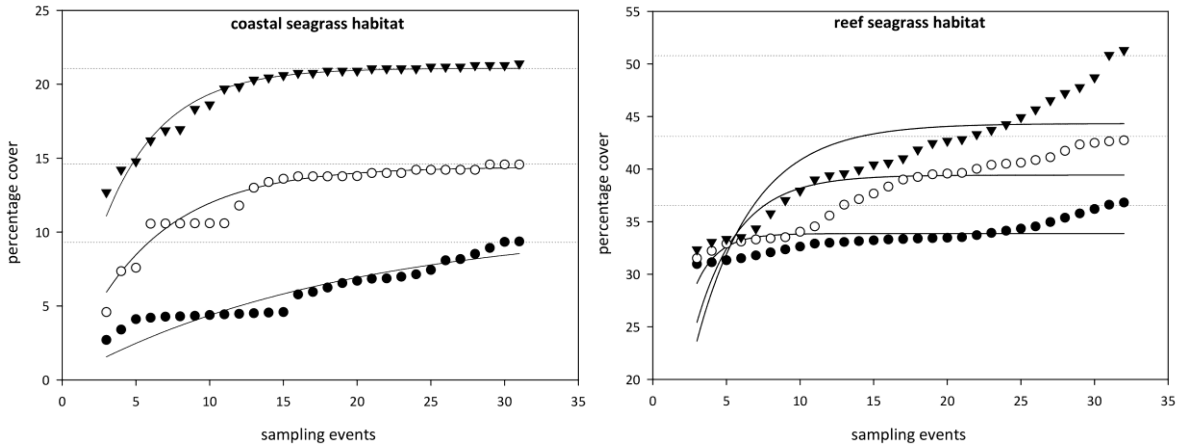

Figure 89. Relationship between sample size and the error in estimation of percentile values for seagrass abundance (per cent cover) in coastal and reef seagrass habitats in the Wet Tropics NRM. ▼ = 75th percentile, ○ = 50th percentile,● = 20th percentile. Horizontal lines are asymptotic averages for each percentile plot.

As sampling events occur every 3-6 months depending on the site, this is equivalent to 3–10 years of monitoring to establish percentile values. Based on the analyses, it was recommended that estimates of the 20th percentile at a reference site should be based on a minimum of 18 samples collected over at least three years. For the 50th percentile a smaller minimum number of samples (approximately 10–12) would be adequate but in most situations it would be necessary to collect sufficient data for the 20th percentile anyway. For seagrass habitats with low variability, a more appropriate guideline was the 10th percentile primarily the result of seasonal fluctuations (as nearly every seasonal low would fall below the 20th percentile). Percentile variability was further reduced within a habitat type of each region by pooling at least two (preferably more) reference sites to derive guidelines. The subregional guideline is calculated from the mean of all reference sites within a habitat type within a region.

Using the seagrass guidelines, seagrass state can be determined for each monitoring event at each site and allocated as:

- good (median abundance at or above 50th percentile)
- moderate (median abundance below 50th percentile and at or above 20th percentile)
- poor (median abundance below 20th or 10th percentile).

For example, when the median seagrass abundance for Yule Point is plotted against the 20th and 50th percentiles for coastal habitats in the Wet Tropics (Figure 90), it indicates that the meadows were in a poor condition in mid-2000, mid-2001 and mid-2006 (based on abundance).

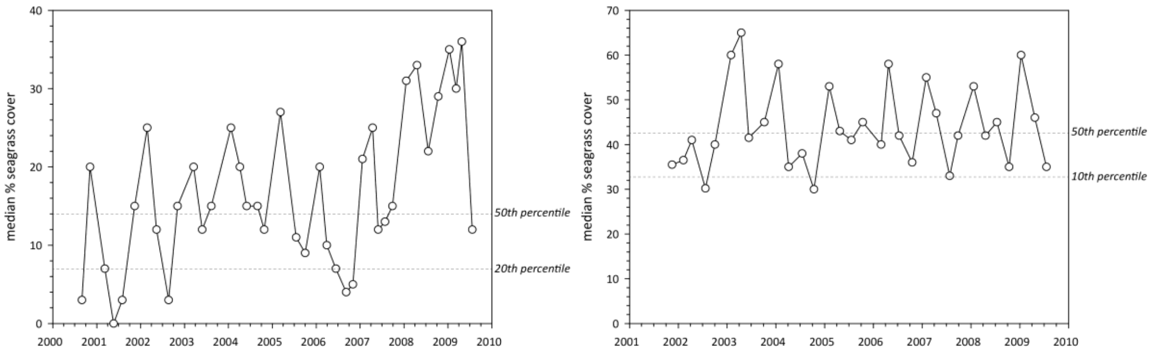

Figure 90. Median seagrass abundance (per cent cover) at Yule Point (left) and Green Island (right) plotted against the 50th and 20th percentiles for coastal and intertidal reef seagrass habitat in the Wet Tropics.

Similarly, when the median seagrass abundance for Green Island is plotted against the 20th and 50th percentiles for intertidal reef habitats in the Wet Tropics, it indicates that the meadows were in a poor condition in the middle of most years (based on abundance). However, the poor rating is most likely a consequence of seasonal lows in abundance. Therefore, in this instance, it was more appropriate to set the guideline at the 10th rather than the 20th percentile.

Using this approach, subregional seagrass abundance guidelines (hereafter known as "the seagrass guidelines") were developed for each seagrass habitat type where possible (Table 18). If an individual site had 18 or more sampling events and no identified impacts (e.g. major loss from cyclone), an abundance guideline was determined at the site or location level rather than using the subregional guideline from the reference sites (i.e. as more guidelines are developed at the site level, they contribute to the subregional guideline).

After discussions with GBRMPA scientists and the Paddock to Reef integration team, the seagrass guidelines were further refined by allocating the additional categories of:

- very good (median abundance at or above 75th percentile)
- very poor (median abundance below 20th or 10th percentile and declined by >20 per cent since previous sampling event).

Seagrass state was then rescaled to a five point scale from 0 to 100 to allow integration with other components of the Paddock to Reef report card (Department of the Premier and Cabinet 2014). Please note that the scale from 0 to 100 is unitless and should not be interpreted as a proportion or ratio.

Table 18. Seagrass percentage cover guidelines ("the seagrass guidelines") for each site/location and the subregional guidelines (bold) for each NRM habitat. Values in light grey not used. ^ denotes regional reference site, * from nearest adjacent region. For site details, see Tables 3 & 4.

NRM region	site/ location	Habitat	percentile guideline			
			10th	20th	50th	75th
Cape York	AP1^	reef intertidal	11	16.8	18.9	23.7
	AP2	reef intertidal	11		18.9	23.7
	FR	reef intertidal		16.8	18.9	23.7
	ST	reef intertidal		16.8	18.9	23.7
	YY	reef intertidal		16.8	18.9	23.7
	NRM	***reef intertidal***	***11***	***16.8***	***18.9***	***23.7***
	FG	reef subtidal	22	26	33	39.2
	NRM	***reef subtidal****	***22***	***26***	***33***	***39.2***
	SR*	coastal intertidal		6.6	12.9	14.8
	BY*	coastal intertidal		6.6	12.9	14.8
	NRM	***coastal intertidal****	***5***	***6.6***	***12.9***	***14.8***
	LR*	coastal subtidal		6.6	12.9	14.8
	BY*	coastal subtidal		6.6	12.9	14.8
	NRM	***coastal subtidal****		***6.6***	***12.9***	***14.8***
Wet Tropics	LB	coastal intertidal		6.6	12.9	14.8
	YP1^	coastal intertidal	4.3	7	14	15.4

	YP2^	coastal intertidal	5.7	6.2	11.8	14.2
	NRM	***coastal intertidal***	***5***	***6.6***	***12.9***	***14.8***
	MS	coastal subtidal		6.6	12.9	14.8
	NRM	***coastal subtidal***		***6.6***	***12.9***	***14.8***
	DI	reef intertidal	27.5		37.7	41
	GI1^	reef intertidal	32.5	38.2	42.7	45.5
	GI2^	reef intertidal	22.5	25.6	32.7	36.7
	LI1	reef intertidal	27.5		37.7	41
	GO1	reef intertidal	27.5		37.7	41
	NRM	***reef intertidal***	***27.5***	***31.9***	***37.7***	***41***
	DI3	reef subtidal	22	26	33	39.2
	GI3^	reef subtidal	22	26	33	39.2
	LI2	reef subtidal	22	26	33	39.2
	NRM	***reef subtidal***	***22***	***26***	***33***	***39.2***
Burdekin	BB1^	coastal intertidal	16.3	21.4	25.4	35.2
	SB1^	coastal intertidal	7.5	10	16.8	22
	SB2	coastal intertidal		10	16.8	22
	JR	coastal intertidal		15.7	21.1	28.6
	BW	coastal intertidal		15.7	21.1	28.6
	NRM	***coastal intertidal***	***11.9***	***15.7***	***21.1***	***28.6***
	MI1^	reef intertidal	23	26	33.4	37
	MI2^	reef intertidal	21.3	26.5	35.6	41
	NRM	***reef intertidal***	***22.2***	***26.3***	***34.5***	***39***
	MI3^	reef subtidal	18	22.5	32.7	36.7
	NRM	***reef subtidal***	***18***	***22.5***	***32.7***	***36.7***
Mackay–Whitsunday	SI	estuarine intertidal		18	34.1	54
	NRM	***estuarine intertidal***	***10.8****	***18****	***34.1****	***54****
	PI2^	coastal intertidal	18.1	18.7	25.1	27.6
	PI3^	coastal intertidal	6.1	7.6	13.1	16.8
	MP2	coastal intertidal		18.9	22.8	25.4
	MP3	coastal intertidal		17.9	20	22.3
	CV	coastal intertidal		13.2	19.1	22.2
	SH1	coastal intertidal		13.2	19.1	22.2
	NRM	***coastal intertidal***	***12.1***	***13.2***	***19.1***	***22.2***
	NB	coastal subtidal		13.2	19.1	22.2
	NRM	***coastal subtidal***	***12.1***	***13.2***	***19.1***	***22.2***
	HB1^	reef intertidal		10.53	12.9	14.2
	HB2^	reef intertidal		7.95	11.59	13.4
	HM	reef intertidal		9.2	12.2	13.8
	NRM	***reef intertidal***		***9.2***	***12.2***	***13.8***
	TO	reef subtidal		22.5	32.7	36.7
	LN	reef subtidal		22.5	32.7	36.7
	NRM	***reef subtidal****	***18****	***22.5****	***32.7****	***36.7****
Fitzroy	GH	estuarine intertidal		18	34.1	54
	NRM	***estuarine intertidal***	***10.8****	***18****	***34.1****	***54****
	RC1^	coastal intertidal	18.6	20.6	24.4	34.5
	WH1^	coastal intertidal	13.1	14.4	18.8	22.3
	NRM	***coastal intertidal***	***15.85***	***17.5***	***21.6***	***28.4***
	GK	reef intertidal		9.2	12.2	13.8
	NRM	***reef intertidal***		***9.2****	***12.2****	***13.8****
Burnett–Mary	RD	estuarine intertidal		18	34.1	54
	UG1^	estuarine intertidal	10.8	18	34.1	54
	UG2	estuarine intertidal		18	34.1	54
	NRM	***estuarine intertidal***	***10.8***	***18***	***34.1***	***54***
	BH1^	coastal intertidal		7.8	11.9	21.6
	BH3	coastal intertidal		7.8	11.9	21.6
	NRM	***coastal intertidal***		***7.8***	***11.9***	***21.6***

A1.2 Seagrass reproductive effort

The reproductive effort is the number of reproductive structures (inflorescence, fruit, spathe, seed) per core. Given the high diversity of seagrass species that occur in the Reef coastal zone (Waycott *et al.* 2007), and their variability in production of reproductive structures (e.g. Orth *et al.* 2006), a metric that incorporates all available information on the production of flowers and fruits per unit area is used.

The production of seeds also reflects a simple measure of the capacity of a seagrass meadow to recover following large scale impacts (Collier and Waycott 2009). As it is well recognized that coastal seagrasses are prone to small scale disturbances that cause local losses (Collier and Waycott 2009) and then recover in relatively short periods of time, the need for a local seed source is considerable. In the Reef, the production of seeds comes in numerous forms and seed banks examined at MMP sites are limited to foundational seagrass species (seeds >0.5mm diameter). At this time, seed banks have not been included in the metric for reproductive effort, but methods for future incorporation are being explored.

Using the annual mean of all species pooled in the late dry and comparing with the long-term (2005–2010) average for Reef habitat (coastal intertidal = 8.22±0.71, estuarine intertidal = 5.07±0.41, reef intertidal = 1.32±0.14), the reproductive effort is scored as the number of reproductive structures per core and the overall status determined as the ratio of the average number observed divided by the long term average.

A1.3 Seagrass nutrient status.

The molar ratios of seagrass tissue carbon relative to nitrogen (C:N) were chosen as the indicator for seagrass nutrient status, as an atomic C:N ratio of <20 may suggest either reduced light availability or nitrogen enrichment. Both of these deviations may indicate reduced water quality.

As changing leaf C:N ratios have been found in a number of experiments and field surveys to be related to available nutrient and light levels (Abal *et al.* 1994; Grice *et al.* 1996; Cabaço and Santos 2007; Collier *et al.* 2009) they can be used as an indicator of the light that the plant is receiving relative to nitrogen availability or N surplus to light. With light limitation, seagrass plants are unable to build structure, hence the proportion of carbon in the leaves decreases relative to nitrogen. Experiments on seagrasses in Queensland have reported that at an atomic C:N ratio of <20, may suggest reduced light availability relative to nitrogen availability (Abal *et al.* 1994; AM Grice*, et al.*, 1996;). The light availability to seagrass is not necessarily an indicator of light in the water column, but an indicator of the light that the plant is receiving as available light can be highly impacted by epiphytic growth or sediment smothering photosynthetic leaf tissue. However, C:N must be interpreted with caution as the level of N can also influence the ratio in oligotrophic environments (Atkinson and Smith 1983; Fourqurean *et al.* 1992). Support for choosing the elemental C:N ratio as the indicator also comes from preliminary analysis of MMP data in 2009 which found that the C:N ratio was the only nutrient ratio that showed a significant relationship (positive) with seagrass cover at coastal and estuarine sites; seagrass tissue C:N ratios explained 58 per cent of the variance of the inter-site seagrass cover data (McKenzie and Unsworth 2009). Using the guideline ratio of 20:1 for the foundation seagrass species, C:N ratios were categorised on their departure from the guideline and transformed to a 0 to 100 score using:

Equation 1 $$\overline{R} = (\mathrm{C:N} \times 5) - 50$$

NB: C:N ratios >35 scored as 100, C:N ratios <10 scored as 0

The score was then used to represent the status to allow integration with other components of the report card.

Appendix 2 Detailed data

Table 19. Samples collected at each inshore monitoring site per parameter for each season. Activities include: SG = seagrass cover & composition, SB=seed bank monitoring, TN=tissue nutrients, EM=edge mapping, RH=reproductive health, TL=temperature loggers, LL=light loggers. ^=subtidal.

GBR region	NRM region	Basin	Monitoring location		late dry Season (2019)							late wet Season (2020)					
					SG	SB	TN	EM	RH	TL	LL	SG	SB	EM	RH	TL	LL
Far Northern	Cape York	Jacky Jacky / Olive Pascoe	Shelburne Bay	SR1	33	30	3	✓	15	✓							
				SR2	33	30	3	✓	15	✓	✓						
			Piper Reef	FR1	33	30	3	✓	15	✓							
				FR2	33	30	3	✓	15	✓	✓						
		Lockhart	Weymouth Bay	YY1													
			Lloyd Bay	LR1^	10												
				LR2^	9												
		Normanby / Jeanie	Flinders Group	ST1	33	30	3	✓	15	✓	✓						
				ST2	33	30	3	✓	15	✓							
				FG1^	9												
				FG2^	10												
			Bathurst Bay	BY1	33	30	3	✓	15	✓							
				BY2	33	30	3	✓	15	✓	✓						
				BY3^	20												
				BY4^	10												
		Endeavour	Archer Point	AP1													
				AP2													
Northern	Wet Tropics	Daintree	Low Isles	LI1	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
				LI2^	33	30			15	✓	✓	33	30	✓	15	✓	✓
		Mossman / Barron / Mulgrave - Russell / Johnstone	Yule Point	YP1	33	30	3	✓	15	✓		33	30	✓	15	✓	
				YP2	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
			Green Island	GI1	33	30	3	✓	15	✓	✓					✓	✓
				GI2	33	30	3	✓	15	✓						✓	
				GI3^	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
		Tully / Murray / Herbert	Mission Beach	LB1	33	30	3	✓	15								
				LB2	33	30	3	✓	15								
			Dunk Island	DI1	33	30	3	✓	15	✓						✓	
				DI2	33	30	3	✓	15	✓	✓					✓	✓
				DI3^	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
			Rockingham Bay	GO1													
			Missionary Bay	MS1^	9												
				MS2^	6												
Central	Burdekin	Ross / Burdekin	Magnetic Island	MI1	33	30	3	✓	15	✓		33	30	✓	15	✓	
				MI2	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
				MI3^	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
			Townsville	SB1	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
				SB2	33	30				✓		33	30	✓	15	✓	
				BB1	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
			Bowling Green Bay	JR1	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
				JR2	33	30	3	✓	15	✓		33	30	✓	15	✓	
	Mackay Whitsunday		Bowen	BW1	33	30						33	30				
				BW2	33	30						33	30				
		Don	Shoal Bay	HB1	33	30				✓		33	30			✓	
				HB2	33	30				✓		33	30			✓	

GBR region	NRM region	Basin	Monitoring location		late dry Season (2019)							late wet Season (2020)					
					SG	SB	TN	EM	RH	TL	LL	SG	SB	EM	RH	TL	LL
		Proserpine	Pioneer Bay	**PI2**	33	30				✓		33	30			✓	
				PI3	33	30				✓		33	30			✓	
		Proserpine / O'Connell	Repulse Bay	**MP2**	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
				MP3	33	30	3	✓	15	✓		33	30	✓	15	✓	
			Hamilton Is.	**HM1**	33	30	3	✓	15	✓						✓	
				HM2	30	30	3	✓	15	✓	✓					✓	✓
			Whitsunday Island	**TO1^**	10												
				TO2^	10												
			Lindeman Island	**LN1^**	33	30	3	✓	15	✓	✓					✓	✓
				LN2^	33	30	3	✓	15	✓						✓	
		O'Connell	St Helens Bay	**SH1**	33	30						33	30				
			Newry Islands	**NB1^**	10												
				NB2^	10												
		Plane	Sarina Inlet	**SI1**	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
				SI2	33	30	3	✓	15	✓		33	30	✓	15	✓	
			Clairview	**CV1**	33	30											
				CV2	33	30											
Southern	Fitzroy	Fitzroy	Shoalwater Bay	**RC1**	33	30	3	✓	15	✓		33	30	✓	15	✓	
				WH1	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
			Great Keppel Island	**GK1**	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
				GK2	33	30	3	✓	15	✓		33	30	✓	15	✓	
		Boyne	Gladstone Harbour	**GH1**	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
				GH2	33	30	3	✓	15	✓		33	30	✓	15	✓	
	Burnett–Mary	Burnett	Rodds Bay	**RD1**	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓
				RD3	33	30	3	✓	15	✓		33	30	✓	15	✓	
		Burrum	Burrum Heads	**BH1**	33	30	3	✓	15	✓		33	30	✓	15	✓	
				BH3	33	30	3	✓	15	✓		33	30	✓	15	✓	
		Mary	Hervey Bay	**UG1**	33	30	3	✓	15	✓		33	30	✓	15	✓	
				UG2	33	30	3	✓	15	✓	✓	33	30	✓	15	✓	✓

A2.1 Environmental pressures

A2.1.1 Tidal exposure

Table 20. Height of intertidal monitoring meadows/sites above lowest astronomical tide (LAT) and annual daytime tidal exposure (total hours) when meadows become exposed at a low tide. Year is June–May. Observed tidal heights courtesy Maritime Safety Queensland, 2020. NB: Meadow heights have not yet been determined in the far northern Cape York.

NRM	Site	Meadow height (above LAT)	Site depth (bMSL)	Meadow height (above LAT) relative to Standard Port	Annual median hours exposed during daylight (long-term)	Per cent of annual daylight hours meadow exposed (long-term)	Annual daytime exposure 2019–20 (hrs)	Per cent of annual daylight hours meadow exposed (2019–20)
Cape York	AP1	0.46	1.02	0.46	56.92	1.58	58.33	1.33
	AP2	0.46	1.02	0.46	56.92	1.58	41.67	0.95
Wet Tropics	LI1	0.65	0.90	0.65	172.17	3.96	141.00	3.21
	YP1	0.64	0.94	0.64	165.00	3.78	135.50	3.09
	YP2	0.52	1.06	0.52	93.42	2.15	74.67	1.70
	GI1	0.51	1.03	0.61	115.00	2.60	119.50	2.72
	GI2	0.57	0.97	0.67	152.50	3.44	153.50	3.49
	DI1	0.65	1.14	0.54	74.17	1.65	86.00	1.96
	DI2	0.55	1.24	0.44	43.00	0.97	37.50	0.85
	LB1	0.42	1.37	0.31	19.50	0.39	17.17	0.39
	LB2	0.46	1.33	0.35	19.83	0.48	16.33	0.37
Burdekin	BB1	0.58	1.30	0.58	80.83	1.94	35.17	0.80
	SB1	0.57	1.31	0.57	65.67	1.58	31.33	0.71
	MI1	0.65	1.19	0.67	182.17	4.04	69.00	1.57
	MI2	0.54	1.30	0.56	166.67	3.62	27.67	0.63
	JR1	0.47	1.32	0.47	63.33	1.48	37.50	0.85
	JR2	0.47	1.32	0.47	63.33	1.48	37.50	0.85
Mackay–Whitsunday	PI2	0.28	1.47	0.44	80.42	1.85	90.00	2.05
	PI3	0.17	1.58	0.33	40.75	0.95	46.50	1.06
	HM1	0.68	1.52	0.38	55.92	1.29	61.50	1.40
	HM2	0.68	1.52	0.38	55.92	1.29	61.50	1.40
	SI1	0.60	2.80	0.54	25.17	0.51	39.17	0.89
	SI2	0.60	2.80	0.54	25.17	0.51	39.17	0.89
Fitzroy	RC1	2.03	1.30	1.06	163.67	3.69	219.17	4.99
	WH1	2.16	1.17	1.19	237.33	5.35	312.83	7.12
	GK1	0.52	1.93	0.43	33.83	0.85	25.50	0.58
	GK2	0.58	1.87	0.49	50.50	1.22	38.83	0.88
	GH1	0.80	1.57	0.69	98.50	2.31	75.83	1.73
	GH2	0.80	1.57	0.69	91.83	2.15	75.83	1.73
Burnett–Mary	RD1	0.56	1.48	0.56	67.00	1.59	60.67	1.38
	RD2	0.63	1.41	0.63	94.50	2.25	85.17	1.94
	UG1	0.70	1.41	0.70	143.42	3.30	105.33	2.40
	UG2	0.64	1.47	0.64	103.83	2.41	57.67	1.31

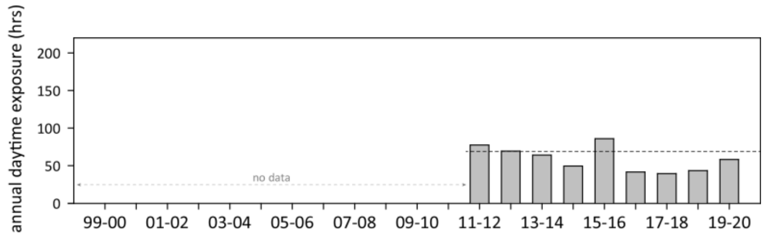

Figure 91. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of intertidal reef seagrass meadows at Archer Point, Cape York NRM region; 2011–2020. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 20. Observed tidal heights courtesy Maritime Safety Queensland, 2020. NB: Meadow heights have not yet been determined in the far northern Cape York sites.

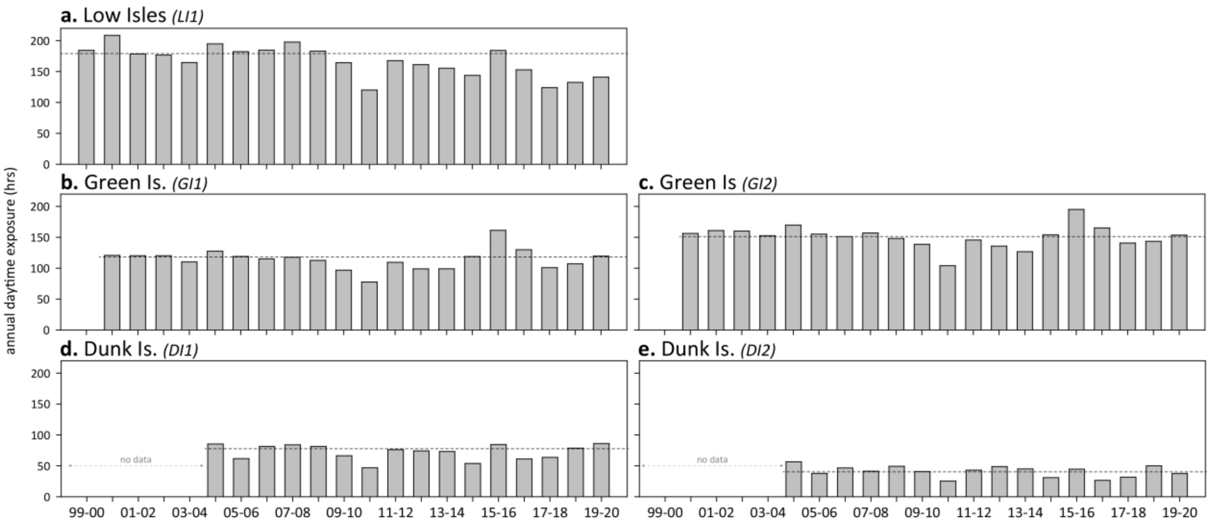

Figure 92. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of intertidal reef seagrass meadows in the Wet Tropics NRM region; 1999–2020. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 20. Observed tidal heights courtesy Maritime Safety Queensland, 2020.

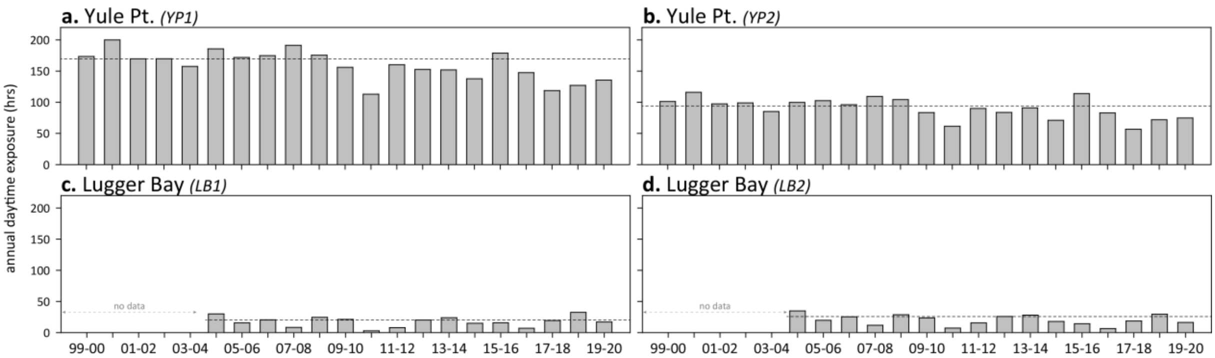

Figure 93. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of intertidal coastal seagrass meadows in Wet Tropics NRM region; 1999–2020. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 20. Observed tidal heights courtesy Maritime Safety Queensland, 2020.

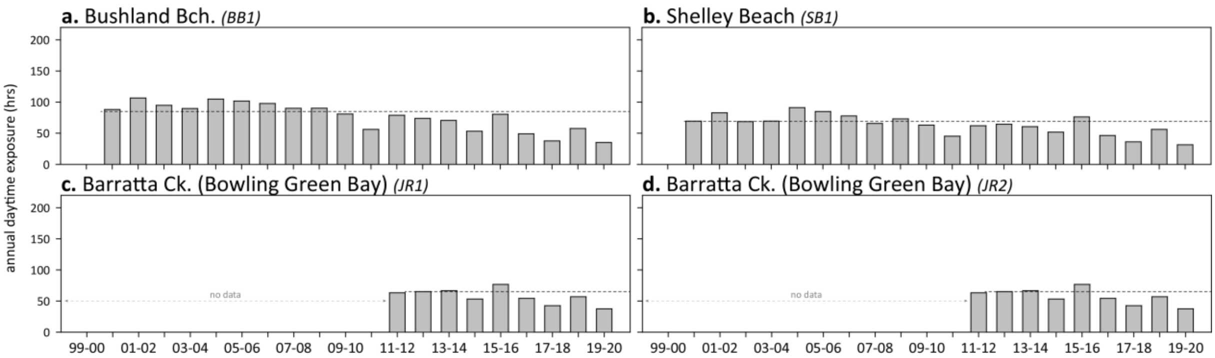

Figure 94. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of intertidal coastal seagrass meadows in Burdekin NRM region; 2000–2020. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 20. Observed tidal heights courtesy Maritime Safety Queensland, 2020.

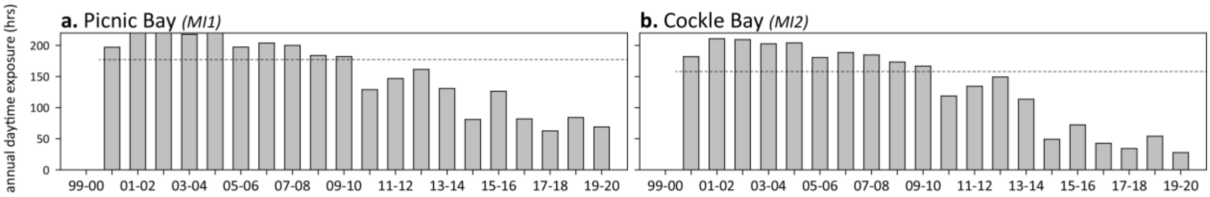

Figure 95. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of intertidal reef seagrass meadows in Burdekin NRM region; 2000–2020. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 20. Observed tidal heights courtesy Maritime Safety Queensland, 2020.

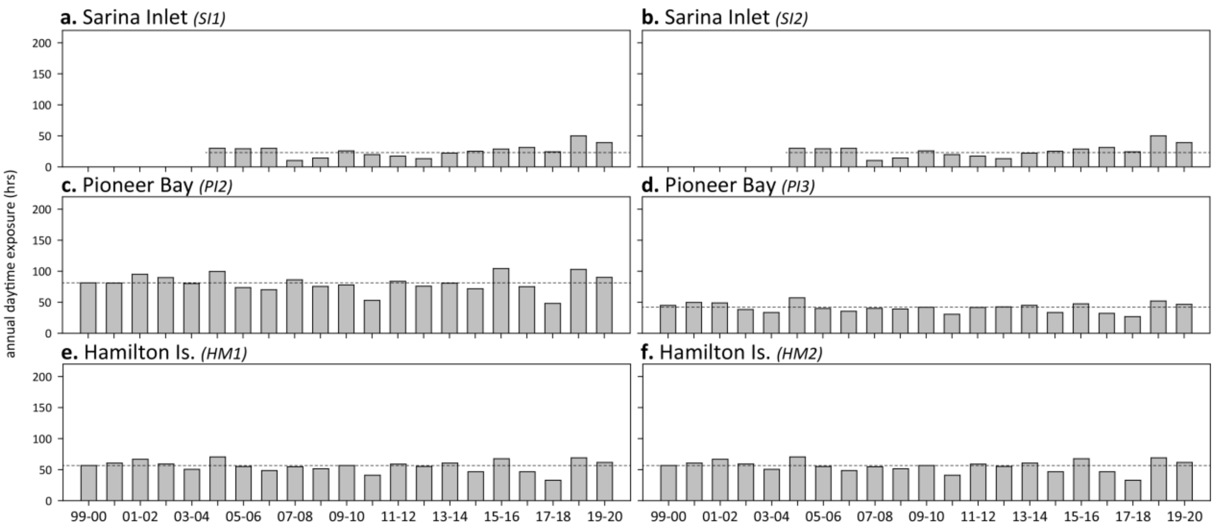

Figure 96. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of intertidal estuarine (a, b) coastal (c, d) and reef (e, f) seagrass meadows in Mackay–Whitsunday NRM region; 1999–2020. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 20. Observed tidal heights courtesy Maritime Safety Queensland, 2020.

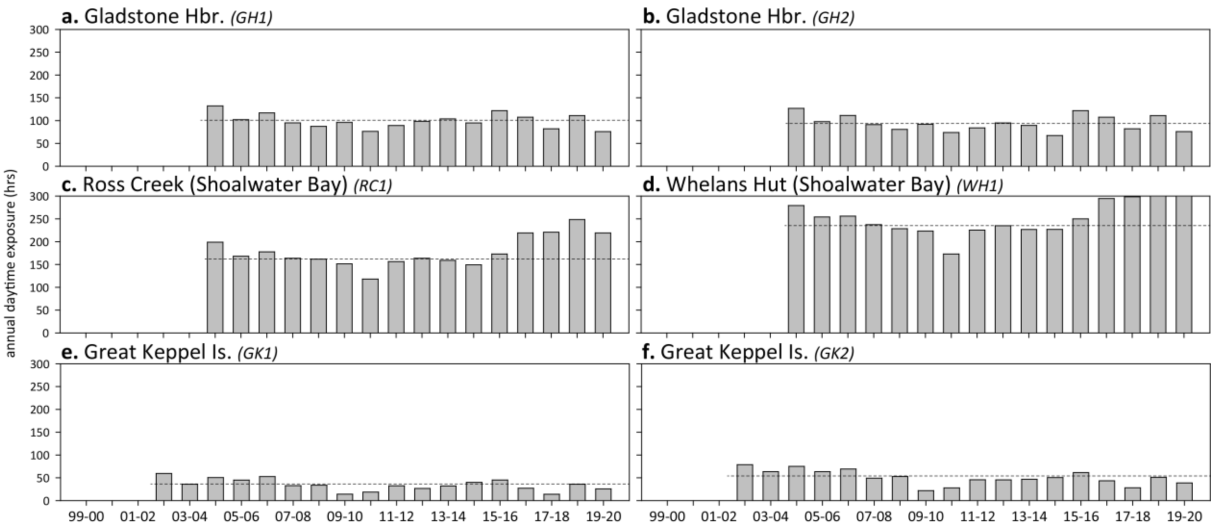

Figure 97. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of intertidal estuarine (a, b) coastal (c, d) and reef (e, f) seagrass meadows in the Fitzroy NRM region; 1999–2020. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 20. Observed tidal heights courtesy Maritime Safety Queensland, 2020.

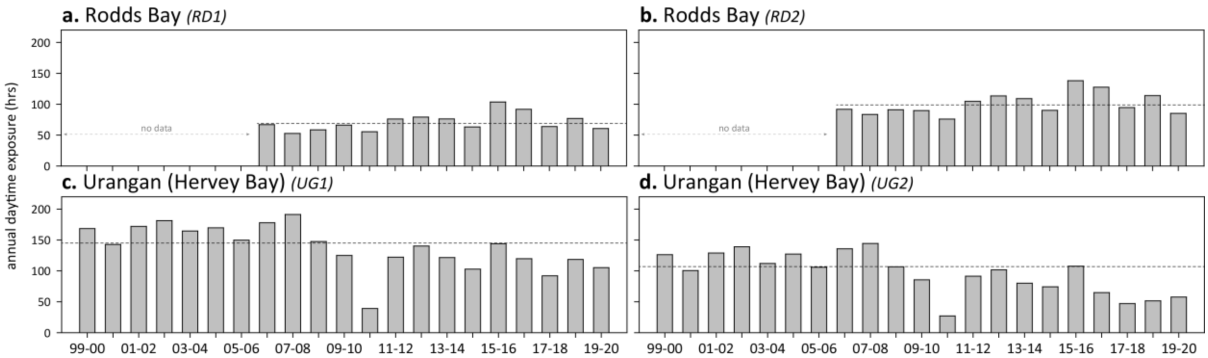

Figure 98. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of intertidal estuarine seagrass meadows in the Burnett–Mary NRM region; 1999–2020. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 20. Observed tidal heights courtesy Maritime Safety Queensland, 2020.

A2.1.2 Light at seagrass canopy

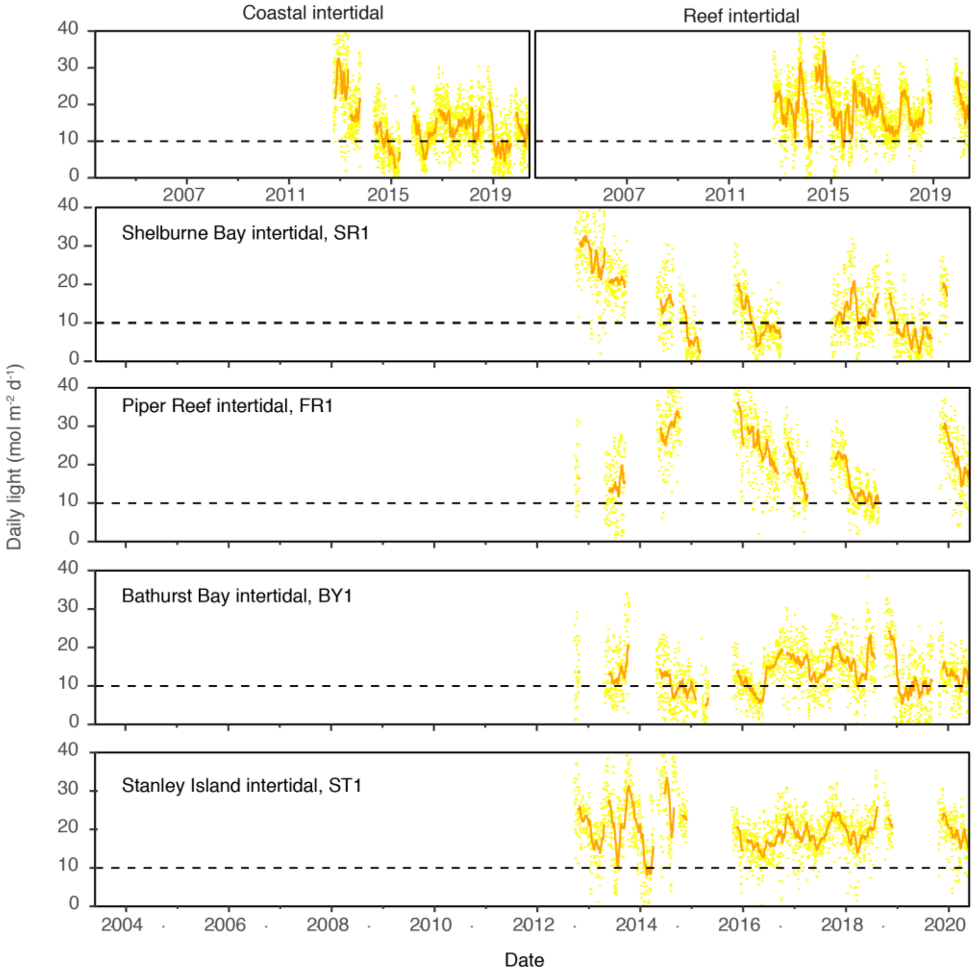

Figure 99. Daily light (yellow points) and 28-day rolling average (orange, bold line) as habitat averages (top) and at monitoring locations in the Cape York NRM region.

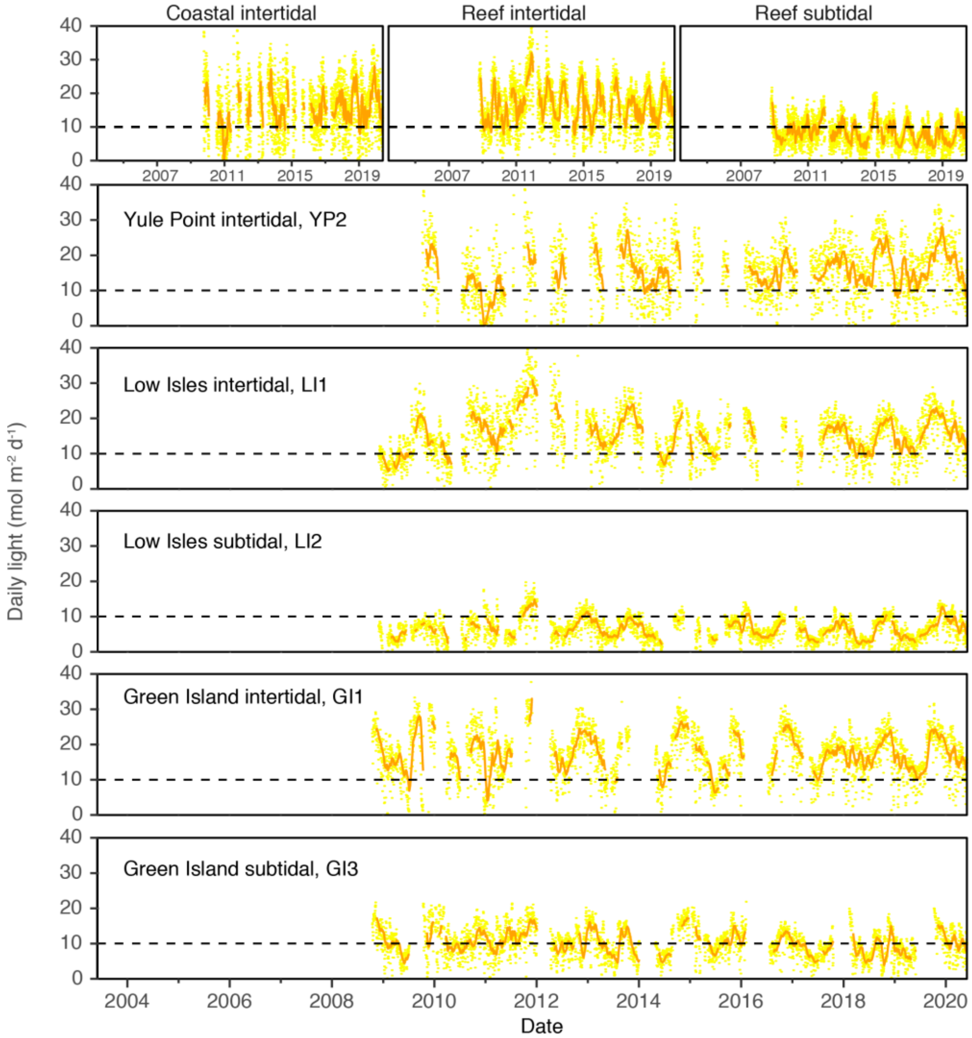

Figure 100. Daily light (yellow line) and 28-day rolling average (orange, bold line) as habitat averages (top) and at monitoring locations in the northern Wet Tropics.

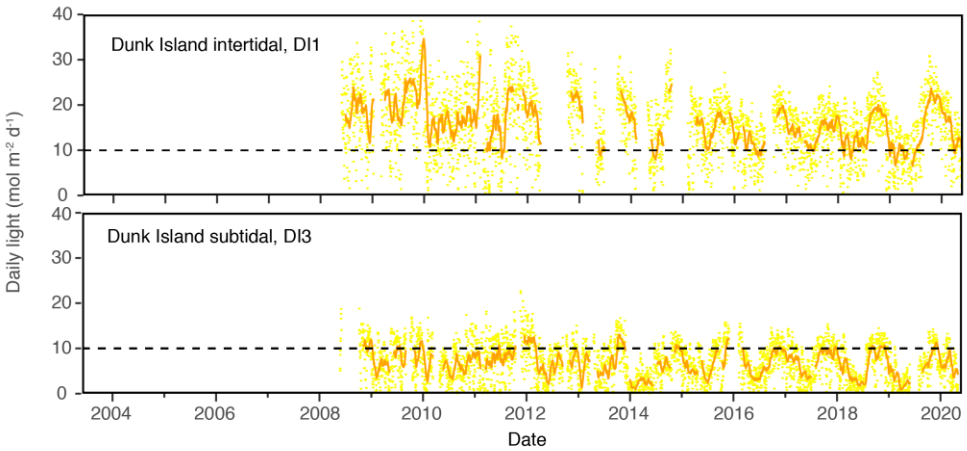

Figure 101. Daily light (yellow line) and 28-day rolling average (orange, bold line) as habitat averages (top) and at monitoring locations in the southern Wet Tropics.

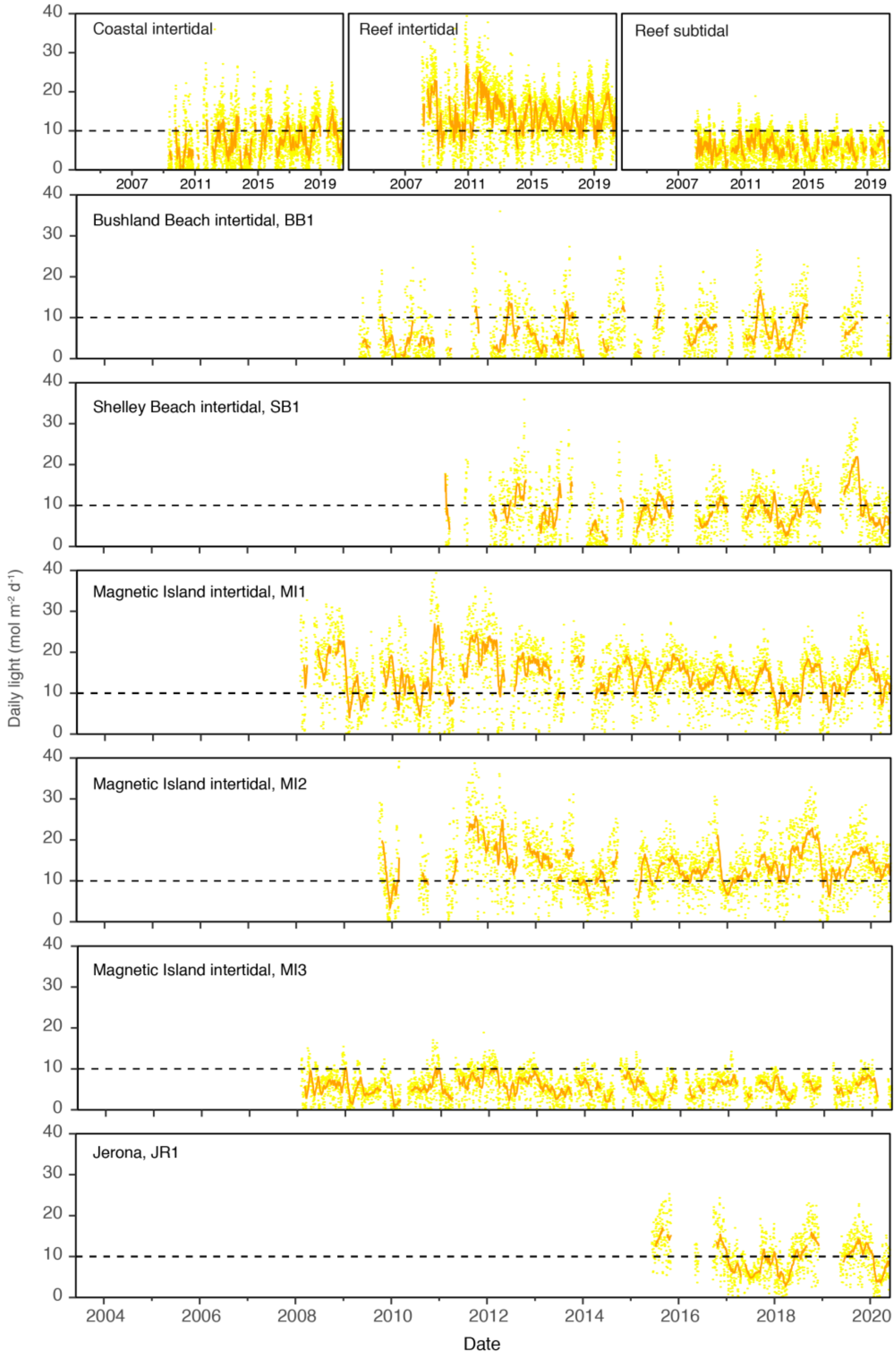

Figure 102. Daily light (yellow line) and 28-day rolling average (orange, bold line) as habitat averages (top) and at monitoring locations in the Burdekin region.

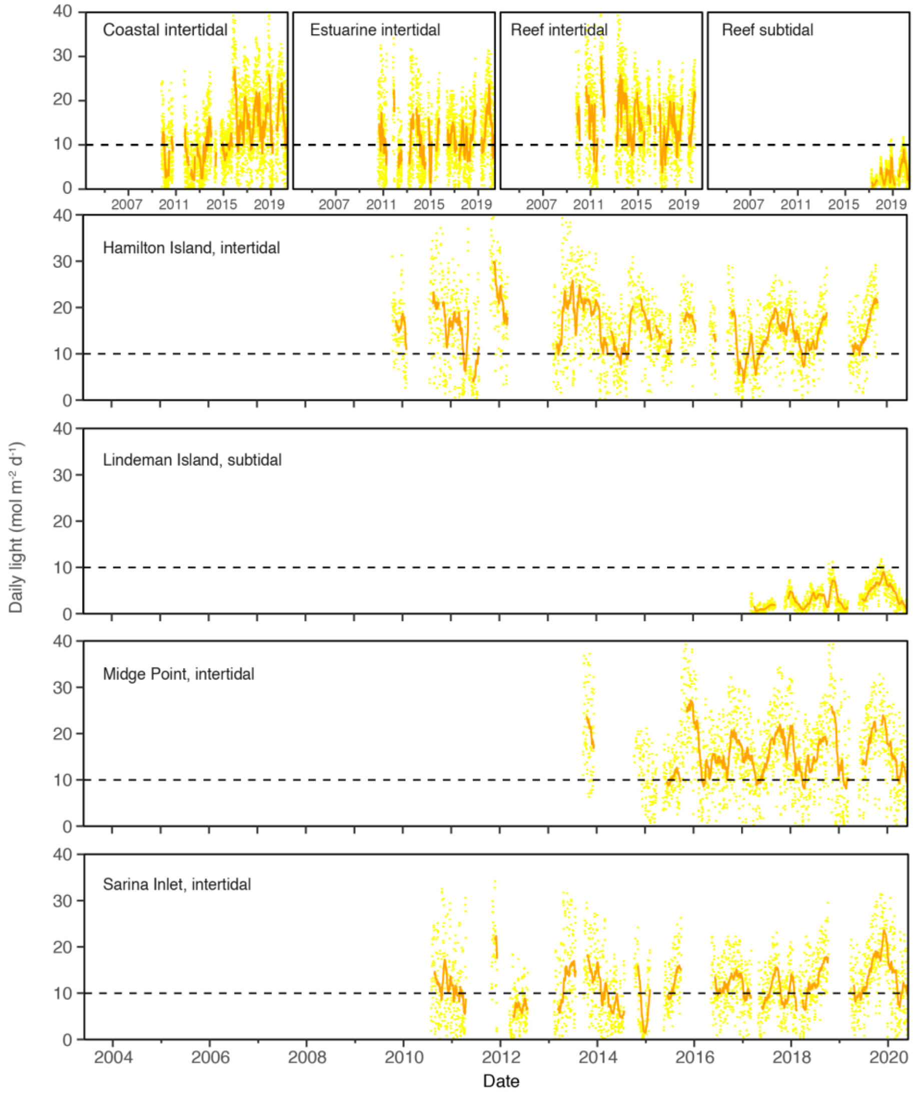
Coastal intertidal
Estuarine intertidal
Reef intertidal
Reef subtidal
Hamilton Island, intertidal
Lindeman Island, subtidal
Midge Point, intertidal
Sarina Inlet, intertidal
Daily light (mol m-2 d-1)
Date
40
30
20
10
0
2007
2011
2015
2019
2004
2006
2008
2010
2012
2014
2016
2018
2020

Figure 103. Daily light (yellow line) and 28-day rolling average (orange, bold line) as habitat averages (top) and at monitoring locations in the Mackay–Whitsunday NRM region.

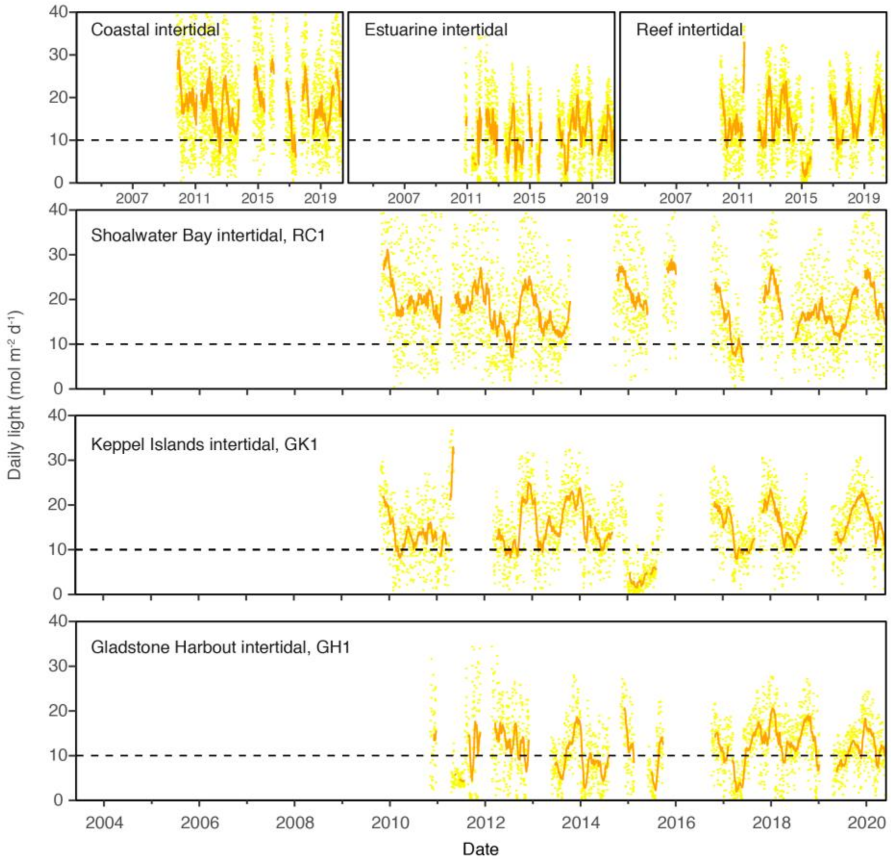

Figure 104. Daily light (yellow line) and 28-day rolling average (orange, bold line) as habitat averages (top) and at monitoring locations in the Fitzroy NRM region.

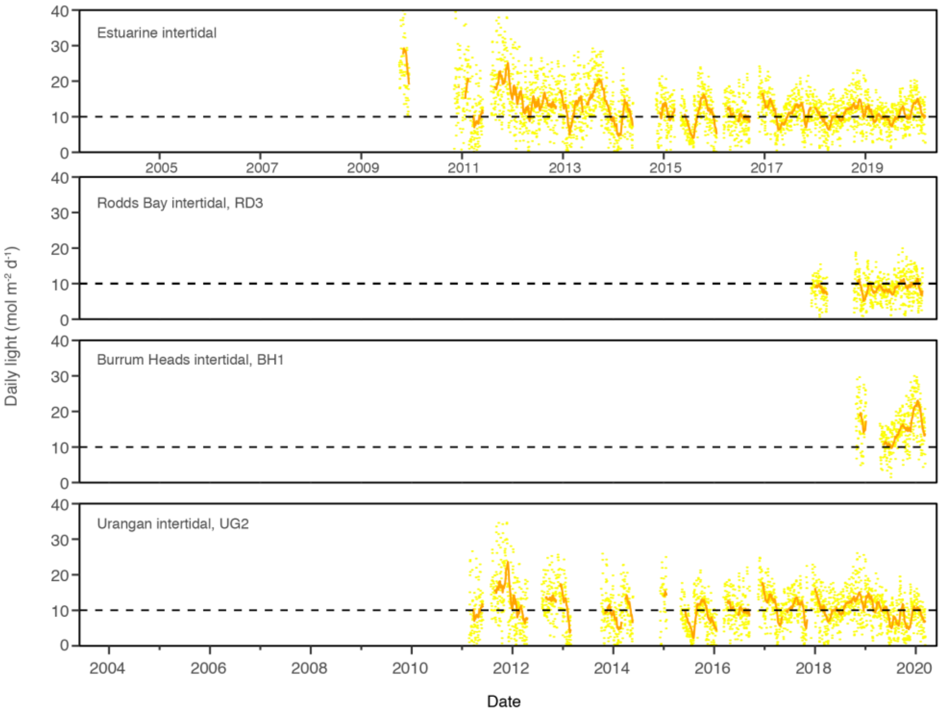

Figure 105. Daily light (yellow line) and 28-day rolling average (orange, bold line) as habitat averages (top) and at monitoring locations in the Burnett–Mary NRM region.

A2.2 Seagrass habitat condition: Sediments composition

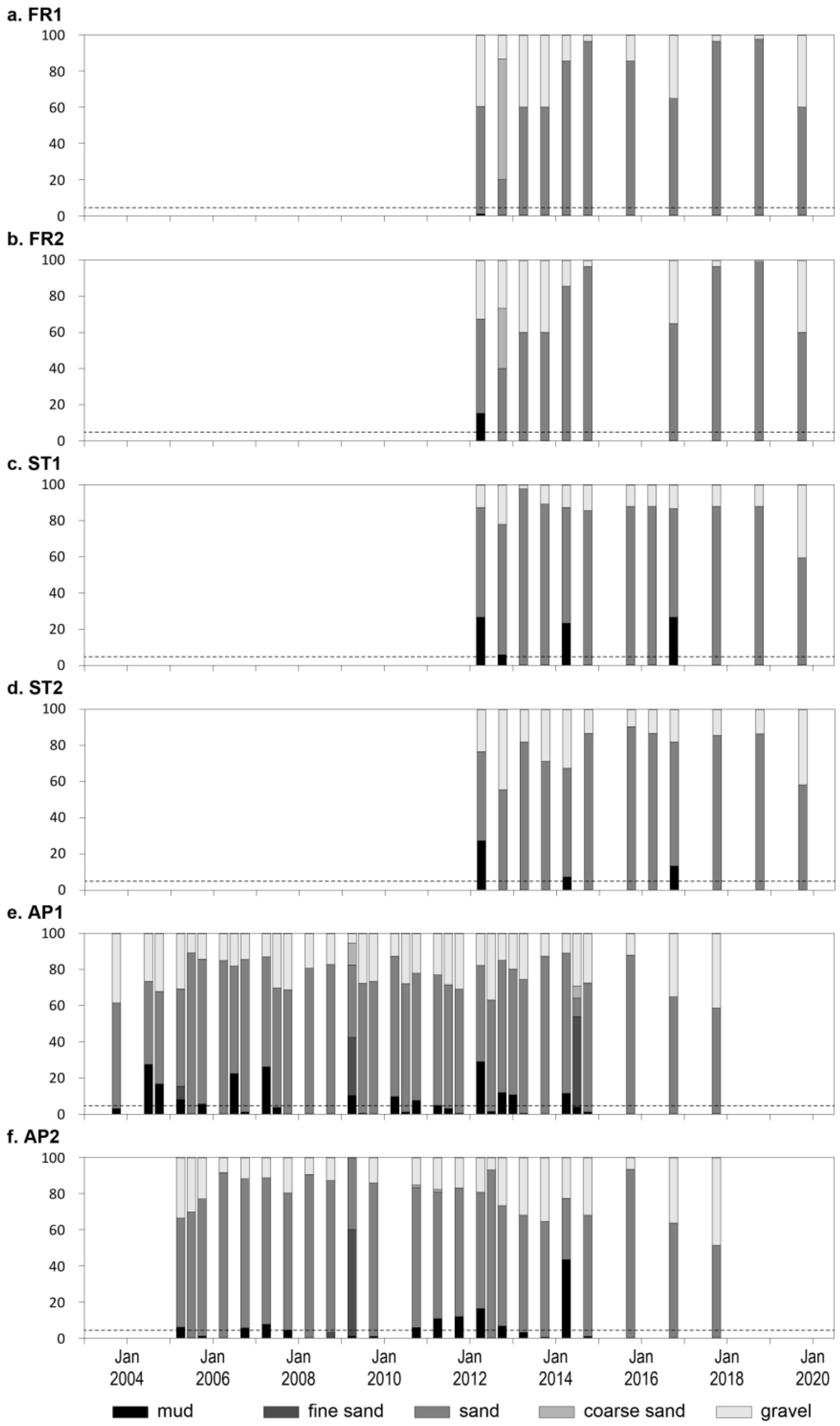

Figure 106. Sediment grain size composition at reef habitat monitoring sites in the Cape York region, 2003–2020. Dashed line is the Reef long-term average proportion of mud.

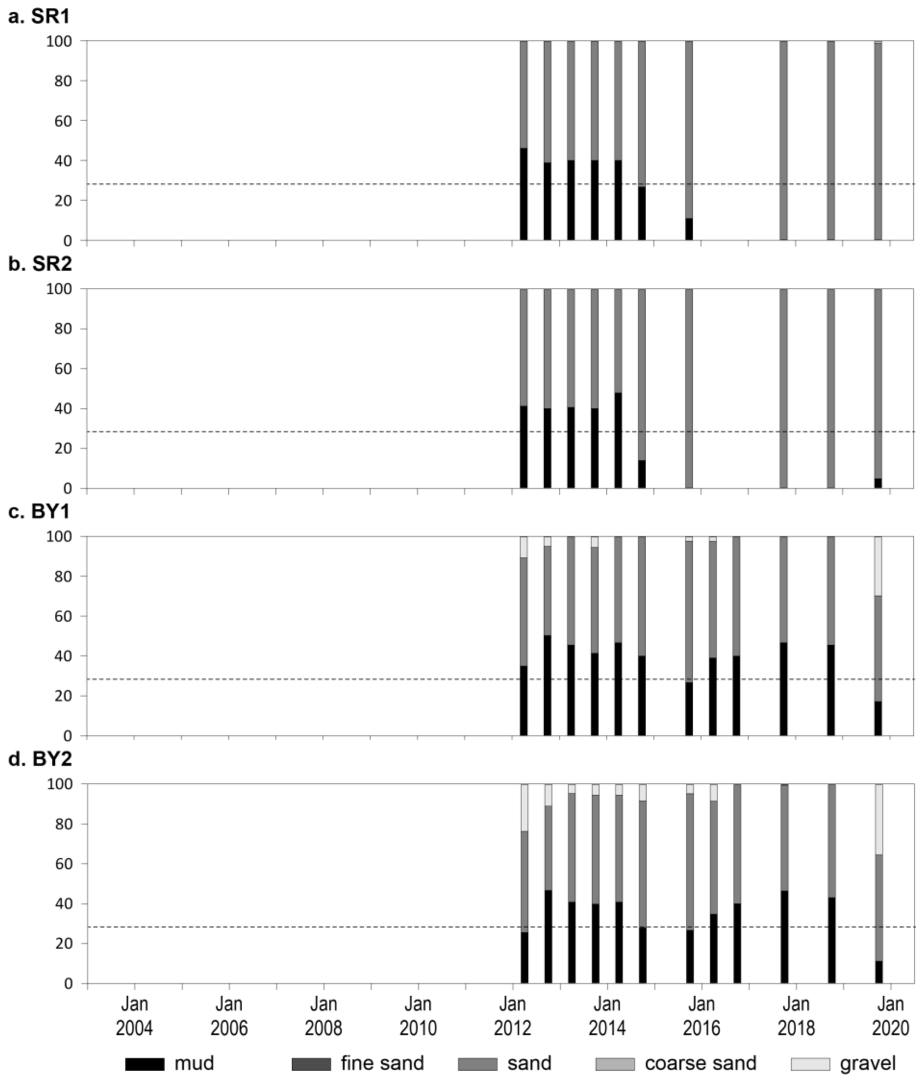

Figure 107. Sediment grain size composition at coastal habitat monitoring sites in the Cape York region, 2010–-2020. Dashed line is the Reef long-term average proportion of mud.

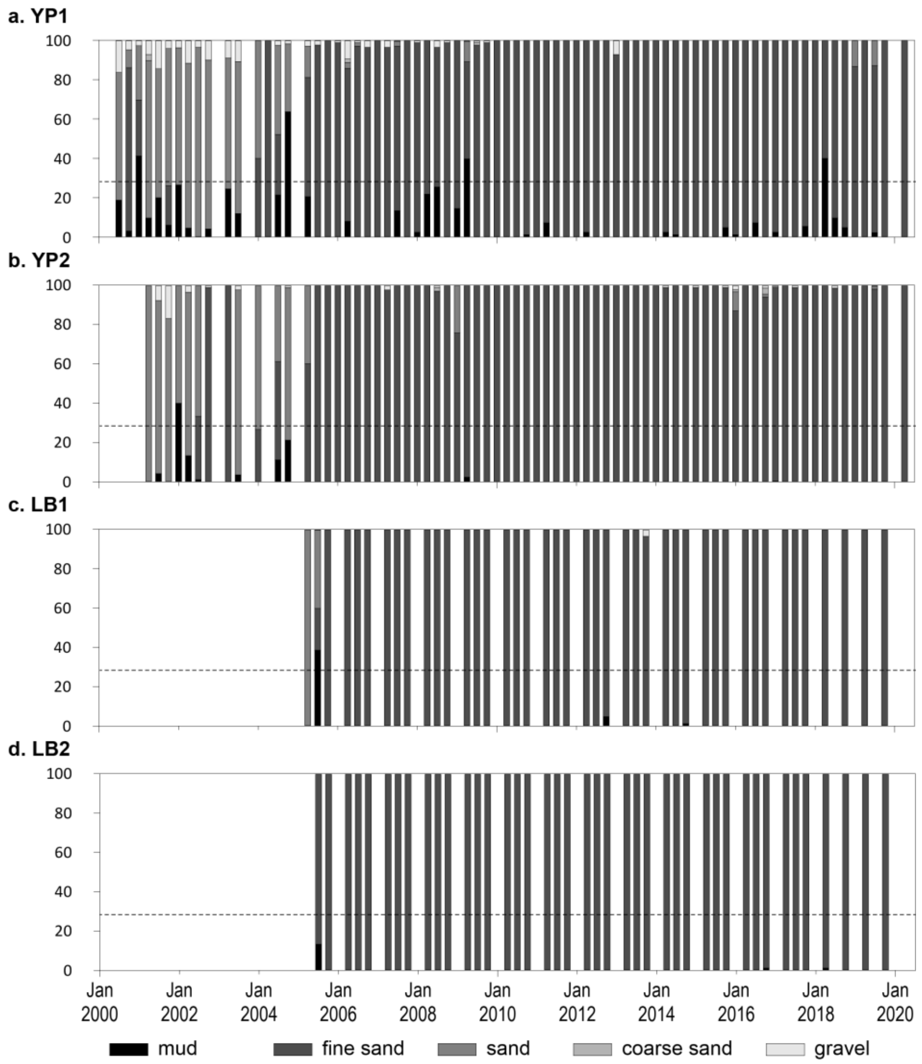

Figure 108. Sediment grain size composition at intertidal coastal habitat monitoring sites in the Wet Tropics region, 2001–2020. Dashed line is the Reef long-term average proportion of mud.

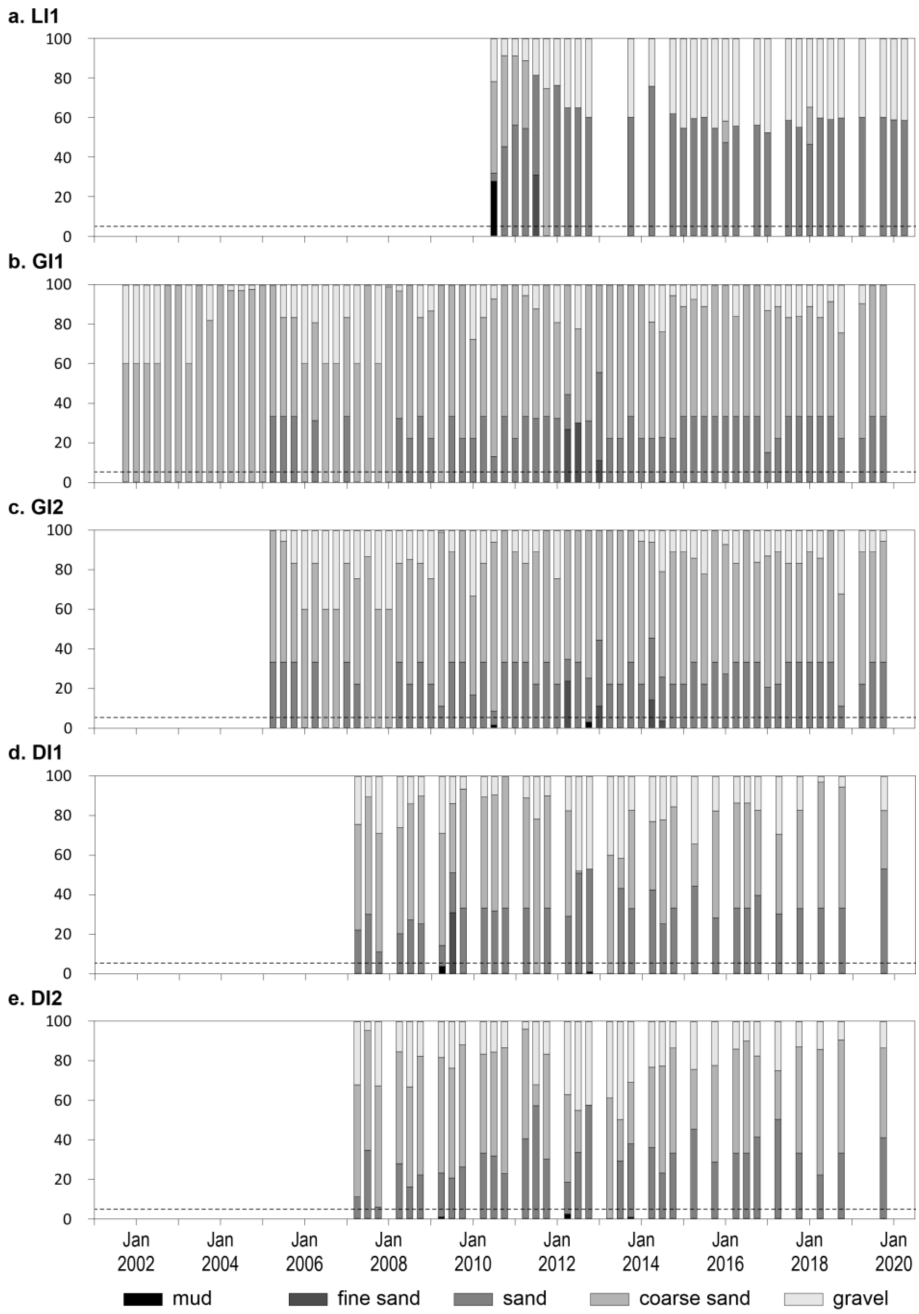

Figure 109. Sediment grain size composition at intertidal reef habitat monitoring sites in the Wet Tropics region, 2001–2020. Dashed line is the Reef long-term average proportion of mud.

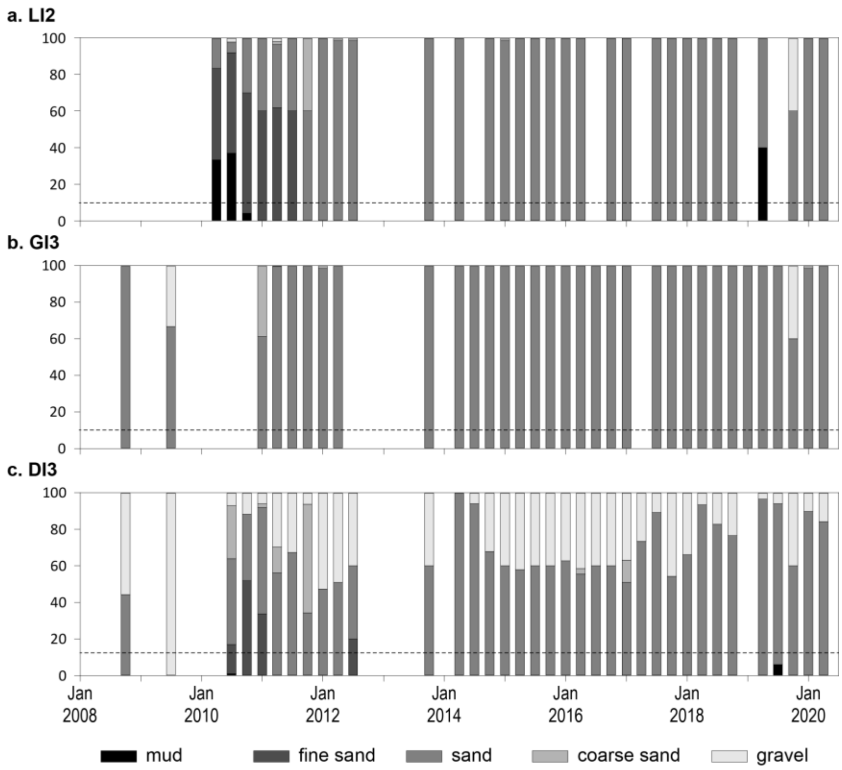

Figure 110. Sediment grain size composition at subtidal reef habitat monitoring sites in the Wet Tropics region, 2008–2020. Dashed line is the Reef long-term average proportion of mud.

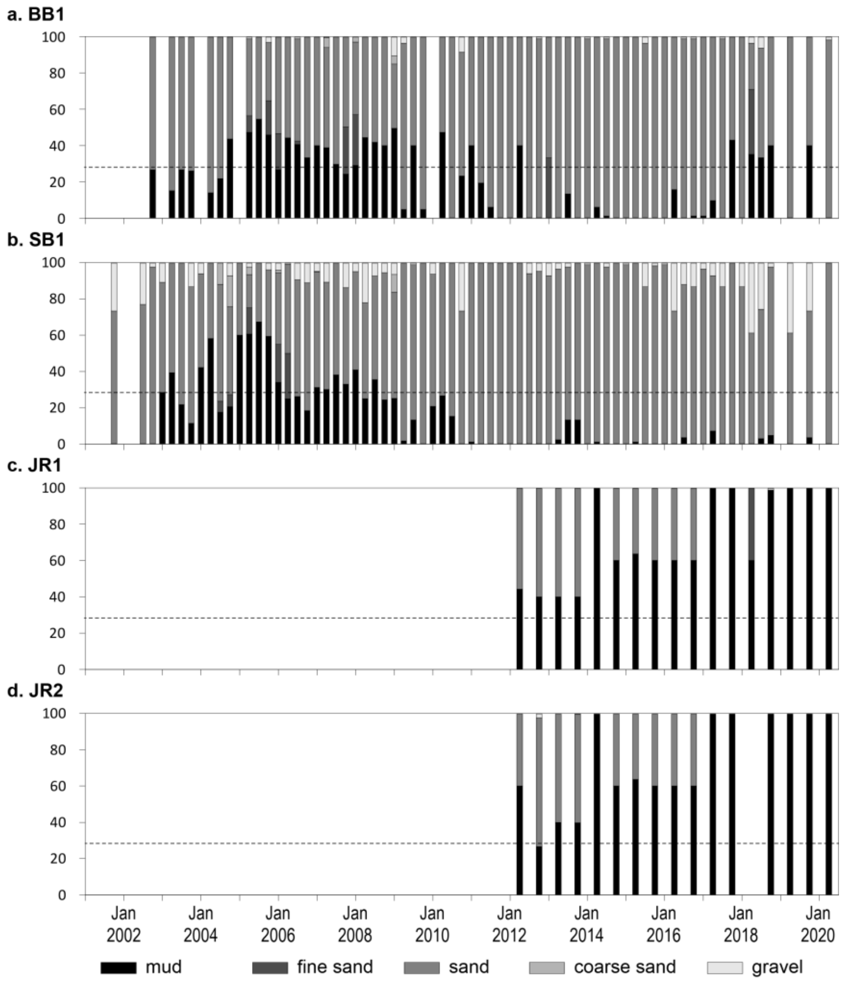

Figure 111. Sediment grain size composition at intertidal coastal habitat monitoring sites in the Burdekin region, 2001–2020. Dashed line is the Reef long-term average proportion of mud.

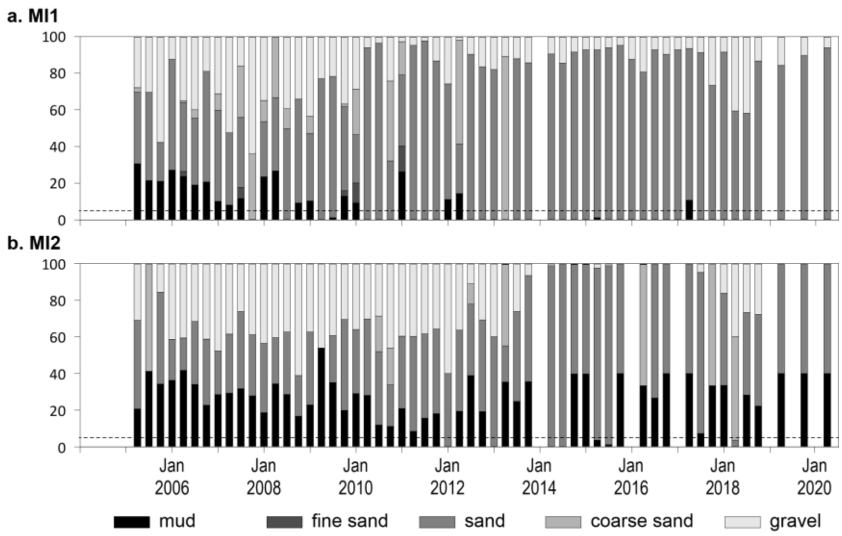

Figure 112. Sediment grain size composition at intertidal reef habitat monitoring sites in the Burdekin region, 2004–2020. Dashed line is the Reef long-term average proportion of mud.

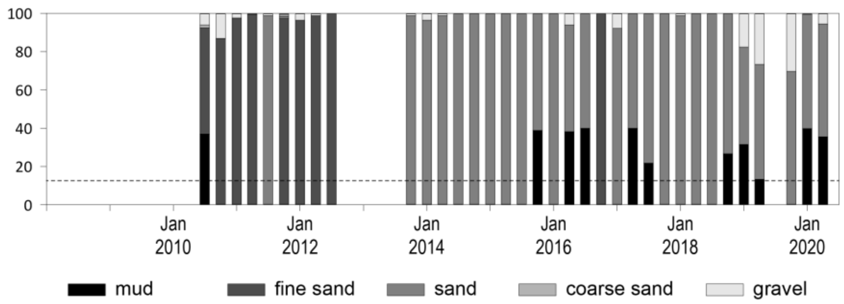

Figure 113. Sediment grain size composition at subtidal reef habitat monitoring sites in the Burdekin region, 2010–2020. Dashed line is the Reef long-term average proportion of mud.

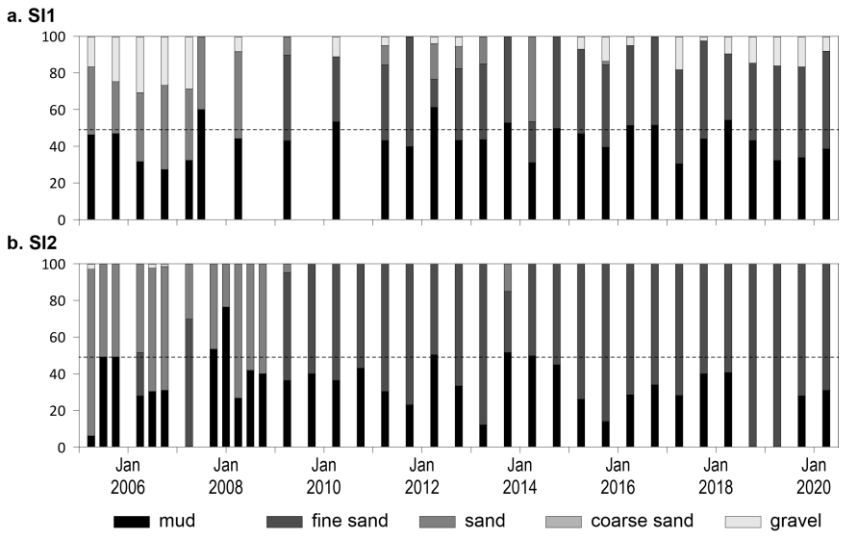

Figure 114. Sediment grain size composition at intertidal estuary habitat monitoring sites in the Mackay–Whitsunday region, 2005–2020. Dashed line is the Reef long-term average proportion of mud.

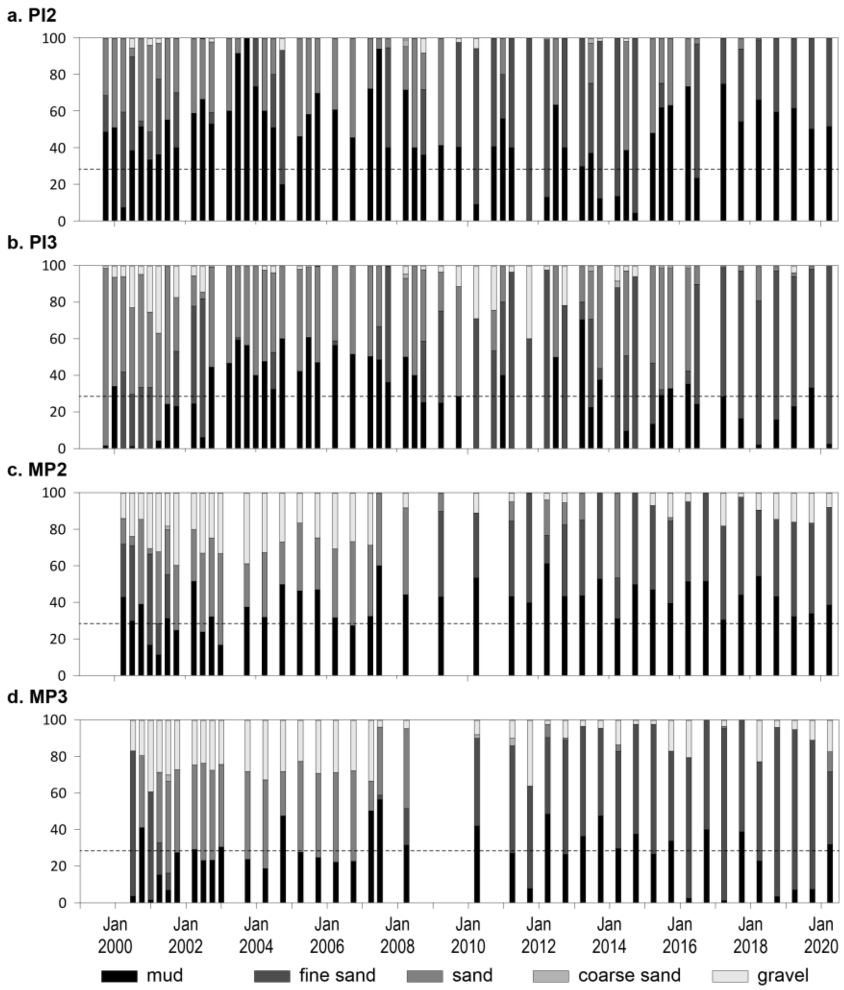

Figure 115. Sediment grain size composition at intertidal coastal habitat monitoring sites in the Mackay–Whitsunday region, 1999–2020. Dashed line is the Reef long-term average proportion of mud.

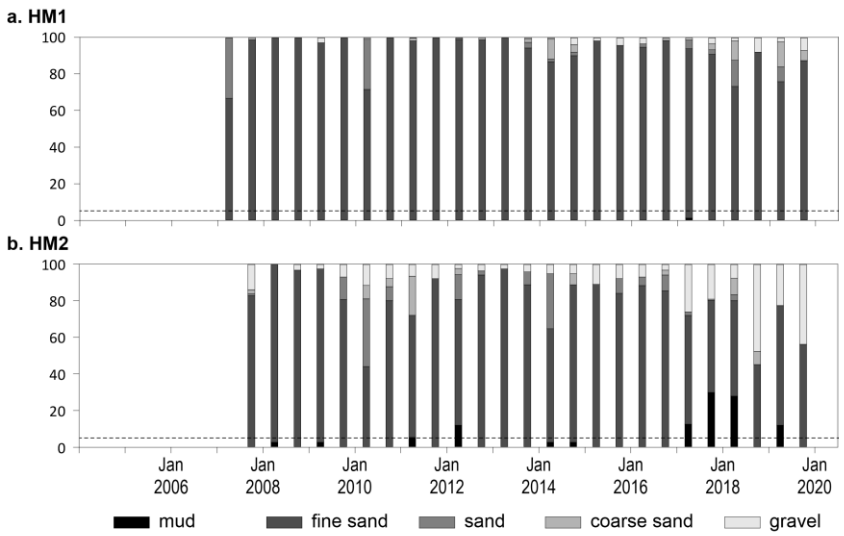

Figure 116. Sediment grain size composition at intertidal reef habitat monitoring sites in the Mackay–Whitsunday region, 2007–2020. Dashed line is the Reef long-term average proportion of mud.

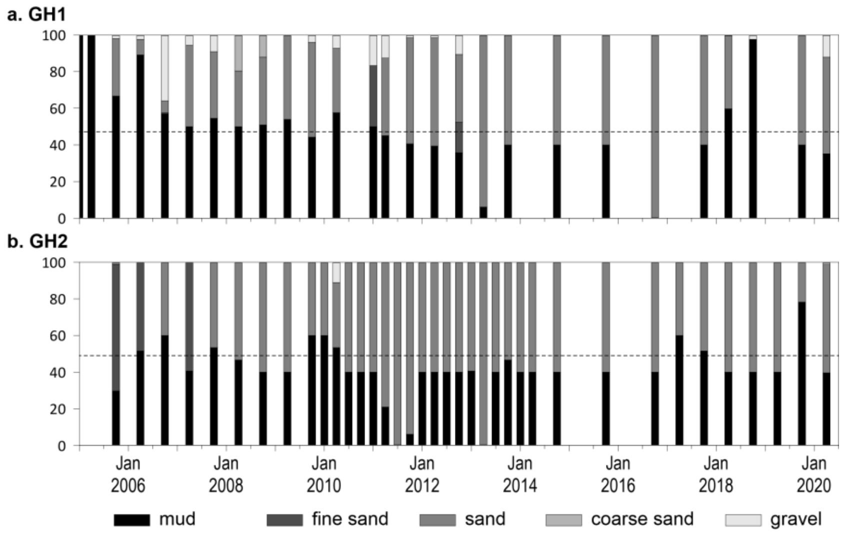

Figure 117. Sediment grain size composition at intertidal estuary habitat monitoring sites in the Fitzroy region, 2005–2020. Dashed line is the Reef long-term average proportion of mud.

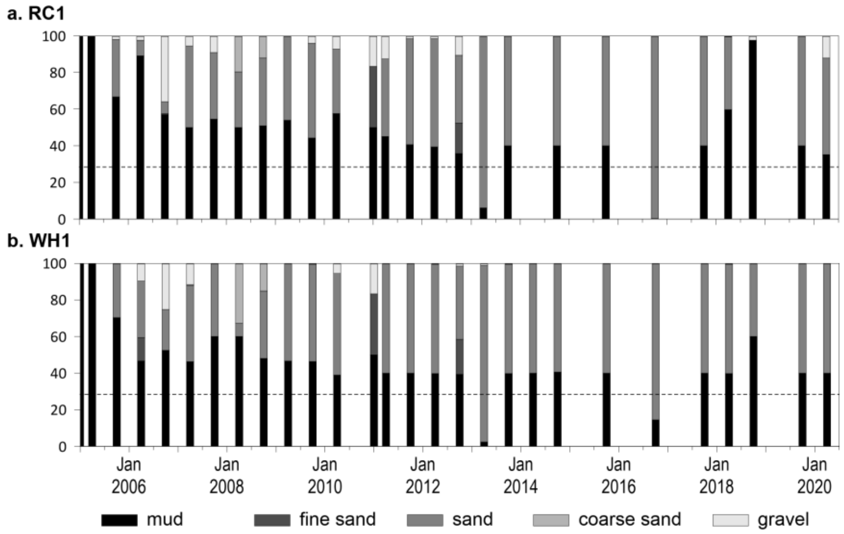

Figure 118. Sediment grain size composition at intertidal coastal habitat monitoring sites in the Fitzroy region, 2005–2020. Dashed line is the Reef long-term average proportion of mud.

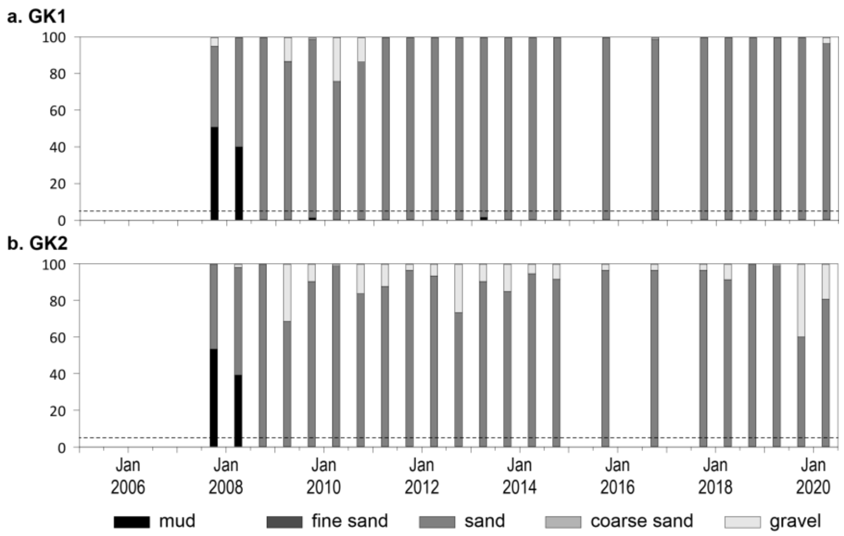

Figure 119. Sediment grain size composition at intertidal reef habitat monitoring sites in the Fitzroy region, 2007–2020. Dashed line is the Reef long-term average proportion of mud.

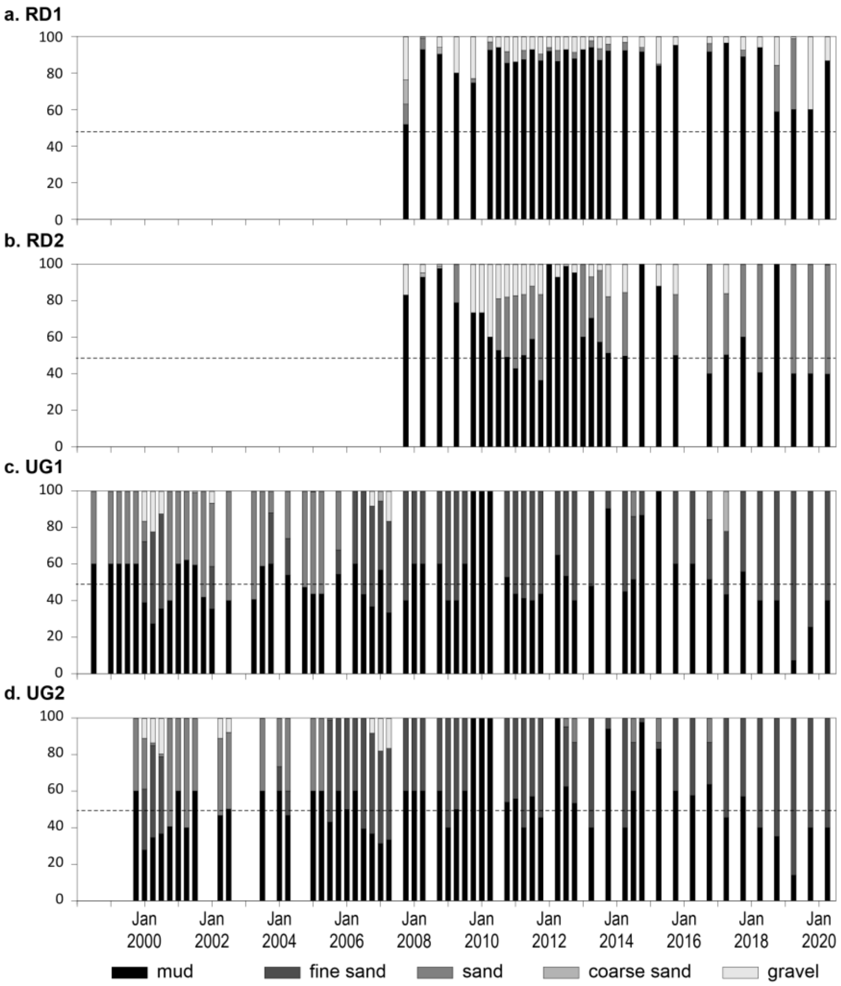

Figure 120. Sediment grain size composition at intertidal estuary habitat monitoring sites in the Burnett–Mary region, 1999–2020. Dashed line is the Reef long-term average proportion of mud.

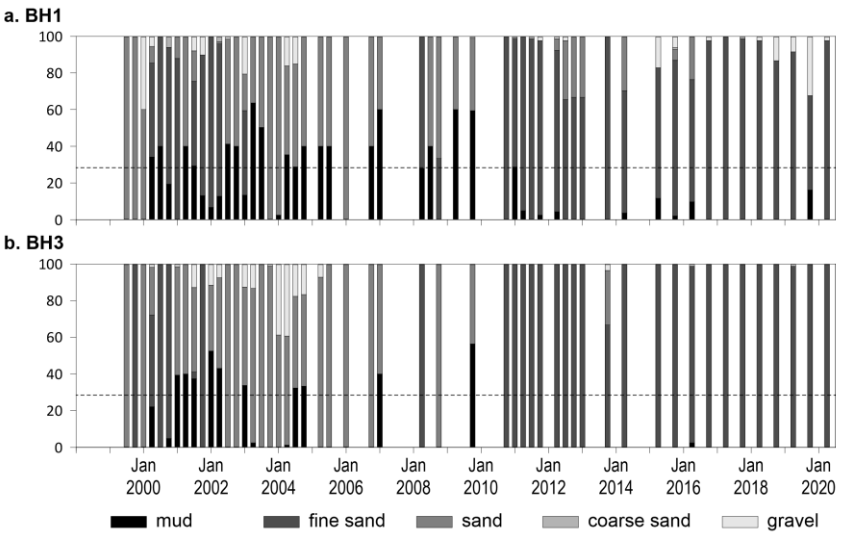

Figure 121. Sediment grain size composition at intertidal coastal habitat monitoring sites in the Burnett–Mary region, 1999–2020. Dashed line is the Reef long-term average proportion of mud.

Appendix 3 Results of statistical analysis

Table 21. Results of Mann-Kendall analysis to assess for a significant trend (decline or increase) over time in seagrass abundance (per cent cover).The reported output of the tests performed are Kendall's tau coefficient (Kendall-τ), two-sided p-value (significant at α = 0.05 in bold), the Sen's slope (showing sign and strength of trend –confidence intervals if significant) and the long-term trend.

NRM region	Habitat	Site	First Year	Last Year	*n*	*Kendall -τ*	*p* (2-sided)	Sen's slope (confidence interval)	trend
Cape York	coastal intertidal	BY1	2012	2019	12	0.061	0.837	0.331	no trend
		BY2	2012	2019	12	0.212	0.373	0.538	no trend
		SR1	2012	2019	10	-0.333	0.251	-0.697	no trend
		SR2	2012	2019	10	0.222	0.466	0.261	no trend
	coastal subtidal	LR1	2015	2019	4	0	1.0000	0.800	no trend
		LR2	2015	2019	4	-0667	0.308	-12.048	no trend
	reef intertidal	**AP1**	2003	2017	35	**-0.459**	**0.0001**	**-0.533** (-0.763 to -0.283)	**decrease**
		AP2	2005	2017	24	-0.022	0.9013	-0.030	no trend
		FR1	2012	2019	11	0	1	0	no trend
		FR2	2012	2019	10	-0.378	0.152	-1.253	no trend
		ST1	2012	2019	12	**0.667**	**0.003**	**0.666 (**0.359 to 1.303)	**Increase**
		ST2	2012	2019	12	**0.748**	**0.001**	**0.838** (0.495 to 1.177)	**increase**
		YY1	2012	2014	3	0.333	1.0000	1.045	no trend
	Reef subtidal	FG1	2016	2019	4	0.667	0.308	6.696	no trend
		FG2	2016	2019	4	0.333	0.734	2.781	no trend
	pooled		2003	2019	38	**-0.366**	**0.001**	**-0.276** (-0.416 to -0.083)	**decrease**
Wet Tropics	coastal intertidal	**LB1**	2005	2019	43	**-0.500**	**<0.001**	**-0.038** (-0.113 to -0.002)	**decrease**
		LB2	2005	2019	42	**-0.353**	**0.002**	**-0.038** (-0.088 to 0)	**decrease**
		YP1	2000	2020	76	0.135	0.084	0.096	no trend
		YP2	2001	2020	72	0.106	0.189	0.053	no trend
	coastal subtidal	MS1	2015	2019	3	0.333	1	6.222	no trend
		MS2	2015	2019	3	0.333	1	1.889	no trend
	reef intertidal	DI1	2007	2019	34	-0.141	0.247	-0.093	no trend
		DI2	2007	2019	34	-0.114	0.350	-0.092	no trend
		GI1	2001	2019	72	-0.119	0.139	-0.070	no trend

NRM region	Habitat	Site	First Year	Last Year	*n*	*Kendall -τ*	*p* (2-sided)	Sen's slope (confidence interval)	trend
		GI2	2005	2019	58	-0.053	0.559	-0.044	no trend
		GO1	2008	2016	7	-0.429	0.2296	-1.682	no trend
		LI1	2008	2020	41	**-0.324**	**0.003**	**-0.122** (-0.228 to -0.047)	**decrease**
	reef subtidal	DI3	2008	2020	47	-0.097	0.348	-0.010	no trend
		GI3	2008	2020	45	**-0.388**	**<0.001**	**-0.540** (-0.756 to -0.290)	**decrease**
		LI2	2008	2020	41	0.180	0.101	0.117	no trend
	pooled		2000	2020	85	-0.139	0.060	-0.067	no trend
Burdekin	coastal intertidal	BB1	2002	2020	64	0.042	0.631	0.037	no trend
		SB1	2001	2020	70	-0.082	0.318	-0.047	no trend
		SB2	2001	2020	69	**-0.189**	**0.022**	**-0.167** (-0.327 to -0.022)	**decrease**
		JR1	2012	2020	17	0.191	0.303	1.455	no trend
		JR2	2012	2020	16	**0.383**	**0.043**	**2.505** (0.019 to 3.762)	**increase**
	reef intertidal	MI1	2005	2020	57	-0.108	0.239	-0.152	no trend
		MI2	2005	2020	55	**-0.219**	**0.019**	**-0.393** (-0.727 to -0.080)	**decrease**
	reef subtidal	MI3	2008	2020	48	0.044	0.663	0.049	no trend
	pooled		2001	2020	77	0.022	0.781	-0.030	no trend
Mackay–Whitsunday	estuarine intertidal	**SI1**	2005	2020	35	**-0.304**	**0.011**	**-0.300** (-0.625 to -0.053)	**decrease**
		SI2	2005	2020	30	-0.002	1	-0.004	no trend
	coastal intertidal	**MP2**	2000	2020	42	**0.256**	**0.018**	**0.210** (0.039 to 0.361)	**increase**
		MP3	2000	2020	40	0.062	0.584	0.042	no trend
		PI2	1999	2020	58	**-0.318**	**<0.001**	**-0.286** (-0.453 to -0.138)	**decrease**
		PI3	1999	2020	58	-0.157	0.082	-0.117	no trend
		CV1	2017	2019	6	0.067	1	0.157	no trend
		CV2	2017	2019	6	-0.333	0.452	-0.269	no trend
		SH1	2017	2020	7	0.238	0.548	1.006	no trend
	coastal subtidal	NB1	2015	2019	5	-0.200	0.806	-2.557	no trend

NRM region	Habitat	Site	First Year	Last Year	*n*	*Kendall -τ*	*p* (2-sided)	Sen's slope (confidence interval)	trend
		NB2	2015	2019	5	0.600	0.221	2.551	no trend
	reef intertidal	**HB1**	2000	2020	44	**-0.258**	**0.014**	**-0.165** (-0.281 to -0.030)	**decrease**
		HB2	2000	2020	43	-0.014	0.900	-0.013	no trend
		HM1	2007	2019	26	**-0.465**	**0.001**	**-0.229** (-0.398 to -0.109)	**decrease**
		HM2	2007	2019	25	**-0.372**	**0.010**	**-0.136** (-0.307 to -0.034)	**decrease**
	Reef subtidal	TO1	2015	2019	5	-0.400	0.462	-1.423	no trend
		TO2	2015	2019	5	-0.200	0.806	-0.660	no trend
		LN1	2017	2019	5	0.400	0.462	1.913	no trend
		LN2	2017	2019	4	0.667	0.308	1.990	no trend
	pooled		1999	2020	67	**-0.395**	**<0.001**	**-0.175** (-0.240 to -0.110)	**decrease**
Fitzroy	estuarine intertidal	**GH1**	2005	2020	37	**-0.396**	**0.001**	**-0.671** (-1.031 to -0.273)	**decrease**
		GH2	2005	2020	37	-0.036	0.764	-0.048	no trend
	coastal intertidal	RC1	2002	2020	37	-0.056	0.638	-0.089	no trend
		WH1	2002	2020	38	0.044	0.706	0.037	no trend
	reef intertidal	**GK1**	2007	2020	23	**-0.459**	**0.002**	**-0.110** (-0.186 to -0.049)	**decrease**
		GK2	2007	2020	23	-0.055	0.731	-0.017	no trend
	pooled		2002	2020	49	**-0.329**	**0.001**	**-0.190** (-0.300 to -0.090)	**decrease**
Burnett–Mary	estuarine intertidal	RD1	2007	2020	32	0.114	0.372	0.007	no trend
		RD2	2007	2017	28	**-0.409**	**0.003**	**-0.009** (-0.096 to -0.001)	**decrease**
		RD3	2017	2020	6	-0.467	0.260	-1.458	no trend
		UG1	1998	2020	63	0.108	0.220	0.005	no trend
		UG2	1999	2020	59	**0.231**	**0.010**	**0.052** (0.005 to 0.198)	**increase**
	coastal intertidal	BH1	1999	2020	54	0.126	0.179	0.066	no trend
		BH3	1999	2020	52	**0.388**	**<0.001**	**0.173** (0.104 to 0.239)	**increase**
	pooled		1998	2020	76	0.022	0.781	0.007	no trend