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Inshore seagrass monitoring
Annual Report
2021–22

TropWATER

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Front cover image: Sea turtle feeding on a inshore seagrass meadow. © Abbi Scott, TropWater/James Cook University.

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:

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Acronyms, abbreviations and units

Reef Authority	Great Barrier Reef Marine Park Authority
BoM	Bureau of Meteorology
CQU	Central Queensland University
CV	coefficient of variation
DES	Department of Environment and Science, Queensland
GAM	generalised additive model
JCU	James Cook University
km	kilometre
m	metre
MMP	Great Barrier Reef Marine Monitoring Program
NRM	Natural Resource Management
Paddock to Reef program	Paddock to Reef Integrated Monitoring, Modelling and Reporting Program
PAR	Photosynthetically available radiation
QA/QC	quality assurance/quality control
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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Executive summary

This document reports on the long-term health of inshore seagrass meadows in the Great Barrier Reef (the Reef). Results are presented in the context of the pressures faced by the ecosystem. Long-term health of inshore seagrass meadows is measured through seagrass abundance and resilience, which are summarised as the seagrass condition index, and supported by information on the proportion of colonising species, reproductive status, meadow extent, epiphytes on seagrass leaves and macroalgal presence.

Trends in key inshore seagrass indicators

Inshore seagrass meadows across the Reef marginally improved in overall condition in 2021–22, with the condition grade remaining **moderate** (Figure 1). Seagrass condition in the three northern most regions (Cape York, Wet Tropics and Burdekin) remained moderate, whereas Mackay–Whitsunday grade improved from poor to moderate. In contrast, the two southern most regions (Fitzroy and Burnett–Mary) remained poor and their condition continued to decline.

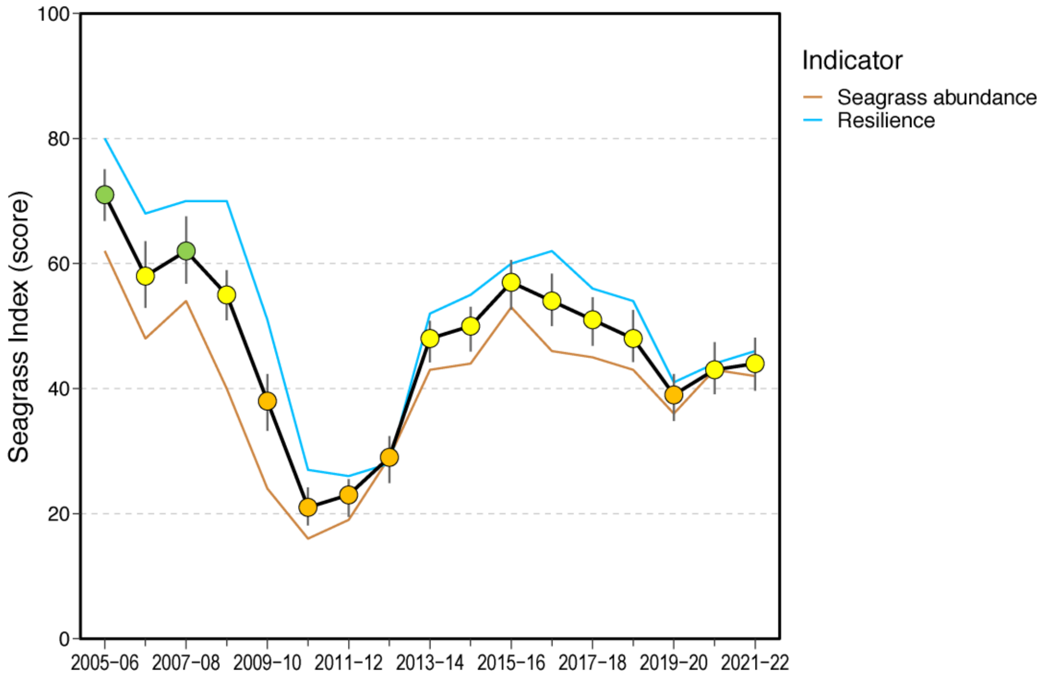


Figure 1. Overall inshore Reef seagrass condition index (±SE) with contributing indicator scores over the life of the MMP. The index is derived from the aggregate of metric scores for indicators of seagrass condition: abundance and resilience. Index scores scaled from 0–100 and graded: ● = very good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

Reef-wide inshore seagrass abundance has been improving since 2019–20, following four consecutive years of declines. Abundances at sixty per cent of the monitoring sites assessed in 2020–21 either improved or remained stable in 2021–22. Declines between 2015 and 2019 were driven mostly by losses in the Mackay–Whitsunday and Burdekin regions, with smaller declines simultaneously occurring in Cape York and the Wet Tropics. Since 2019, these losses in the northern most regions have abated, with the greatest improvement in the Burdekin as it recovered from the effects of heavy rainfall and above-average discharge from rivers in early 2019. There were, however, declining abundances in all three southern regions during 2020–21, and although these declines have abated in Mackay–Whitsunday, they have continued in the Fitzroy and Burnett–Mary.

Resilience continued improving in 2021–22, suggesting a recovering trajectory for Reef seagrass habitats following the seven-year low in 2019–20, however, seagrass in the very southern regions remain vulnerable to further disturbances.

There are further signs of recovery based on additional criteria, including:

- continued decreasing or stable proportion of colonising species, which are the first to establish after a disturbance. The decreasing trend indicates recovery towards species that are foundational to the meadows.
- increasing or stable meadow extent at three quarters of sites, culminating in the greatest meadow extents in the last four years. However, seagrass within estuarine and reef habitats in the southern regions remain vulnerable to large disturbances because meadow-scapes remain highly fragmented.
- increasing seed banks at coastal habitats, but decrease or absence of seed banks across other habitats.
- decreasing and low epiphyte cover on seagrass leaves across coastal habitats, accompanied by continued low macroalgae abundance across all habitats.

Influencing pressures

Pressures affecting inshore Reef seagrass habitats were low, but variable among regions and habitats in 2021–22. There was limited cyclone activity in 2021-22, with only TC Tiffany entering Reef waters and crossing the Cape York coast in early January 2022. However, the season was characterised by some relatively late rainfall events in April and May 2022 in the very southern NRM regions. Overall, rainfall and river discharge were just above the long-term median for the Reef. The northern NRM regions (Cape York, Wet Tropics and Burdekin) had discharges around the long-term median while the Mackay–Whitsunday region was around half of the long-term median and the Fitzroy region was 1.5 times above the long-term median. The Burnett–Mary region had very high discharge in the 2021-22 water year at nearly 9 times above the long- term median.

Benthic light availability was slightly above the long-term average for inshore Reef seagrass meadows but lower than the long-term average (by more than 0.5 mol m^{-2} d^{-1}) at 9 of the 23 monitoring locations across all regions, and around or higher than the long-term average at the remainder of locations.

The most significant environmental pressure affecting inshore Reef seagrass meadows was within-canopy water temperatures, which were the second highest since the MMP commencement, at around half a degree higher than the long-term average, and where the number of days of excessive temperatures (>38°C) were the highest in six consecutive years.

To summarise by region for this reporting year, wet season rainfall and discharge were generally similar to the long-term in all except the most southern regions. As a consequence, northern regions (Cape York, Wet Tropics, Burdekin, Mackay–Whitsunday) experienced below average exposure to turbid water types I and II, which resulted in slightly above average light availability. However, this was offset to some degree by near record above average water temperatures. In these regions, seagrass condition marginally improved. Wet season rainfall and river discharge were above average in the southern most regions (Fitzroy, Burnett–Mary), resulting in lower light availability, which coupled with near record water temperatures likely exacerbated chronic stress conditions, impacting growth in seagrass already in a poor condition from the previous year.

There is a history of cumulative pressures facing Reef inshore seagrass meadows since the MMP 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

Reef-wide inshore seagrass condition marginally improved in 2021–22, with the condition grade remaining moderate. Inshore seagrass condition remained a moderate grade in the northern Natural Resource Management (NRM) regions (Cape York, Wet Tropics and Burdekin), improved to a moderate grade in the central region (Mackay–Whitsunday), while condition deteriorated in the most southern regions (Fitzroy and Burnett–Mary), with the grade remaining poor.

Of concern is the inshore seagrass condition in the most southern regions; Fitzroy and Burnett–Mary. In these regions, seagrass abundance has decreased over the long-term, meadow extents remain low and highly fragmented, a considerable portion of meadows are dominated by colonising rather than foundational seagrass species, reproductive effort and seed banks are low or absent, and overall resilience is poor. These declines in seagrass condition in the most southern regions appear either a legacy of recent (4–5 years) extreme events (e.g. cyclone) or localised disturbances. Findings from the current monitoring period suggest seagrass ecosystems in the Fitzroy and Burnett–Mary regions may be more vulnerable to adverse or severe disturbances in the near future.

Climate change is the most significant threat to the Reef's long-term outlook, and the 2022–23 wet season is expected to include intensifying pressures (rainfall, river discharge and tropical storms) as a consequence of a La Niña climatic phenomena. Maintaining and building seagrass resilience is now a priority to secure a future for Reef seagrass ecosystems. 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 building resilience and restoring degraded meadows need to be explored.

1 Introduction

Approximately 3,464 km^2 of inshore seagrass meadows have been mapped in the Great Barrier Reef World Heritage Area (the World Heritage Area) in waters shallower than 15 m (McKenzie *et al.* 2014b; Saunders *et al.* 2015; Carter *et al.* 2016; McKenzie *et al.* 2016; Howley, Unpublished data). The remaining predominantly modelled extent (90 per cent or 32,215 km^2) of seagrass in the World Heritage Area is located in the deeper waters (>15 m) of the lagoon (McKenzie *et al.* 2022). These deepwater 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 (35,679 km^2) within the World Heritage Area represents nearly half 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 and community types is provided by extensive bays, estuaries, rivers and the 2,300 km length of the Reef with its inshore lagoon and reef platforms. Seagrasses can be found on sand or muddy beaches, on reef platforms and in reef lagoons, and on sandy and muddy bottoms down to 70 m or more below Mean Sea Level (MSL) (Carter *et al.* 2021b).

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.* 2021a) (Figure 2). 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.

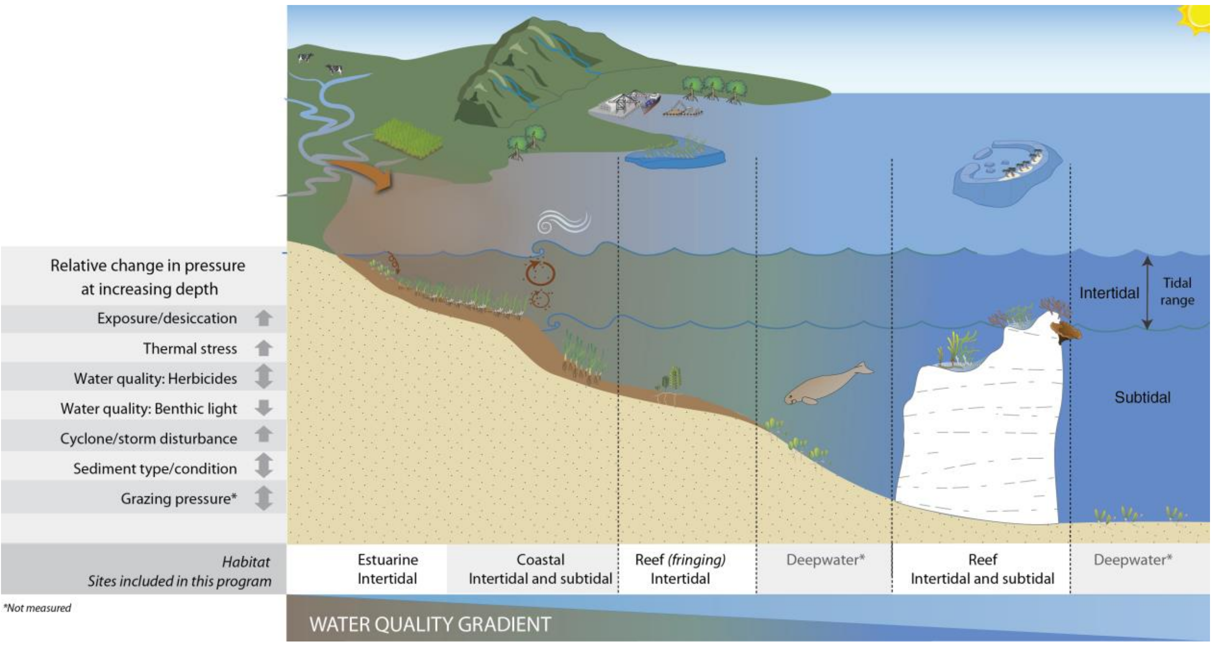


Figure 2. General conceptual model of seagrass habitats in north east Australia and the water quality impacts affecting the habitat (adapted from Carruthers *et al.* 2002, and Collier *et al.* 2014). Grey arrows indicate increase, decease or variable response with increasing depth.

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* spp.), 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 Reef Authority) is to sustain the Reef's outstanding universal value, build resilience and improve ecosystem health over each successive decade (GBRMPA 2014). Improving water quality is a key objective, because good water quality aids the resilience of coastal and inshore ecosystems of the 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 Reef Authority since 2005. The seagrass sub-program is also supported by contributions from the Seagrass-Watch program (Burdekin and Mackay–Whitsunday) 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 2022; https://bit.ly/3Ym7a42).

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 that can be used to assess how they respond to environmental pressures, and these measures are referred to herein as indicators (Table 1).

These indicators 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 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 (e.g. abundance, reproductive effort), to months and even years (e.g.

composition and meadow extent). Furthermore, indicators are conceptually linked to each other and to environmental drivers of concern, in particular, water quality.

Report Card category	Indicator category	Minutes-Days	Weeks	Months	Years	Seagrass report	Report card
Water quality	**Climate**	Cyclones				Y	
		Rainfall & river discharge^				Y	
		Wind (resuspension of sediments, scouring of sediments, currents)				Y	
		Extreme water temperature (hours/days > threshold)				Y	
			Chronic temperature rise (weekly anomalies)			Y	
	Water quality		Total suspended solids, turbidity, Secchi depth^				Y
			Chlorophyll a^				Y
			Nutrients (dissolved and particle forms of N, P & C)^				
			Temperature and salinity^				
			Water colour (weekly colour classes)^			Y	
			Benthic light (at seagrass canopy)			Y	
Seagrass	**Habitat features**			Sediment composition		Y	
			Epiphytes and macroalgae			Y	
	Seagrass condition		Abundance (per cent cover)			Y	Y
				Spatial extent		Y	
	Seagrass resilience		Reproductive structures			Y	
			Species composition			Y	Y
			Abundance threshold			Y	
			Seed bank			Y	

^Water quality monitoring program (TropWATER James Cook University, Australian Institute of Marine Science, Howley consulting)
*Coral monitoring program (Australian Institute of Marine Science)

Table 1. Climate, environmental, seagrass condition and seagrass resilience indicators reported as part of inshore seagrass monitoring (see Table 2 for details on data source). Indicators that are used to calculate the Seagrass Index and Water Quality Index (indicating potential water quality pressures on Reef habitats) for the Reef Report Card are also indicated. All indicators are shown against their response time. Indicators colour grouped by category.

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) (Table 1).

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).

Indicators that 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).

- Daily light levels 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.
- Elevated 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 (Table 1). Abundance can respond to change on time-scales ranging from weeks to months (depending on species) in the Reef, while meadow extent tends to adjust over longer time-scales (months to years). Seagrass extent 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 mega herbivores, such as dugongs and turtles. Therefore, extent and abundance 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).

Seagrasses expand and produce new shoots through clonal growth, but seagrasses are also angiosperms (flowering plants). Sexual reproductive structures (flowers, fruits, and seeds) are an important feature of a healthy seagrass meadow (Kenworthy 2000; Jarvis and Moore 2010; Rasheed *et al.* 2014). Sexual reproduction is necessary to form seed banks, which facilitate meadow recovery following periods of decline, and seed germination increases clonal diversity of the meadow (richness). The level of reproductive effort (reproductive structures per unit area) by a meadow in each season provides the basis of new propagules for recruitment in the following year (Lawrence and Gladish 2018; McKenzie *et al.* 2021a).

Seagrasses possess the ability to resist disturbances through physiological processes and modifications to morphology (i.e. growth form), and recover following loss by regeneration from seed and through clonal growth (sexual and asexual reproduction, respectively). Seagrass species vary in their dependence on resistance and recovery strategies. Broadly, we categorise species as having either persistent or colonising traits based on their ability to resist or recover, and species with a mixture of those traits are categorised as opportunistic (Kilminster *et al.* 2015) (Figure 3). The contributions of species, with different life history strategies, differs between seagrass habitats, and varies through time based on pressures acting on the habitats. Meadows dominated by colonising species have lower ability to resist pressures, but higher capacity to recover from disturbances. Therefore, changes in the species composition of a meadow can indicate meadow state and infer disturbance levels. For example, 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 3).

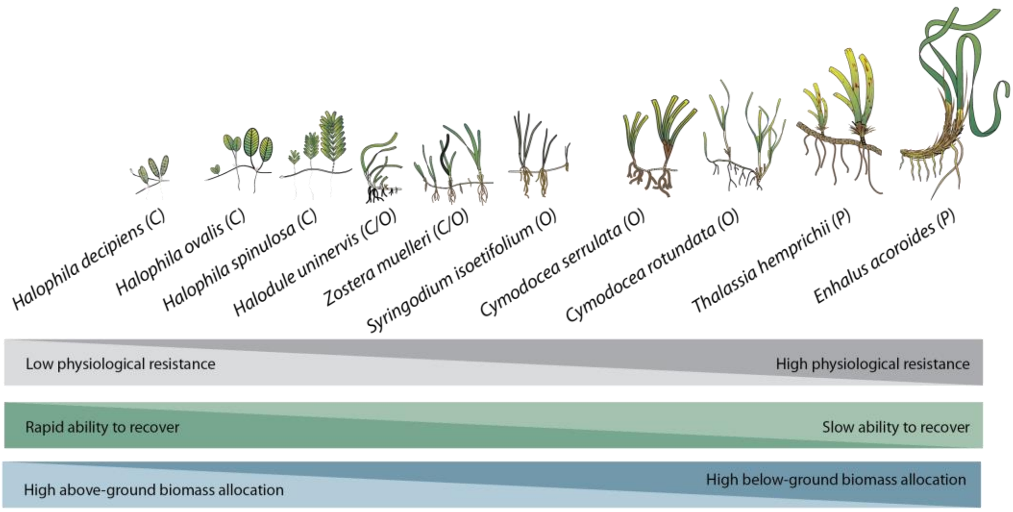


Figure 3. Dominant traits among the Reef seagrass species, with emphasis on their ability to either resist disturbances, or to recover following loss: colonising (C), opportunistic (O), or persistent (P). Adapted from Collier *et al*. (2021b) and Kilminster *et al*. (2015).

1.3 Structure of the Report

This report presents data from the fifteenth period of monitoring inshore seagrass ecosystems of the Reef under the MMP (undertaken from June 2020 to May 2021; hereafter called 2020–21). The inshore seagrass monitoring sub-program of the MMP reports on:

- abundance and species composition of seagrass (including seascape mapping) in the late dry season of 2020 and the late wet season of 2021 at inshore intertidal and subtidal locations
- resilience, including reproductive status of the seagrass species present at inshore intertidal and subtidal locations
- spatial and temporal patterns in light, turbidity, and temperature at sites where autonomous loggers are deployed
- trends in seagrass condition, measured as abundance (per cent cover) and resilience
- seagrass species composition 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 3 describes the drivers and pressures on the Reef during 2020–21, in the Driver-Pressure-State-Impact-Response (DPSIR) framework, followed by Section 4, which describes the condition and trend of inshore seagrass in the context of environmental factors.

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 Moran *et al*. (2023) are replicated to support the interpretation of the inshore seagrass results.

2 Methods summary

In the following, an overview is given of the data 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.* (2021b).

2.1 Climate and environmental pressures

Climate and environmental pressures affect seagrass condition and resilience (Figure 2). The pressures of greatest concern are:

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

The measures are either climate variables, which are generally not collected at a site-specific level, and within-canopy measure recorded at each site. The data source and sampling frequency is summarised in Table 3.

2.1.1. Climate

Cyclone tracks and total daily rainfall were accessed from the Australian Bureau of Meteorology from meteorological stations which were proximal to monitoring locations and provided by the MMP water quality sub-program (Moran *et al.* 2023).

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.

Information on exposure to different optical water types is generated by the MMP water quality sub-program (Moran *et al.* 2023). The inshore water quality sub-program includes a remote sensing component, which describes water quality characteristics for 22 weeks of the wet season (December–April). Water quality is described as water types of turbid, brown primary water, green secondary water, and tertiary waters. Colours are based on the Florel-Ule scale and are derived from daily Sentinel-3 OLCI Level 2 colour satellite images (Petus *et al.* 2019). Methods are detailed in Moran *et al*. (2023). Water colour has been confirmed as a predictor of changes in seagrass abundance (Petus *et al.* 2016). Primary and secondary water types (WT1 and WT2) have the greatest effect on seagrass habitats because light is attenuated by the high levels of suspended particulate matter, phytoplankton (chlorophyll-*a*) and dissolved matter. Exposure maps are therefore based on frequency of exposure to primary and secondary water types, while tertiary water (WT3) exposure is also presented in summary tables for each site. It is important to note that Reef water types, do not always correspond to direct catchment discharge influence, and can be due to marine processes (especially the Reef WT3) and to resuspension in shallow areas (especially the Reef WT1).

Table 2 Reef optical water types used to assess exposure of seagrass to water quality pressures (from Moran *et al.* 2023).

Reef water type	Description	Colour of water to the eye
WT1 (Primary)	Waters with high phytoplankton levels and increasing sediment and dissolved organic matter	Brownish-green
WT2 (Secondary)	Waters with colour still dominated by algae, but increased dissolved organic matter and some sediment may be present	Greenish water
WT3 (Tertiary)	Slightly below ambient water quality, but with high light penetration	Greenish-blue
WT4 (Marine)	Ambient marine water with high light penetration	Blue

Tidal height observations were used to determine if the tidal exposure regime may be increasing stress on seagrass and hence drive seagrass decline. Tidal observations were accessed from Maritime Safety Queensland and duration of annual air-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 21).

2.1.2. Environment within or at the seagrass canopy

Autonomous iBTag™ submersible temperature loggers (iBCod™22L) were deployed at all sites identified in Appendix 2, Table 20. The loggers recorded temperature (accuracy 0.0625°C) within the seagrass canopy every 30–90 minutes (Table 3). 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 20). The light sensor is positioned upright at the seagrass canopy. 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}), hereinafter daily light. 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.* 2020). 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 (see 2.2.2) 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 3. 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	1968–2021	remote sensing and observations at nearest weather station	yearly	No. yr^{-1}	Bureau of Meteorology
Rainfall	1889–2021*	rain gauges at nearest weather station	daily	mm mo^{-1} mm yr^{-1}	Bureau of Meteorology
Riverine discharge	1970–2021	water gauging stations at river mouth		L d^{-1} L yr^{-1}	DES#, compiled by (from Moran *et al.* 2023)
Plume exposure	2006–2021 wet season (Nov–Apr)	remote sensing and field validation	weekly	frequency of water type (1–6) at the site	MMP inshore water quality program (from Moran *et al.* 2023)
Tidal exposure	1999–2021	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	2002–2021	iBTag	30–90 min	°C, temperature anomalies, exceedance of thresholds	MMP Inshore Seagrass monitoring
Light	2008–2021	Odyssey 2Pi PAR light loggers with wiper unit	15 min	daily light (mol m^{-2} d^{-1}) frequency of threshold exceedance (per cent of days)	MMP Inshore Seagrass monitoring
Sediment grain size	1999–2021	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 (NRM) regions with catchments draining into the Reef: Cape York, Wet Tropics, Burdekin, Mackay–Whitsunday, Fitzroy and Burnett–Mary (Table 4, Figure 4). Seventy–five sites across 35 locations were assessed during the 2021–22 monitoring period (Table 4, Appendix 2, Table 20). This covered fifteen coastal, four estuarine, and twelve reef locations.

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 monitoring 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 (1) covered the greater extent within the inshore region, (2) were generally the dominant seagrass community type and (3) those meadows 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.

Table 4. 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	2020–21	2021–22
Cape York	Shelburne Bay	MMP								●	●	◐	◐		◐	◐	◐	◐	◐
	Margaret Bay	RJFMP																	◐
	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	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Cid Harbour	RJFMP																	◐
	Tongue Bay	RJFMP											◐	◐	◐	◐	◐	◐	◐
	Whitehaven Beach	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	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

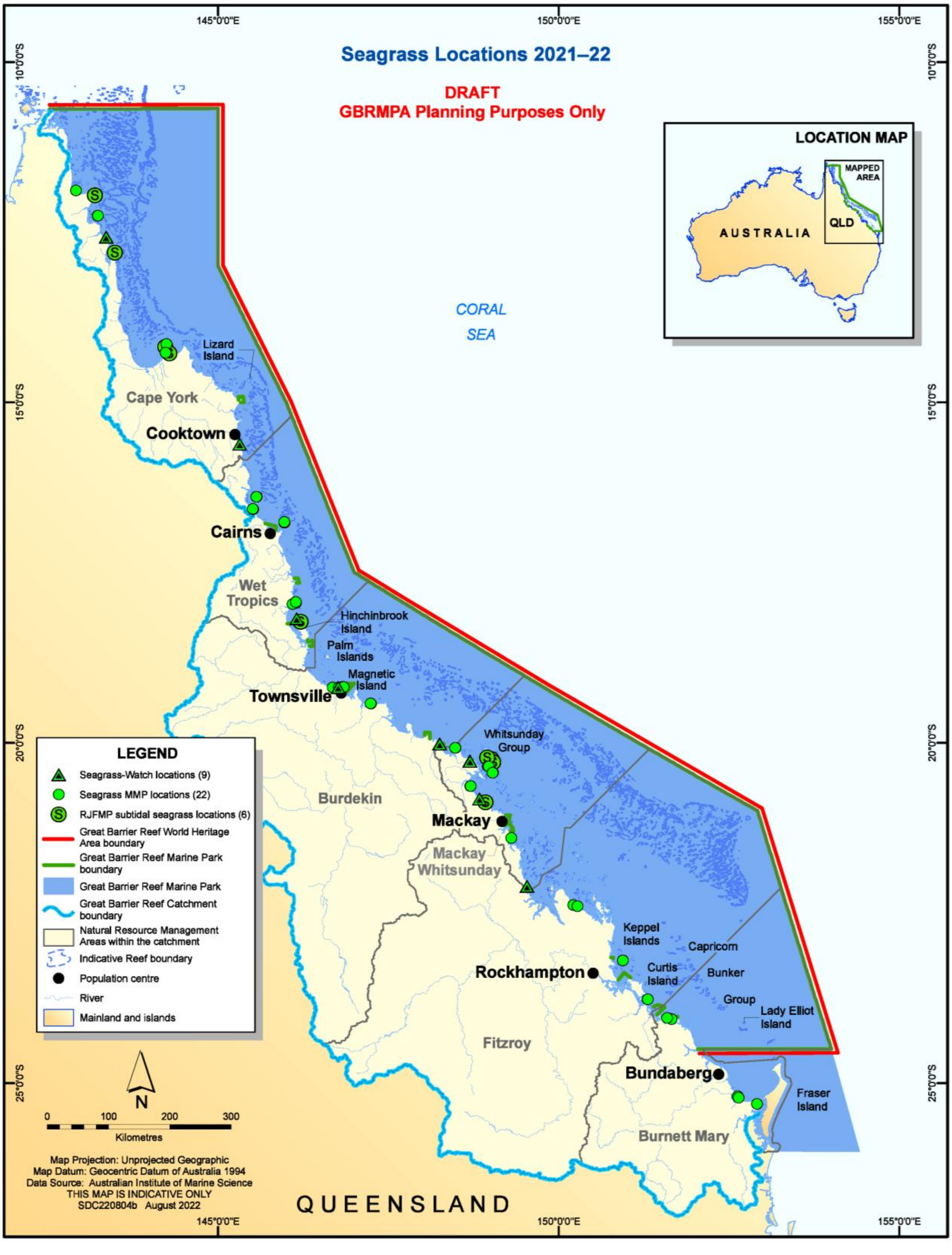


Figure 4. Inshore seagrass survey locations that exist as of 2021-22. However, not all locations were surveyed in 2021-22 (see Table 2).

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. reproductive effort, seed banks).

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 21). 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 depth) 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).

The meadows chosen for monitoring were in fact lower littoral (rarely exposed to air), although classified intertidal within the MMP. 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, such as reef locations in Cape York, Wet Tropics, Burdekin and Mackay–Whitsunday (Table 5).

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 opportunistic 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 that 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, Syringodium, Thalassia* and *Zostera* (Table 5).

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 at sites sampled in the late dry only (e.g. Cape York) are most likely to be in response to wet season conditions in the previous reporting period.

Apart from the 47 MMP long-term monitoring sites, data included 14 sites from Seagrass-Watch and 18 sites from QPWS to improve the spatial resolution and representation of subtidal habitats (Table 6).

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 20). The seagrass species (including foundation) present at each monitoring site is listed in Table 5 and Table 6.

2.2.2 Seagrass abundance, composition and extent

Seagrass abundance, species composition, and meadow spatial extent were assessed from samples collected in the late dry 2021 and late wet 2022 at locations identified in Table 5. 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. Sites were defined as a 5.5 hectare area intertidally and 3.1 hectares subtidally, within a relatively homogenous section of a representative seagrass community/meadow (McKenzie *et al.* 2003).

Monitoring at sites in the late dry (September-November 2021) and late wet (March-May 2022) 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). Transects are placed in the same position (±3 m) each assessment.

The sampling strategy for subtidal sites was modified in 2021–22, as a result of the discontinuation of SCUBA diving; driven by budgetary constraints, logistic and occupational health and safety issues relating to diving in poor visibility coastal waters. At each site, a GoPro® drop–camera assembly (incl. frame with 0.25 m^2 quadrat in field of view), was used to visually assess the seabed and the photoquadrat footage captured for post-field analysis. Along three 50 m transects within a 50 m radius of a central point, between 10 and 33 photoquadrats were assessed for seagrass percentage cover, species composition and macroalgae abundance. Subtidal assessments were conducted using a real time drop-camera slaved to a surface tablet, to ensure photoquadrats were sufficiently spaced apart and the vision captured was suitable for post-field analysis. A van Veen grab was used to validate seagrass species observed on the tablet screen and to assess sediment composition.

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.* 2021b).

Table 5. Inshore sentinel seagrass long-term monitoring site details including presence of foundation (■) and other (□) seagrass species in the current or previous reporting periods. ^ =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 / 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					□		■			
				LN3	Lindeman Is.	149.033	-20.438					□		■			
			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 6. 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 in the current or previous reporting periods. NRM region from www.nrm.gov.au. ^ =subtidal, ~ =not assessed in 2021–22.

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)*	Jacky	Margaret Bay *coastal*	MA1^	Margaret Bay	143.19358	-11.9574					□	□	■			
				MA2^	Margaret Bay	143.20338	-11.9559										
		Lockhart	Weymouth Bay *reef*	YY1~	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	Cid Harbour *reef*	CH4^	Cid Harbour	148.9506	-20.213		■		□	□	□	■	■		
				CH5^	Cid Harbour	148.9451	-20.222										
			Tongue Bay *reef*	TO1^	Tongue Bay	149.016	-20.240					□		■		■	
				TO2^	Tongue Bay	149.012	-20.242										
			Whitehaven Beach *reef*	WB1^	Whitehaven Bch	149.0386	-20.2808		■			□	□	■	■		
				WB2^	Whitehaven Bch	149.0475	-20.2903										
		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										

Mapping of the meadow extent and meadow–scape (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 at intertidal sites and drop-camera at subtidal sites. Seagrass meadow–scape that tended to grade from dense continuous cover to no cover (i.e. over a continuum that included small patches and shoots of decreasing density) had the meadow edge delineated where there was a non-vegetated space with the distance of more than 3 metres (i.e. accuracy of the GPS). Each entire site (5.5 ha intertidal and 3.1 ha subtidal) was mapped (seagrass and no seagrass). It should be noted that within a site, areas that are not suitable for seagrass can occur, e.g. consolidated sediments, coral reef or dry sandy beach. The relative spatial extent was calculated by dividing the mapped seagrass area by the total habitable area for seagrass within the entire site.

2.2.3 Seagrass reproductive status

Seagrass reproductive state was assessed from samples collected in the late dry 2020 and late wet 2021 at locations identified in Table 5. Samples were processed according to standard methodologies (McKenzie *et al.* 2021b).

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 (2 mm mesh) 30 cores (50 mm diameter, 100 mm 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 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 Calculating Report Card scores

2.3.1 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 19).

Abundance 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 7) 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 7. Scoring threshold table to determine seagrass abundance grade. low = 10th or 20th percentile guideline. NB: scores are unitless.

Grade	Percentile category	Score
very good	75–100	100
good	50–75	75
moderate	low–50	50
poor	<low	25
very poor	<low by >20 per cent	0

2.3.2 Seagrass resilience

Resilience can be described as the capacity of an ecosystem to cope with disturbance (Connolly *et al.* 2018), and to adapt to change without switching to an alternative state (Holling 1973; Unsworth *et al.* 2015). For monitoring and reporting, '*a set of measurable biological characteristics that exemplify seagrass meadows' resistance to pressures and essential mechanisms for recovery*' are required to assess resilience (Udy *et al.* 2018). The resilience indicator takes a subset of measurable characteristics for which long-term data is available to develop a score.

The seagrass resilience indicator is based on the premise that resilience includes a resistance and recovery element. Seagrass species vary in their dependence on these traits. 'Colonising' species generally have low levels of resistance traits and 'persistent' species have high levels of these traits. Resistance is incorporated into the metric through meadow condition, and whether abundance and species composition exceed critical thresholds (<20th percentile or >50 per cent, respectively). It is also influenced by the proportion of persistent species. Sites that are dominated by colonising species therefore have low levels of resistance, making them highly vulnerable to events such as periods of elevated turbidity caused by flood plumes. Sites that are in impacted state and have low abundance relative to the average for that site are also vulnerable.

Reproductive effort indicates potential for recovery from seeds and likelihood of high clonal diversity. By contrast, traits that enable the species to recover following an impact are the highest in 'colonising' species and lowest in 'persistent' species. These traits include forming a seed bank from flowers and rapid growth rates. 'Opportunistic' species have traits of both resistance and recovery.

The resilience score is calculated using a decision tree. It includes resistance potential and likelihood of recovery based on reproductive effort (as a proxy for seed/propagules) graded according to the species in the habitat.

Sites are scored from 0 to 100 in each year using a decision tree (Collier *et al.* 2021a). The three main categories within the tree are:

- low resistance sites
- high resistance sites but non-reproductive (low recovery potential)
- high resistance and reproductive (increased recovery potential).

The conceptual basis for the resilience indicator and the statistical analysis supporting the decisions in the tree are detailed in Appendix 1, Figure 89.

The resilience scores are graded as: very poor (<20), poor (20≤40), moderate (40≤60), good (60≤80), very good (80≤100).

Table 8. Scoring thresholds and decisions for the resilience metric. *Foundational = opportunistic and persistent species. NB: scores are unitless.

Description	Species composition / abundance	Reproductive effort	Score calculation	Score	Category
1 Low resistance	Per cent colonising species >50 per cent AND/OR total per cent cover <20^{th} percentile of site	Reproduction not present	Proportion of colonising species	0–15	1.1
		Reproduction present (any species)	Proportion of foundational species and reproductive presence/absence	5–30	1.2
2.1 High resistance but low recovery potential	Per cent foundational species > 50 per cent AND total cover >20^{th} percentile of site	Reproduction (foundational) not present last 3 years	Proportion of persistent species present (min <10^{th} percentile, max 95^{th} percentile)	30–50	2.1.1
		Not reproductive this year, but reproductive (foundational) in last 3 years (seed bank is likely to be present)		50–70	2.1.2
2.2 High resistance and high recovery potential	Per cent foundational species >50 per cent AND total cover >20^{th} percentile of sites AND persistent species present	Reproduction (foundational) present	Reproductive structure count (min <10th percentile, max 95^{th} percentile)	70–100	2.2.1
				85–100	2.2.2

2.3.3 Seagrass condition index

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

- seagrass abundance (per cent cover)
- seagrass resilience.

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 9). *Please note: Cape York omitted from the score in reporting prior to 2012 due to poor representation of inshore monitoring sites*.

Table 9. Area of seagrass shallower than 15 m in each region within the World Heritage Area boundaries.(from McKenzie *et al.* 2014a; McKenzie *et al.* 2014b; 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**

2.4 Data analyses

All analysis was run in the software R-4.2.2 (R Core Team 2022).

2.4.1 Score propagation of error

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 Reef), 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 two seagrass indicators and overall index.

2.4.2 Abundance (per cent cover) generalised additive models (GAM)

Due to the high proportion of zeros and the unbalance of the per cent cover data through time (different sites monitored at each seasonal sampling period), we used a two-step approach to show the temporal trend.

1) Modelling the per cent cover average and confidence intervals for each sampling event.

The first step of the analysis was to accurately estimate the mean and 95 per cent CI for each season sampling period across various level (e.g. Reef wide, per NRM region, per habitat types). Because the data we want to analysed is a percentage with a high proportion of 0, we need to use a zero-inflated beta distribution (ZABE) (Zuur, Beginner's Guide to Zero-Inflated Models with R ,2016). The package gamlss (Rigby and Stasinopoulos 2005) was used for the analysis with the family BEZI (https://search.r-project.org/CRAN/refmans/gamlss.dist/html/BEZI.html).

The zero-inflated beta distribution is given as:

1) if (y=0) – Binomial model

    f(y) = nu

2) if y=(0,1) – Beta model

    f(y|mu,sigma)=(1-nu)*(Gamma(sigma)/Gamma(mu*sigma)*Gamma((1-mu)*sigma))*y^(mu*sigma-1)*(1-y)^(((1-mu)*sigma)-1)

    The parameters satisfy 0<mu<1, sigma>0 and 0<nu<1.

The expected values (E) and variance (VAR) are:

    E(y)=(1-nu)*mu

    Var(y)=(1-nu)*(mu*(1-mu))/(sigma+1) + nu*(1-nu)*mu^2

In our models Site was included as a random effect. Because some sites had very drastic changes in their abundance through time with sometimes complete seagrass loss, random effect cannot be accurately estimated over the whole time series. Therefore, per cent cover at the quadrat level for each seasonal date was analysed separately. The inclusion of random effect in the model is important to account for site-specific variance which results in more accurate estimations of confidence intervals around the mean across the various levels. The intercept model fitted was as followed:

Formula : Percent_cover ~ 1 + re (random(~1|Site)

The random effect of site was included in the three parameters estimated (mu, sigma and nu) but was dropped for sigma and nu if a parametrization error was encountered. In the extreme case of a zero-inflation superior to 95 per cent all random effects were dropped due to very limited number of quadrats with seagrass present.

We used a common bootstrapping method where a random distribution of 10000 was produced for mu and nu based on their parameter estimates and standard error outputted by the gamlss package to calculate the mean and 95 per cent CI of the resulting model.. This gave 10000 expected values where the mean, 2.5 quantile and 97.5 quantile were calculated.

In the case where only a few sites were included (<5) and one of the sites only had 0 per cent cover for all quadrats, the algorithm was having difficulties estimating the zero-inflation parameter (nu) with the inclusion of site as a random effect. This resulted in the bootstrapped expected values to not be normally distributed (2 separate peaks of values centred on 0 and on the mean of the sites with seagrass present) which would not lead to an appropriate estimate of the overall mean. In these very rare scenarios, the same zero-inflated beta model was run but with site as a fixed effect which led to a distribution of bootstrapped expected values for each site. The overall mean was obtained as the arithmetic mean of the site bootstrapped mean and the 2.5 quantile and 97.5 quantile were respectively the minimum and maximum of the 2.5 quantile and 97.5 quantile of the site bootstrapped CI.

This process was repeated of each seasonal date at various scales. As part of our regular validation process the residuals of all models were checked for violations of the generalised model assumptions.

2) Trends in per cent cover

Generalised additive models (GAMs) with the beta (logit link) family were fitted to resulting mean and 95 per cent CI from the first process to identify the presence and consistency of trends through time, using the mgcv (Wood 2020) package. The GAMs were used in a multilevel approach to show trends at the Reef, NRM region, habitat, location and site levels. The details and summary outputs of all the GAMs shown in the figures can be found in the Appendix (Table 24 Table 25, Table 26). There was no significant autocorrelation observed for consecutive years of order 1 to 3. However, the GAMs were weighted based on how many sites were included in the mean calculated to ensure the seasonality and unbalanced nature of our sampling was not affecting the long-term trend.

The final results presented were:

- the prediction for the GAM fitted through the mean points
- lower CI as the predictions – 1.96*SE of the GAM fitted through the lower 95 per cent CI points
- upper CI as the predictions + 1.96*SE of the GAM fitted through the upper 95 per cent CI points

2.4.3 Abundance (per cent cover) long-term trends

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. 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).

2.4.4 Resilience

Analysis of trends in the resilience scores was conducted using Generalised Linear Models (GLMs) with a gaussian distribution instead of GAMs, as this metric relies on samples collected once a year. Due to the low frequency of sampling the use of a smoother (GAM) is not recommended.

2.5 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, 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 (GAM 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 National Mapping Division of Geosciences Australia geodata topographic basemap (1:100 000 scale digital data).

3 Drivers and pressures influencing seagrass meadows in 2021–22

The following section provides detail on the overall climate and environmental pressures during the 2021–22 monitoring period, at a relatively broad level as context for understanding trends in seagrass condition. It includes:

- Climate (cyclones and rainfall), river discharge and turbid water exposure
- daily light (within-canopy)
- within-canopy temperature and threshold exceedance
- seagrass meadow sediment characteristics.

Supporting data is detailed within Appendix 2 and 3:

3.1 Summary

Long-term trends in the Water Quality Index indicate improvements in water quality across all regions examined in 2021-22, particularly the Wet Tropics (continuing to improve from moderate in 2019), Cape York (improving from moderate last year) and Mackay-Whitsunday (improving after remaining moderate since 2018). The Burdekin NRM region also showed early signs of improvement this year. The annual condition index (sensitive to year-to-year variability) in 2021–22 was good in Cape York, the Wet Tropics, and Burdekin, but remained moderate in Mackay-Whitsunday (Moran *et al.* 2023).

Environmental stressors in 2021–22 were just above long-term for rainfall and river discharge for the Reef, but variable among regions. The northern NRM regions (Cape York, Wet Tropics and Burdekin) had discharges around the long-term median, while Mackay–Whitsunday was around half and the Fitzroy was 1.5 times above the long-term median (Moran *et al.* 2023). The wet season was characterised by relatively late rainfall events in April and May 2022 in the very southern NRM regions, with the Burnett–Mary experiencing very high discharges at nearly 9 times above the long- term median (Moran *et al.* 2023).

The frequency with which the monitoring sites were exposed to water types one and two was slightly below the long-term average across the Reef, particularly in the majority the northern NRM regions (Figure 8). The presence of this turbid water is affected by resuspension-driven events as well as discharge and the relative attribution to these processes is discussed in further detail by Moran *et al*. (2023).

Table 10. Summary of environmental conditions at monitoring sites across the Reef in 2021–22 compared to previous monitoring period and the long-term average (range indicated for each data set). *intertidal only.

Environmental pressure	Long-term average	2020–21	2021–22
Climate			
Cyclones, number of events (1968–2021)	4	2	1
Wet season daily rainfall, mm d^{-1} (1961–1990)	4.0	4.0	3.3
Riverine discharge, ML yr^{-1} (1986–2016)	51,812,207	64,602,302	71,817,742
Wet season turbid water exposure, per cent (2003–2018)	89	81	83
Within seagrass canopy			
Temperature, °C (±) (max) (2003–2021)*	25.7 ±0.1 (46.6)	25.7 ±0.1 (41.9)	26.2 ±0.1 (45.5)
Daily light, mol m^{-2} d^{-1} (2008–2021) annual average	14.0	14.0	14.1
(min site–max site)	(6.1–20.2)	(7.8–19.4)	(7.2–20.9)
Proportion mud, per cent			
estuarine intertidal (1999–2021)	44.9 ±2.1	39.2 ±2. 6	36.3 ±2.0
coastal intertidal (1999–2021)	27.7 ±2.1	20.6 ±1.6	26.0 ±1.8
coastal subtidal (2015–2021)	53.2 ±2.6	55.2 ±3.9	59.8 ±0.0
reef intertidal (2001–2021)	4.3 ±1.2	4.1 ±0.4	4.2 ±0.6
reef subtidal (2008–2021)	16.8 ±1.3	38.5 ±0.5	29.5 ±0.8

Daily light levels were higher than the long-term Reef average in 2021–22. Light was higher than the long-term average in northern regions (except Cape York where loggers are not maintained year round), but below-average in the Fitzroy and Burnett-Mary regions. It was higher than average at eight of the light monitoring locations, lower than average at nine and around the long-term average at six locations. Light levels were higher than estimated annual light requirements for optimal growth (10 mol m^{-2} d^{-1}) at all but three locations.

Within canopy temperatures in 2021–22 were higher than the previous reporting period (2020–21) period, over half a degree above the long-term average, and the second highest since the MMP was established (Figure 7). The number of extreme heat days (days >40°C) were the highest in the last six years, and occurred across the Wet Tropics, Burdekin and Mackay–Whitsunday NRM regions. The third hottest seawater temperature ever recorded since the MMP was established was 45.5°C in the northern Wet Tropics region. (Figure 11).

There was limited tropical cyclone activity in the 2021–22 wet season, with only one tropical cyclone entering the Reef waters. Tropical cyclone Tiffany was a small system which entered Reef waters as a category 1 cyclone, before intensifying to category 2 during on 9 January near Cape Melville, but rapidly weakened as it moved over Princess Charlotte Bay and crossed the coast late on 10 January at category 1 intensity (Courtney and Boterhoven 2022). The system brought up to 170 millimetres (mm) of rainfall across the Daintree and Mossman river catchments in the 24 hours to 9 am Tuesday 11 Jan, and across the Cape York Peninsula near the track (Courtney and Boterhoven 2022).

Additionally, the remnants of ex- tropical cyclone Seth (a short lived category 2 system) in early January 2022, which, after originating in the eastern Timor Sea as a tropical low and traversing the northern Wet Tropics on 30 December 2021, weakened and caused considerable rainfall along the very southern catchments of the Reef (BOM 2022).

3.2 Rainfall

Rainfall across the Reef regions in the 2021–22 wet season was generally similar to the long-term average of wet seasons from 1961–1990, with the exception of the Burnett Mary NRM region which experienced above average rainfall and particularly elevated in the Mary Basin (Figure 5) (Moran *et al.* 2023). The only other region where a basin deviated above the long-term average was the Stewart, draining into the Reef just north of Princess Charlotte Bay in Cape York.

Several Reef basins received elevated rainfall in May 2022 which was outside of the wet season period (December to April) which accounts for some discrepancies between the rainfall patterns and the basin discharge (Moran *et al.* 2023). This was apparent in the Wet Tropics and northern Burdekin regions where the wet season rainfall map suggests a drier than average year (Figure 6), however, the largest rain event occurred in May and if incorporated into the maps then it would be considered an average wet season (Moran *et al.* 2023).

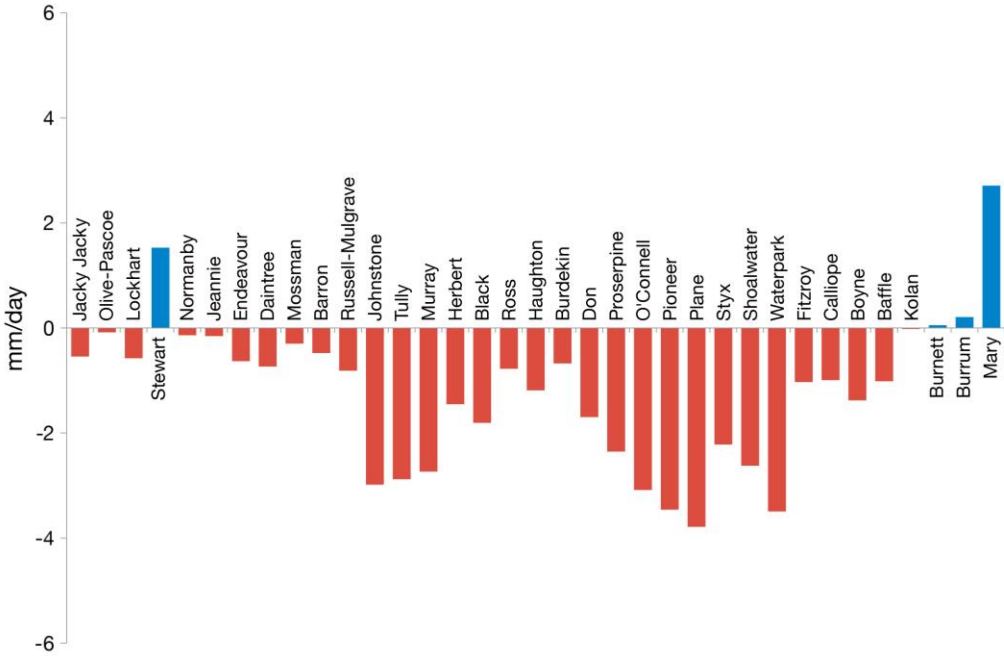


Figure 5. Per basin difference between annual average daily wet season rainfall (December 2021–April 2022) and the long-term average (1961–1990). Red and blue bars denote basins with rainfall below and above the long-term average, respectively. Note that the basins are ordered from north to south (left to right). Basins have been grouped into NRM regions as indicated by shaded panels. Compiled by Moran *et al*. (2023).

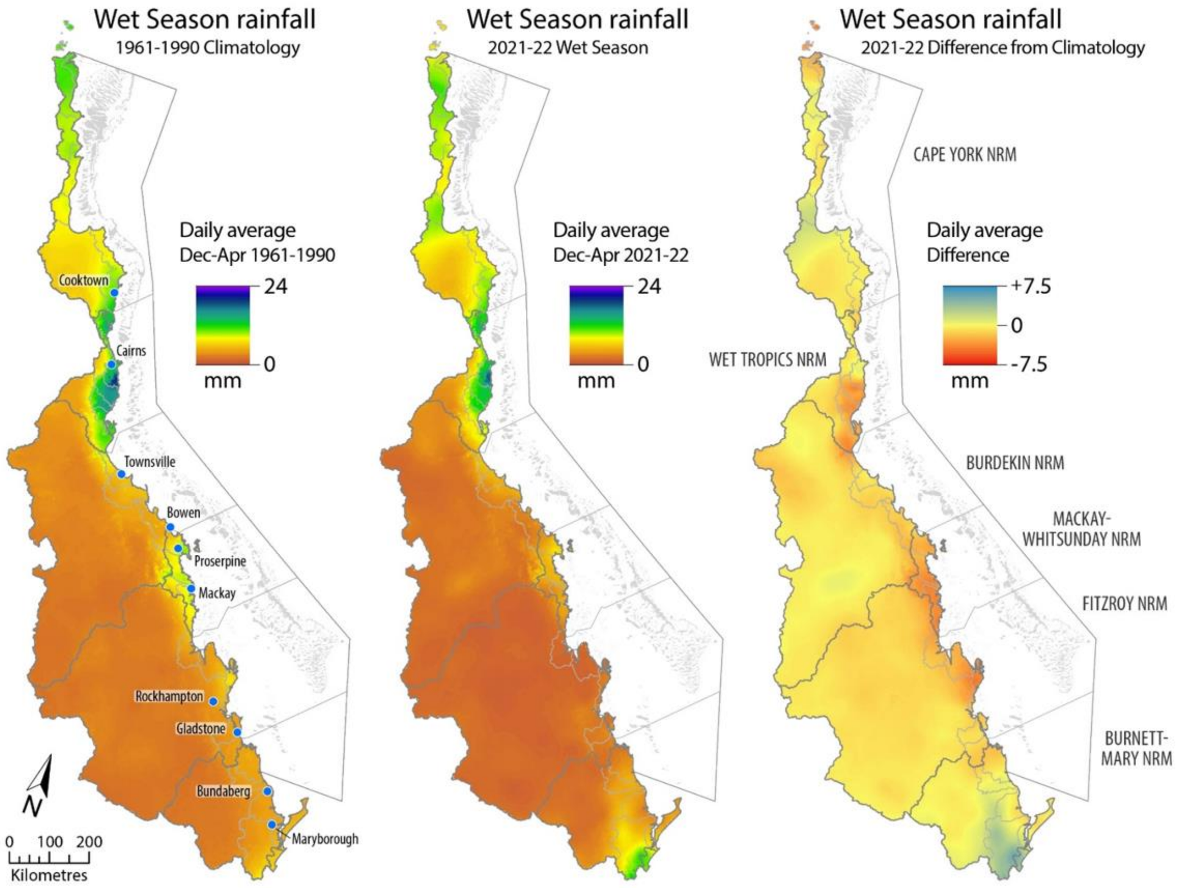


Figure 6. Average daily rainfall (mm day^{-1}) in the Reef catchment: (left) long-term annual average (1961–1990; time period produced by BOM), (centre) 2021–22 and (right) the difference between the long-term annual average and 2021–22 rainfall patterns where negative values indicate less rain. From by Moran *et al*. (2023).

3.3 River discharge

Annual river discharge for the Reef was above the long-term median in 2021–22 following a wet year in 2020–21, and a dry year in 2019–20 (Table 11). Discharges from basins entering the most southern Reef regions were well above median in most except some of the small basins in the Fitzroy region. The highest discharges in 2021–22 occurred in the Burnett–Mary region, with the three most southern rivers (Burnett, Burrum and Mary) discharging greater than 10 times the long-term median. Substantial discharges (>1.5 times the long-term median) also occurred in the northern Cape York (Olive, Pascoe and Lockhart Rivers).

Table 11. Annual water year discharge (ML) of the main Reef rivers (1 October 2021 to 30 September 2022, inclusive) compared to the previous seven wet seasons and long-term (LT) median discharge (1986–87 to 2019–20). 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 Moran *et al*. (2023).

Region	Basin	LT median	2018–19	2019–20	2020–21	2021–22
Cape York	Jacky Creek	2,471,267	3,423,675	2,320,007	3,607,722	2,365,731
	Olive Pascoe River	3,180,267	7,225,892	3,295,502	5,540,683	4,879,388
	Lockhart River	1,538,839	3,496,399	1,594,598	2,680,976	2,360,994
	Stewart River	758,172	3,001,843	564,816	1,419,942	569,738
	Normanby River	3,864,344	11,851,554	2,752,573	6,149,878	3,562,637
	Jeannie River	1,428,920	3,327,549	668,813	1,342,490	1,566,621
	Endeavour River	1,583,881	3,660,507	752,514	1,489,348	1,734,492
Wet Tropics	Daintree River	1,918,174	5,849,018	1,109,229	1,834,774	2,519,318
	Mossman River	604,711	1,355,506	399,108	654,566	800,754
	Barron River	622,447	1,663,883	346,727	667,265	692,908
	Mulgrave-Russell River	4,222,711	5,521,561	2,870,672	4,771,460	4,091,750
	Johnstone River	4,797,163	5,633,064	3,466,725	5,324,040	4,712,174
	Tully River	3,393,025	4,020,452	2,200,744	4,123,338	3,175,489
	Murray River	1,484,246	1,781,225	1,053,705	1,947,050	1,269,280
	Herbert River	3,879,683	6,226,046	1,606,187	6,842,168	3,283,590
Burdekin	Black River	293,525	1,360,539	144,144	429,282	273,677
	Ross River	279,376	2,531,556	293,165	232,975	202,811
	Haughton River	558,735	3,150,945	335,094	595,709	735,754
	Burdekin River	4,406,780	17,451,417	2,203,056	8,560,072	5,442,976
	Don River	496,485	1,134,548	481,577	510,906	383,927
Mackay-Whitsunday	Proserpine River	859,348	2,590,512	592,063	537,613	446,839
	O'Connell River	835,478	2,518,553	575,617	522,680	434,427
	Pioneer River	616,216	1,158,768	383,506	235,359	277,610
	Plane Creek	1,058,985	1,304,733	1,141,784	600,958	489,222
Fitzroy	Styx River	629,037	519,769	796,233	927,219	1,080,829
	Shoalwater Creek	727,306	600,785	920,902	1,072,570	1,250,433
	Water Park Creek	392,614	289,097	551,010	675,102	820,627
	Fitzroy River	2,875,792	1,473,960	2,786,994	436,730	4,505,289
	Calliope River	257,050	97,998	184,697	123,050	250,551
	Boyne River	179,108	3,313	99,139	31,002	171,925
Burnett-Mary	Baffle Creek	347,271	96,312	161,554	112,323	1,000,587
	Kolan River	115,841	28,153	28,792	19,211	818,716
	Burnett River	264,307	202,436	332,366	118,241	3,894,616
	Burrum River	130,835	103,766	112,113	44,691	1,612,683
	Mary River	908,873	767,683	551,344	420,909	10,139,380
	Sum of basins	60,746,947	105,423,018	37,677,067	64,602,302	71,817,742

3.4 Turbid water exposure and flood plume extent

The frequency of exposure to wet season water types, extent of the water types, and the within-canopy environmental pressures daily light and water temperature are summarised in Figure 7.

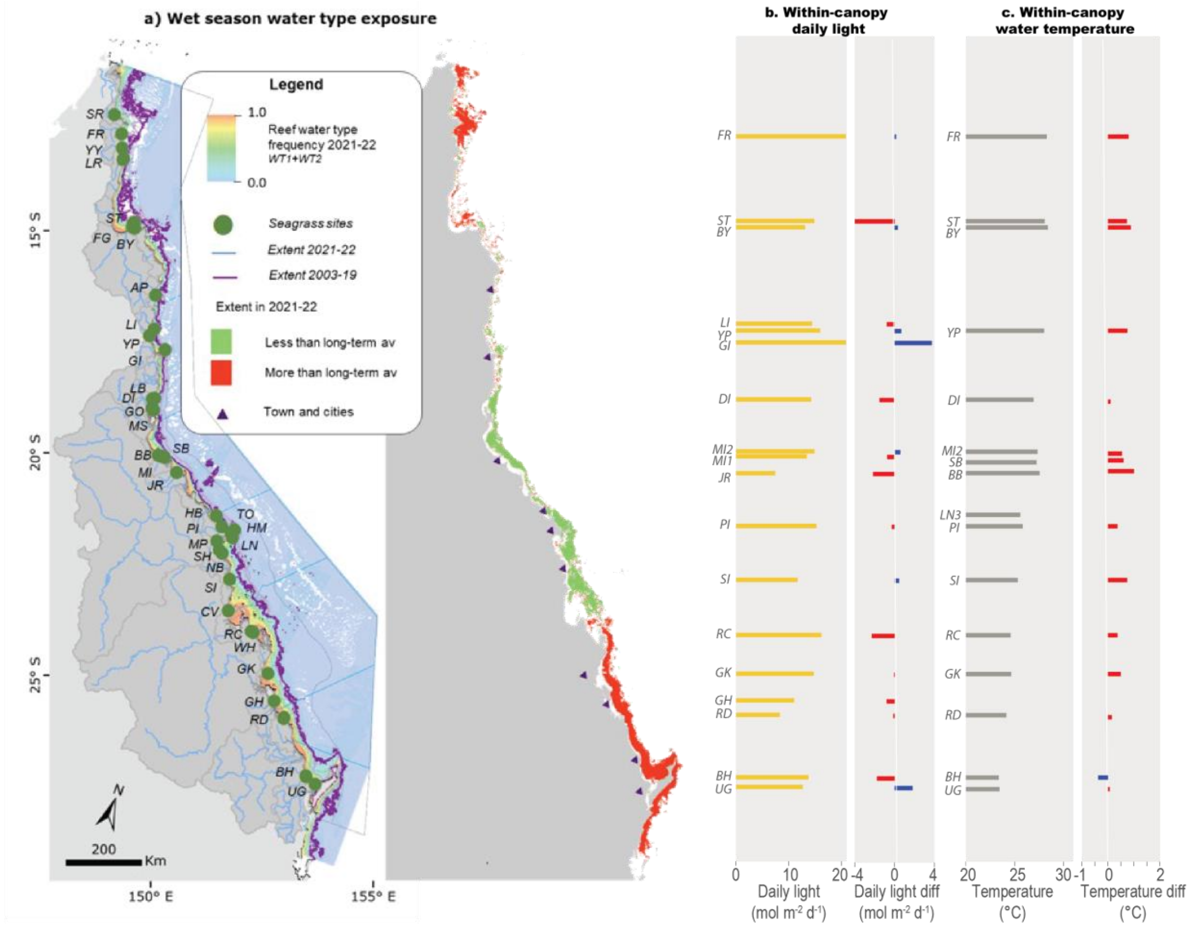


Figure 7. Environmental pressures in the Reef during 2021–22 and relative to long-term: a. Frequency of turbid water (primary and secondary water) exposure shown in the left-hand panel in the Reef from December 2021 to April 2022 ranging from frequency of 1 (orange, always exposed) to 0 (pale blue, never exposed), and right-hand panel the distribution of primary and secondary waters (10 per cent boundary) in 2021–22 relative to the long-term average, with red showing that that these water types extended further in 2021–22 and green showing they did not extend as far; b. within canopy daily light (shown as I_d) for all sites, and the deviation in daily light relative to the long-term average; and c. average within canopy water temperature, and deviation from the long-term average. Panels a and b from Moran *et al*. (2023).

The frequency of exposure to primary water types during the wet season weeks (December 2021–April 2022) is typically very high in the inshore regions of the Reef. Turbid coloured water (water types I and II) dominated the water types in the wet season of 2021–22 as is characteristic of inshore conditions over the long-term (2003–2019, Figure 7, panel 1). However, the water types I and II extended less distance off shore in the central Reef, but further offshore in the southern Reef (Figure 7, panel 2).

The frequency which the seagrass sites were exposed to water types I and II combined in the wet season was below multiannual conditions in all regions with the largest differences occurring in the Fitzroy (water type I), Wet Tropics and Cape York. Frequency of exposure to water type I only was also below average in all regions except the Burnett-Mary for water type I which was slightly above average.

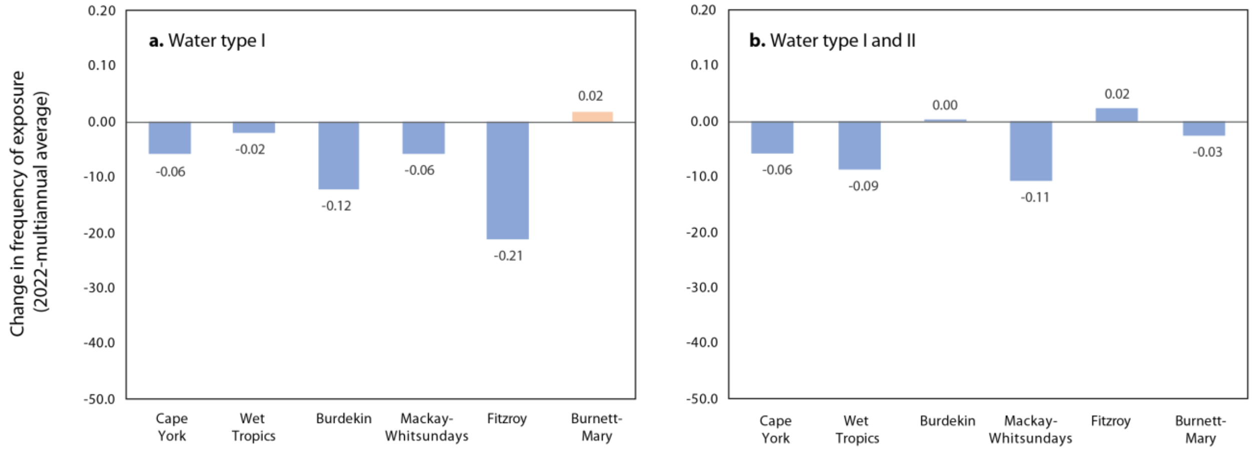


Figure 8. Difference in the frequency of exposure to primary (left) and primary and secondary optical water types (right) at seagrass monitoring sites during the wet season (December 2021–April 2022) compared to the long-term multiannual exposure (2003–2018).

3.5 Daily light

Daily light reaching the top of the seagrass canopy in the Reef in 2021–22 was 14.1 mol m^{-2} d^{-1} when averaged for all sites (Table 10), compared to a long-term average of 12.5 mol m^{-2} d^{-1}. At nine out of 23 of the locations where light is monitored, daily light was lower than the long-term average for the location and these occurred in each NRM region (Figure 7). There are regional, habitat and location levels differences.

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 in the regions in 2021–22 from north to south were (↓ = lower than, ↑ = greater than the long-term, ↕ = similar to long-term i.e. <0.5 mol m^{-2} d^{-1} difference):

- Cape York (15.9 mol m^{-2} d^{-1}) ↕
- northern Wet Tropics (17.2 mol m^{-2} d^{-1}) ↑
- southern Wet Tropics (14.3 mol m^{-2} d^{-1}) ↓
- Burdekin (11.9 mol m^{-2} d^{-1}) ↑
- Mackay–Whitsunday (13.5 mol m^{-2} d^{-1}) ↑
- Fitzroy (14.0 mol m^{-2} d^{-1}) ↓
- Burnett–Mary (11.6 mol m^{-2} d^{-1}) ↕

Daily light in the habitats in 2020–21 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 (15.6 mol m^{-2} d^{-1}) ↕
- coastal intertidal, n = 10 (13.4 mol m^{-2} d^{-1}) ↑
- estuarine, n = 3 (11.2 mol m^{-2} d^{-1}) ↕

Light is no longer measured at the reef subtidal sites and so the value for those sites have been removed from the long-term average calculations. Daily light is generally high in intertidal habitats when averaged for the year because of the occasional exposure to very high light when low tide occurs in daylight hours. However, these periods of exposure to high light occur infrequently during the wet season, because the tides do not drop to low levels during the day at that time of year in the Reef. Reef intertidal sites have the highest daily light levels followed by coastal intertidal and estuarine intertidal sites. Daily light for each of the sites is presented in Figure 7. 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.* 2016a), a coastal site at Jerona in the Burdekin region and an estuarine site at Rodds Bay in the Fitzroy NRM region. Bushland Beach and Shelley Beach often have low light levels, but due to logger failure at these sites, an annual average could not be calculated (Figure 101).

Long-term trends show a peak in within canopy daily light that occurs from September to December, as incident solar irradiation reaches its maximum and prior to wet season conditions (Figure 9). This also coincides with the peak seagrass growth season, and the predominant sampling period in this program. The lowest light levels typically occur in the wet season, particularly in January to July. In 2021–22, daily light steadily increased from post-wet season minima to a peak in November and December and declined through the wet season. The 28-day rolling average for light only remained below the long-term wet season average for a few days into the wet season. It did however decline after the wet season, likely driven by late periods of elevated rainfall.

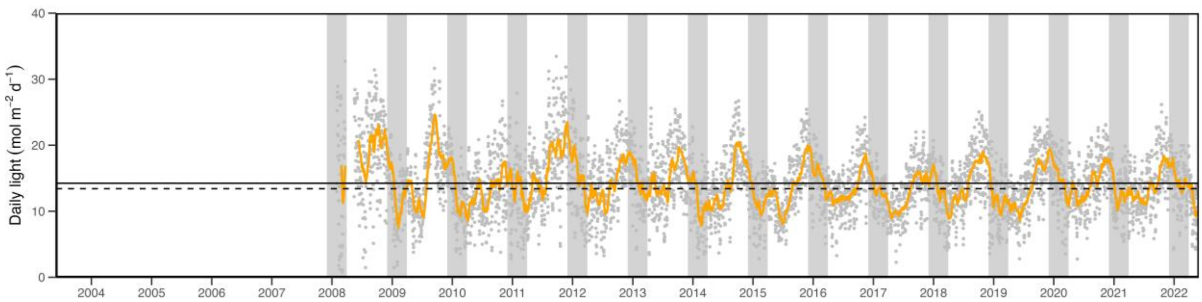


Figure 9. Daily light for all sites combined from 2008 to 2022. In 2008–2009, light data is from the Burdekin and Wet Tropics regions only. Other regions were included from 2009–2010, with Cape York added post 2012–2013 reporting period. Shaded vertical bars indicate the wet season months (December to April) used for analysis of wet season optical water types Moran *et al*. (2023). The solid horizontal line indicates the long-term Reef average, and the dashed line indicates the wet season long-term Reef average.

3.6 Within-canopy seawater temperature

Daily within-canopy seawater temperature across the inshore Reef in 2021–22 was over half a degree higher than the previous reporting period (Figure 10). Since 2013, the frequency of weekly warm water deviations appears to have increased, relative to cooler occurrences (Figure 10). The 2021–22 average temperature (26.2 ±0.1°C) was the second highest since the MMP was established (2016-17 was the highest) and 0.5°C above the long-term (2003–2021, 25.7°C) (Table 10). However, there were regional and habitat differences relative to the long-term (Figure 7).

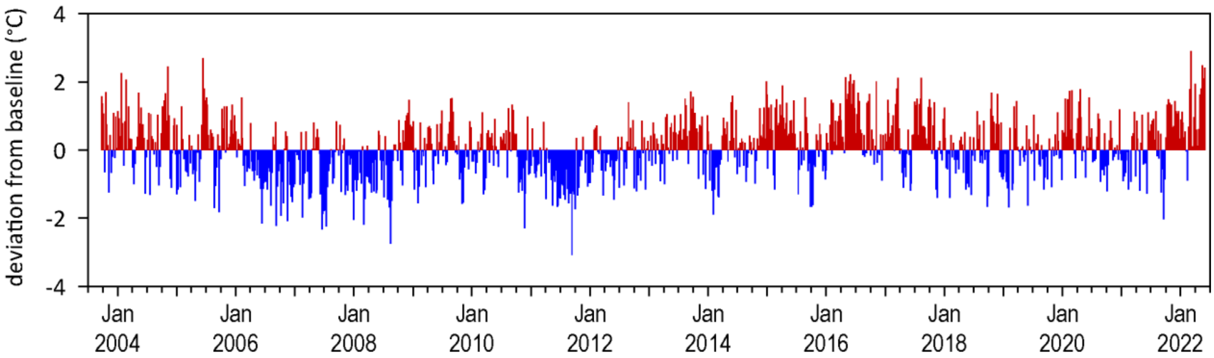


Figure 10. Inshore intertidal sea temperature deviations from baseline for Reef seagrass habitats from 2003 to 2022. Data presented are deviations from 16-year mean weekly temperature records (based on records from September 2003 to June 2021). Weeks above the long-term average are represented as red 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 2021–22 (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 (↑ = above, ↓ = below, ↕ = similar to long-term, difference = greater than 0.3°C) were:

- Cape York (avg = 28.2°C, max = 39.6°C, days$_{>35°C}$ = 49)↑
- northern Wet Tropics (avg = 27.7°C, max = 45.5°C, days$_{>35\leq40°C}$ = 53, days$_{>40°C}$ = 11)↑
- southern Wet Tropics (avg = 26.9°C, max = 39.6°C, days$_{>35°C}$ = 8)↕
- Burdekin (avg = 27.2°C, max = 43.2°C, days$_{>35\leq40°C}$ = 32, days$_{>40°C}$ = 2)↑
- Mackay–Whitsunday (avg = 26.0°C, max = 41.3°C, days$_{>35\leq40°C}$ = 38, days$_{>40°C}$ = 4)↑
- Fitzroy (avg = 24.5°C, max = 41.7°C, days$_{>35\leq40°C}$ = 49, days$_{>40°C}$ = 1)↑
- Burnett–Mary (avg = 23.7°C, max = 38.9°C, days$_{>35°C}$ = 9)↕

Daily within-canopy seawater temperatures in each habitat in 2021–22 relative to respective long-term average (↑ = above, ↓ = below, ↕ = similar to long-term, difference = greater than 0.3°C) were:

- estuarine habitat (avg = 24.3°C, max = 41.3°C)↑
- coastal intertidal habitat (avg = 26.4°C, max = 45.5°C)↑
- reef intertidal habitat (avg = 26.9°C, max = 43.2°C)↑

The hottest seawater temperature recorded at inshore seagrass sites along the Reef during 2021–22 was 45.5°C in the northern Wet Tropics region. This was the third hottest temperature ever recorded since the MMP was established (hottest was 46.6 ºC at Shelley Beach, 3pm on 10Jan08). In 2021-22, the Wet Tropics, Burdekin and Mackay–Whitsunday NRM regions recorded more days of extreme temperatures (>40°C) than last 6 monitoring periods (Figure 11). Extreme temperature days can cause photoinhibition but when occurring at such low frequency, they were unlikely to cause burning or mortality.

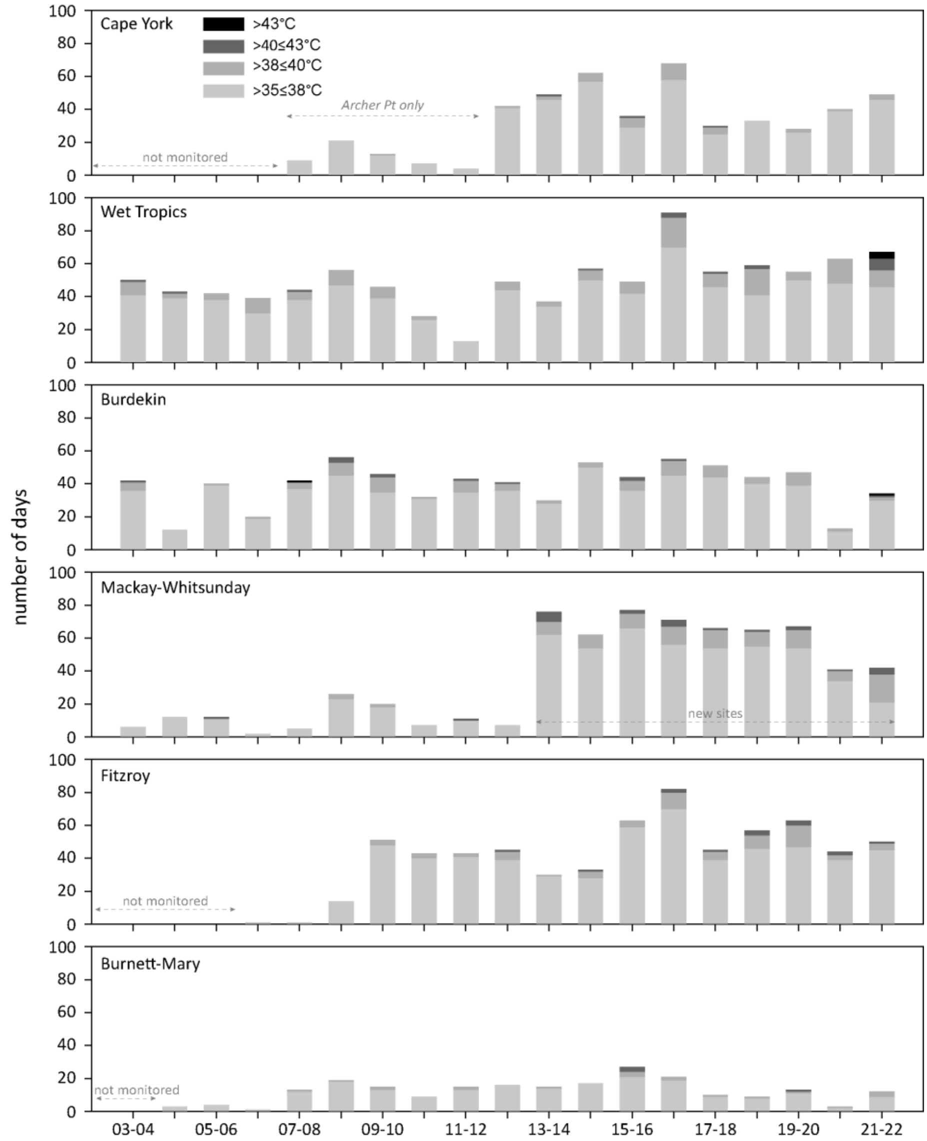


Figure 11. Number of days when inshore intertidal sea temperature exceeded 35°C, 38°C, 40°C and 43°C in each monitoring period in each NRM region.Thresholds adapted from Campbell *et al*. 2006; Collier *et al*. 2012a.

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 12). Sediments at intertidal coastal habitats were predominately medium and fine sands, while reef habitats (intertidal and subtidal) were dominated by medium sands (Table 12).

Table 12. Long-term average (±SE) sediment composition for each seagrass habitat (pooled across regions and time) monitoring within the Reef (1999–2021). *only 6 years of data.

Habitat	Mud	Fine sand	Sand	Coarse sand	Gravel
estuarine intertidal	44.9 ±2.1	22.6 ±2.1	30.6 ±1.9	0.2 ±0.4	1.9 ±0.9
coastal intertidal	27.7 ±2.1	31.1 ±2.4	36.9 ±2.5	0.4 ±0.6	4.0 ±1.2
coastal subtidal*	53.2 ±2.6	9.4 ±0.4	18.6 ±2.5	5.6 ±0.9	13.2 ±1.1
reef intertidal	4.3 ±1.2	6.8 ±1.8	52.9 ±2.9	15.1 ±1.9	20.9 ±2.4
reef subtidal	16.8 ±1.3	14.2 ±1.0	56.4 ±5.3	1.1 ±0.5	11.5 ±5.3

During the 2021–22 monitoring period the contribution of mud to sediment type relative to the previous year increased at coastal intertidal and subtidal habitats (Figure 12). In subtidal habitats, the contribution of mud sediments remained above the long-term average (Figure 12). Historically, the composition of sediments has fluctuated at all habitats, with the proportion of mud declining below the long-term average at estuarine and coastal habitats immediately following periods of physical disturbance from storms when seagrass cover greatly declines (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 nutrient concentrations and greater levels of anoxia. Although anaerobic conditions may stimulate germination in some species, the elevated sulphide 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.

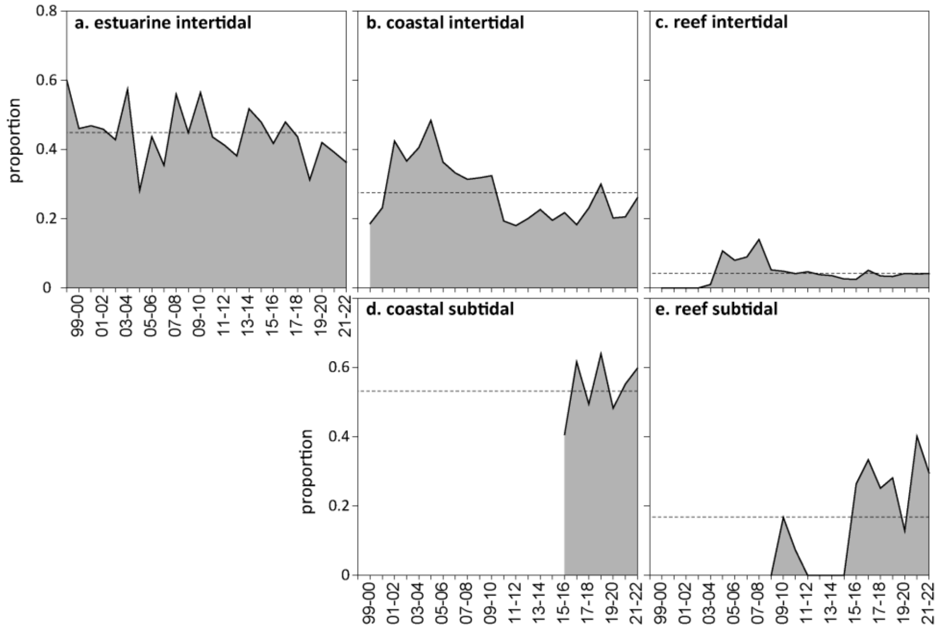


Figure 12. Proportion of sediment composed of mud (grain size <63µm) at inshore Reef seagrass monitoring habitats from 1999–2022. Dashed line illustrates the Reef long-term average for each habitat type.

4 Seagrass condition and trend

The following results section provides detail on the overall seagrass responses for the 2021–22 monitoring period, in context of longer-term trends. It is structured as an overall inshore Reef summary with 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 (per cent cover) and spatial extent
- seagrass species composition based on life history traits
- seagrass reproductive effort and seed banks
- 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 2 and 3.

4.1 Overall inshore Reef seagrass condition and trend

Inshore seagrass meadows across the Reef improved marginally in overall condition in 2021–22, with the condition grade remaining **moderate** (Figure 13).

In summary, the slight improvement was due to the decrease in seagrass abundance being offset by a greater increase in the resilience indicator:

- The seagrass abundance indicator decreased in 2021–22 after improving from poor to moderate in 2020–21, although remains moderate. Seagrass abundance has fluctuated temporally at meadows monitored in the MMP over the life of the programme, displaying periods of decline and variable recovery. The largest declines occurred from 2009 to 2012, caused by consecutive years of above-average rainfall, and resultant discharges of poor quality water, followed by extreme weather events, after which abundance increased (Figure 13, Figure 15b). Following 2012, seagrass recovery proceeded for five years until stalling in 2016-17 as a result of regional climatic events, after which abundances subsequently declined. From late 2020, seagrass abundances improved, although recovery appears somewhat muted with a slight decline relative to the previous reporting period. Based on the average score against the seagrass guidelines (determined at the site level), the abundance of inshore seagrass across the Reef over the 2021–22 were in a moderate condition (Figure 13).

- The resilience indicator continued improving in 2021–22 (Figure 13), suggesting a recovering trajectory for Reef seagrass habitats following the seven-year low in 2019–20, however, seagrass in very southern regions remain vulnerable to further disturbances.

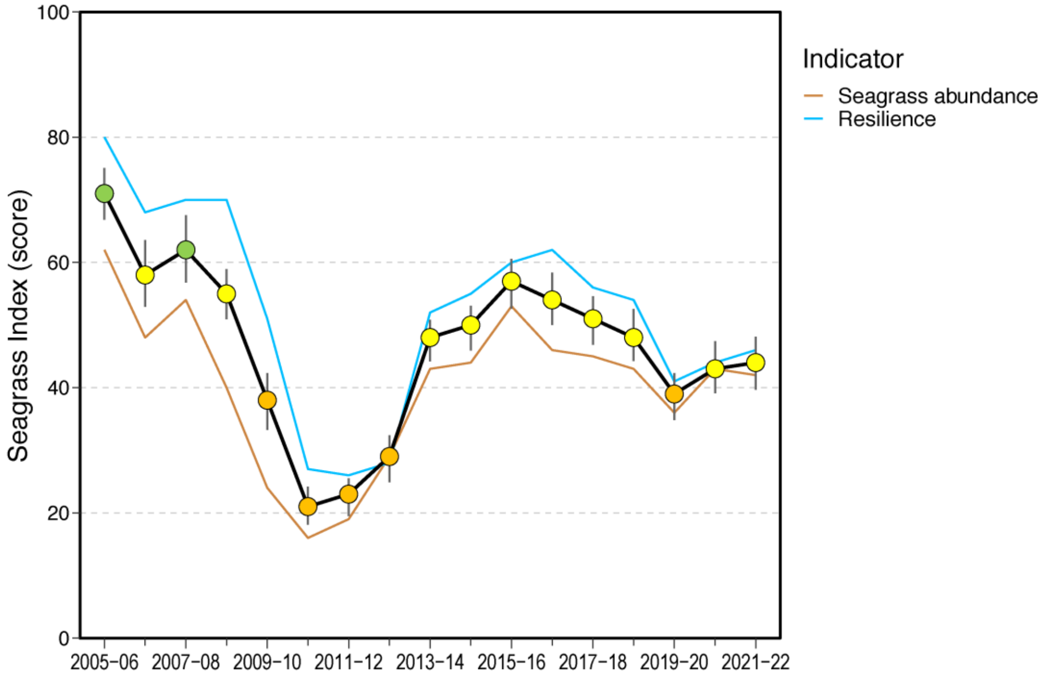


Figure 13. Overall inshore Reef seagrass condition index (± SE) with contributing indicator scores over the life of the MMP. The index is derived from the aggregate of metric scores for indicators of seagrass condition: abundance and resilience. Index scores scaled from 0–100 and graded: ● = very good (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 the six NRM regions, weighted by inshore seagrass area. In 2021–22 the score improved in all except the most southern regions (Fitzroy and Burnett-Mary) (Figure 14). Over the long term, the indicators tend to diverge during periods of elevated disturbance and loss, but converge and follow a similar trend during periods of low disturbance. These patterns and trends in the indicators are more apparent at the regional scale, with the variation among the six regions:

- The seagrass abundance score was moderate in all northern NRM regions, poor in the Mackay–Whitsunday region and very poor in the Fitzroy and Burnett–Mary regions (Figure 14). The abundance score in 2021–22 was similar to the previous year 2020–21 in Cape York and Mackay–Whitsunday regions, increased in the Wet Tropics and Burdekin regions and declined in the Fitzroy and Burnett–Mary regions. The largest changes to the abundance score were in the Fitzroy and Burnett–Mary regions, which had large declines compared to 2020–21 resulting in a drop to very poor from poor in the previous year. It is the first time the score has been very poor in the Fitzroy region and the first time since 2013–14 in the Burnett–Mary region.
- The seagrass resilience scores were moderate in the four northern most regions and poor in the Fitzroy and Burnett–Mary regions in 2021–22 (Figure 14). Resilience declined in the Burnett–Mary region, increased in the Mackay–Whitsunday region, and did not change by much in the other regions compared to the previous monitoring period (Figure 14).

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 in 2018–19 in the Burdekin region and a marine heatwave in the northern and central Reef). There are also local-scale changes influencing regional scores, particularly in the Fitzroy region.

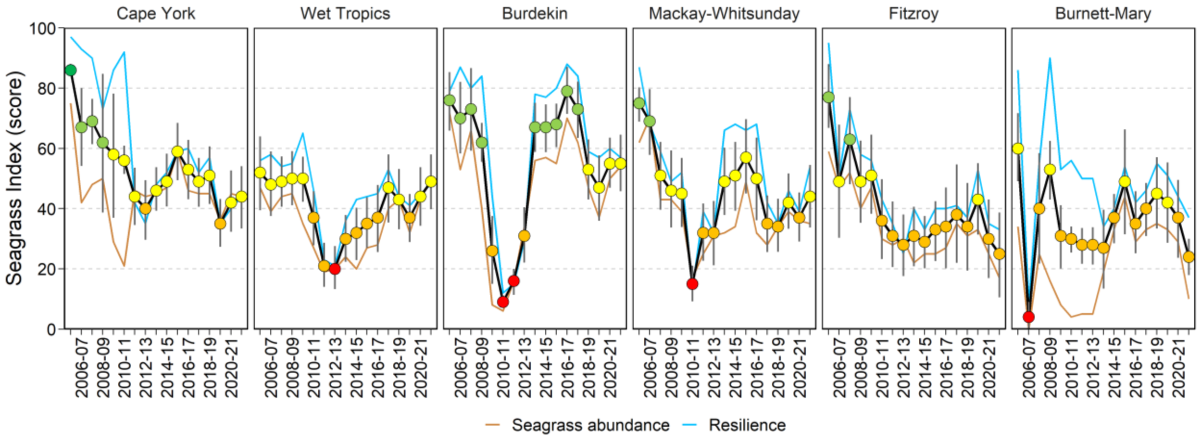


Figure 14. Seagrass condition index (± SE) with contributing indicator scores for each NRM region over the life of the MMP. The index is derived from the aggregate of metric scores for indicators of seagrass condition: abundance and resilience. Values are indexed scores scaled from 0–100 and graded: ● = 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 for each of the contributing indicators used to calculated the Seagrass Index are shown in Figure 15. Results from the generalised additive models are presented for per cent cover to show long-term trends. Seagrass abundance 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 overall trend has been stable since 2018–19. The resilience indicator score has similarly declined to its lowest levels in the 2010–11 through 2012–13 monitoring periods. The resilience score increased in 2020–21 and remained stable in 2021–22.

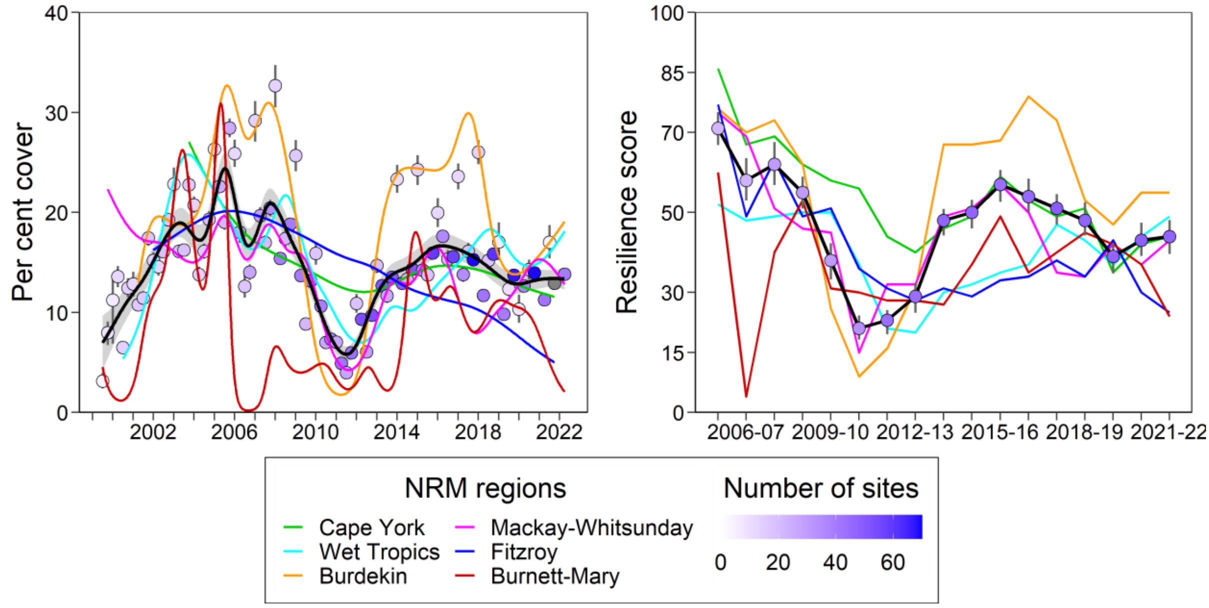


Figure 15. Trends in the seagrass indicators used to calculate the condition index including trends in Reef seagrass abundance (per cent cover, ± SE) represented by a GAM plot (black line with shaded areas defining 95 per cent confidence interval), and coloured lines representing NRM trends (left), and trends in Reef resilience score (black line and circles, ± SE) and coloured lines represent trends in NRM resilience scores (right). Circle colour relates to number of sites assessed. Please note: Reef resilience scores are weighted.

4.3 Trends in seagrass condition indicators by habitat type

4.3.1 Seagrass abundance, composition and extent

Seagrass abundance has fluctuated since monitoring was established. An examination of long-term abundances at inshore Reef sites indicates no significant trend overall, with:

- no significant trends at 67 per cent of long-term monitoring sites assessed, although 13 per cent of sites significantly increased in abundance and 21 per cent decreased (Appendix 3, Table 22)
- the rate of change in abundance was similar at sites increasing (0.7 ±0.3 per cent, sampling event^{-1}) and decreasing (-0.6 ±0.2 per cent sampling event^{-1}) (Appendix 3, Table 22)
- the most variable seagrass habitat in abundance (since 2005) was estuarine intertidal (CV=89.1%), followed by reef habitats (intertidal CV=54% and subtidal CV=47.9%), and lastly, coastal habitats (intertidal CV=42.5% and subtidal CV=31.3%).

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 16). 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 around 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.

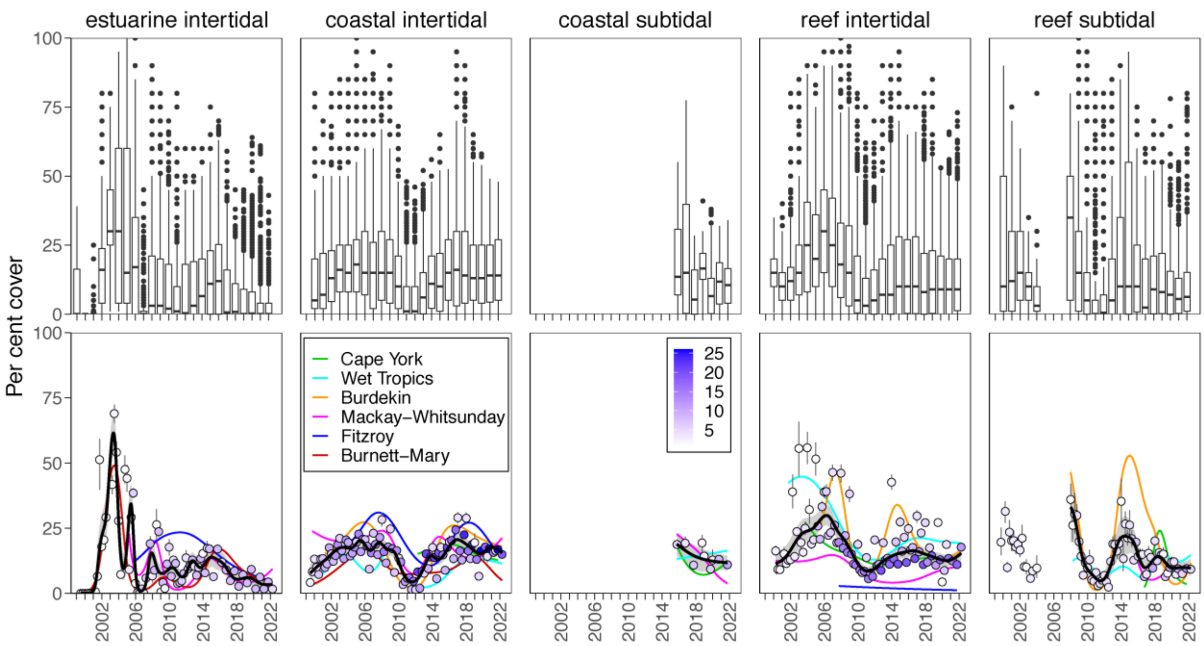


Figure 16. Seagrass per cent cover measures per quadrat from habitats monitored from June 1999 to May 2022 (sites pooled). In the whisker plots (top), the box represents the interquartile range of values, where the boundary of the box closest to zero indicates the 25th percentile, a line within the box 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), showing trends for each NRM (coloured lines) and combined as dark lines with shaded areas defining 95th confidence intervals of those trends. Colour of circles represents the number of sites assessed to calculate the average, and vertical error bars represent standard error.

In 2021–22, coastal habitats continued to have the highest average abundance of all habitat types, and estuarine the lowest (Figure 16). Over the past decade, the patterns of seagrass abundance in each habitat have been similar between intertidal sites in coastal and reef habitats; gradually increasing after the extreme weather events of early 2011 (e.g., cyclone Yasi), followed by declines from 2017 to 2019 (a consequence of cyclone Debbie), before improving from 2020 (Figure 16).

Estuarine habitats, which are monitored only in the southern NRM regions (Mackay–Whitsunday, Fitzroy and Burnett–Mary), reached record per cent cover level prior to the establishment of the MMP, but have remained low since 2005–06. Over the last decade, estuarine abundances have fluctuated at a location level, most often at smaller localised scales where there has been some acute event related changes, e.g. sediment deposition and/or reduced light availability due to discharge events, or sediment movement due to climatic pressures. Following 2016, seagrass abundances have progressively declined to the lowest levels since 2007 (Figure 16).

In 2021–22, the overall inshore Reef relative meadow spatial extent increased relative to the previous year, however late dry season extents remain lower than the baseline (2005), 2014–15 and 2015–16 (Figure 17). The overall trend is seagrass meadow extent since the MMP was established in 2005, shows a gradual decline from 2008–09 to early 2011, recovering within 3–4 years, subsequently declining from late 2016 to early 2019 before once again starting to recover (Figure 17). Similar to seagrass abundance, these periods of decline in relative extent are a consequence of extreme weather and associated flooding or location specific climate (e.g. frequency of strong wind days).

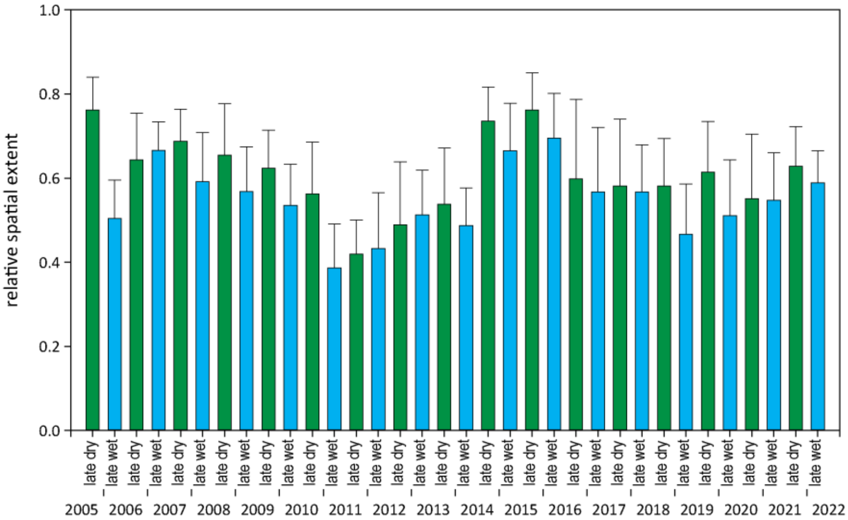


Figure 17. Average relative spatial extent of seagrass distribution at monitoring sites across inshore Reef (locations, habitats and NRM regions pooled, + SE). Green bars represent late dry and Blue bars late wet.

After a series of consecutive above-average wet seasons from 2009, capped with the extreme weather events in 2011 that caused widespread declines in seagrass extent (Figure 17) and abundance, there was increasing proliferation of species displaying colonising traits, such as *H. ovalis,* at coastal and reef sites (Figure 18). Over the 2021–22 monitoring period, with the exception of coastal subtidal habitats, the proportion of species displaying colonising traits remained around or lower than the inshore Reef average for each respective habitat type 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 coastal subtidal habitats, however, the proportion of colonising species was the highest since 2015–16 when monitoring was established. This may indicate an increase in environmental pressures affecting seagrass growth requirements.

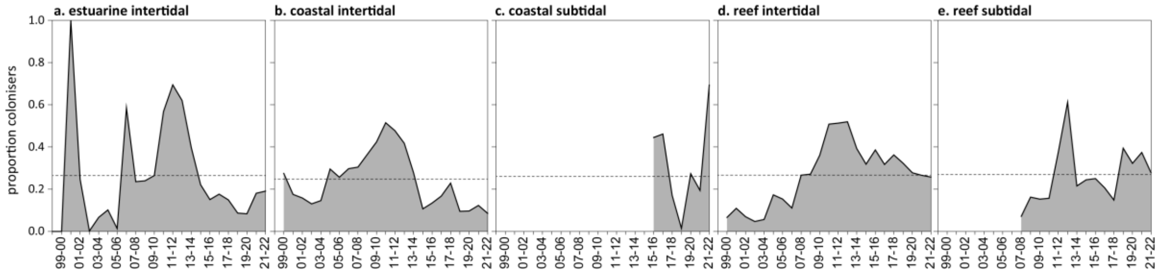


Figure 18. Proportion of total seagrass abundance composed of species displaying colonising traits (e.g. *Halophila ovalis*) in: a) estuarine intertidal, b) coastal intertidal, c) coastal subtidal, d) reef intertidal and e) reef subtidal habitats (sites pooled) of the Reef (regions pooled) for each monitoring 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 for the third consecutive year within all intertidal habitats across the inshore Reef in 2021–22 (Figure 19). Reef subtidal habitats, however, has more reproductive structures than both the previous period and the long-term average (Figure 19). Since the implementation of the MMP, the maximum reproductive effort and the inter-annual variability in reproductive effort has differed between habitats, and varied both within and between years. Reproductive effort across the inshore Reef meadows are typically higher in the late dry season, while seed density fluctuates less seasonally (Figure 19, Figure 20).

Reproductive effort had gradually been increasing at estuarine and coastal habitats since 2011, with large rises from 2013 to 2017, after which it decreased significantly in estuaries in 2017–18 and coastal habitats in 2019–20, and has continued to remain low ever since (Figure 19). This trend was observed across all estuarine habitats monitored and reflects trends in seagrass abundance in these habitats. The greatest declines appear within the *Zostera muelleri* dominated sites within Gladstone Harbour (Fitzroy NRM region) where the numbers of reproductive structures have been below the long-term average for 11 consecutive years. However, as a seed bank in estuarine habitats has persisted across all regions for over a decade, it is likely the declines may be an artefact of a restricted flower period which was missed when the sites are annually assessed (Figure 20).

In coastal habitats, reproductive effort and seed density is highly variable inter-annually, more than in other habitats. The historically high reproductive effort in coastal habitats (2017 to 2019) was due to a record number of reproductive structures in the northern Wet Tropics (Yule Point) and Burdekin (Bushland Beach and Jerona). Since 2019, reproductive effort across inshore Reef coastal habitats has remained low and in 2021–22 was similar to the previous reporting period (Figure 19). Seed bank densities also improved in coastal habitats throughout 2021–22 (Figure 20).

Reef habitats typically have the lowest reproductive effort and seed bank densities of all habitats (Figure 19, Figure 20). This is on account of the predominance of persistent seagrass species which do not produce a seed bank in the majority of Reef habitats. In 2021–22, reproductive effort remained low across reef habitats, with increases limited to the northern Wet Tropics. No seeds have ever been observed at over half of the reef sites (intertidal or subtidal), including sites in Cape York, northern Wet Tropics, Mackay–Whitsunday and Fitzroy regions. During 2021–22, seed banks declined at a quarter of sites, remained absent at nearly three quarter of sites and the only site where the seed bank increased was in the intertidal meadow at Picnic Bay (Burdekin).

Overall, reproductive structures were absent at nearly 15 per cent of sites assessed in 2021-22. The greatest losses occurred in the Fitzroy and Burnett Mary where reproductive structures were absent at a third of sites, while the largest improvement was in the Burdekin region (Figure 19). Seed densities in seed banks decreased or remained absent at two third of sites in 2021-22, relative to the previous reporting period, with the greatest declines in the

Mackay–Whitsunday region. Reductions in seed density are likely the result of reduced reproductive structures and success (failure to form seeds) or loss of seed bank (germination or grazing). This indicates vulnerability of these habitats to future disturbances, as recovery may be hampered although the density of seeds needed to initiate or optimise recovery is unknown.

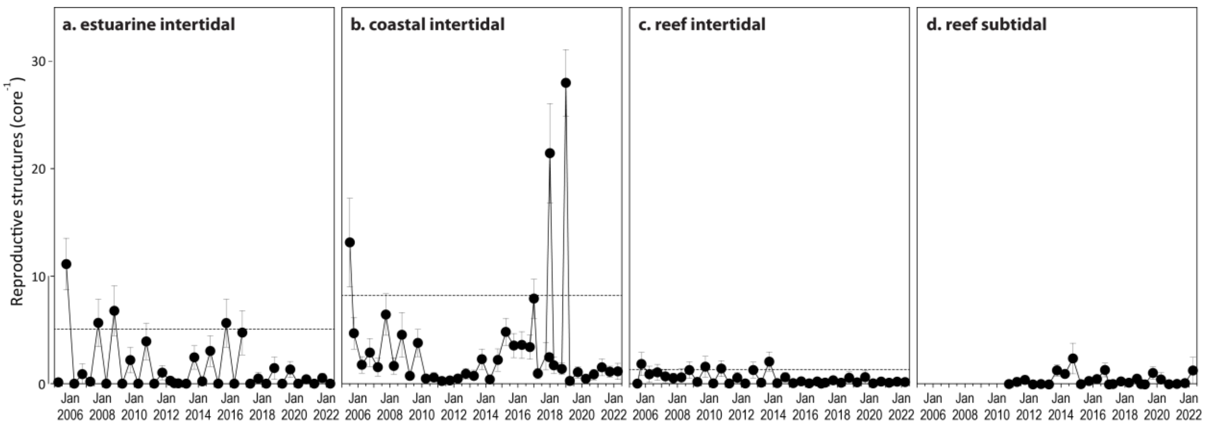


Figure 19. Seagrass reproductive effort (number of reproductive structures produced by all seagrass species, ± SE) in Reef seagrass habitats for a) estuarine intertidal; b) coastal intertidal; c) reef intertidal; d) reef subtidal. Dashed line illustrates Reef long-term average reproductive effort in each habitat type.

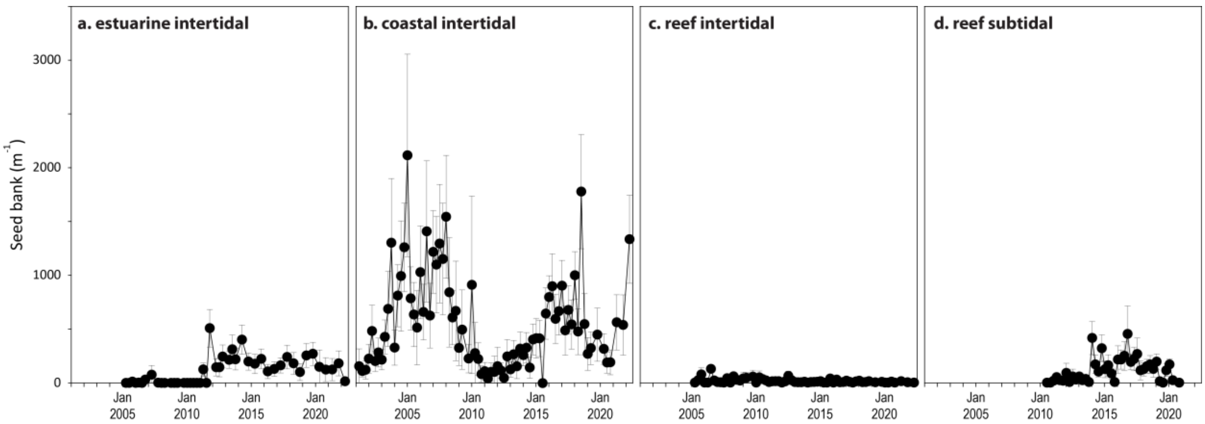


Figure 20. Average seeds banks (seeds per square metre of sediment surface, all sites and species pooled, ± SE) in Reef seagrass habitats: a) estuarine intertidal; b) coastal intertidal; c) reef intertidal; d) reef subtidal.

4.3.2.1 Resilience

Resilience was stable in 2021–22 in estuarine, coastal and reef intertidal habitats (Figure 21, Table 23). The resilience score in estuarine habitats was the second lowest in the history of the program, but improved slightly compared to the previous year. There was a lot of variability in the trends at estuarine sites. Resilience improved at a number of estuarine sites and some reached the highest scores observed since 2008 to 2010. Other sites declined to very low scores. Resilience at coastal intertidal habitats did not vary by much on average and within regions there was also little change in resilience with a few exceptions. The resilience score increased in Cape York coastal habitats with good or improving scores at three out of four coastal sites, while they declined in the Fitzroy region due to a large reduction at one site in Shoalwater Bay.

The resilience score was stable in reef intertidal habitats (Figure 21, Table 23). There were large improvements in the southern Wet Tropics (Dunk Island) reaching the equal highest score on record and in the Fitzroy region, but large decreases in the Burdekin region. There were improvements in reef subtidal habitats in the Burdekin and Mackay Whitsunday regions, but resilience was unchanged into the Wet Tropics.

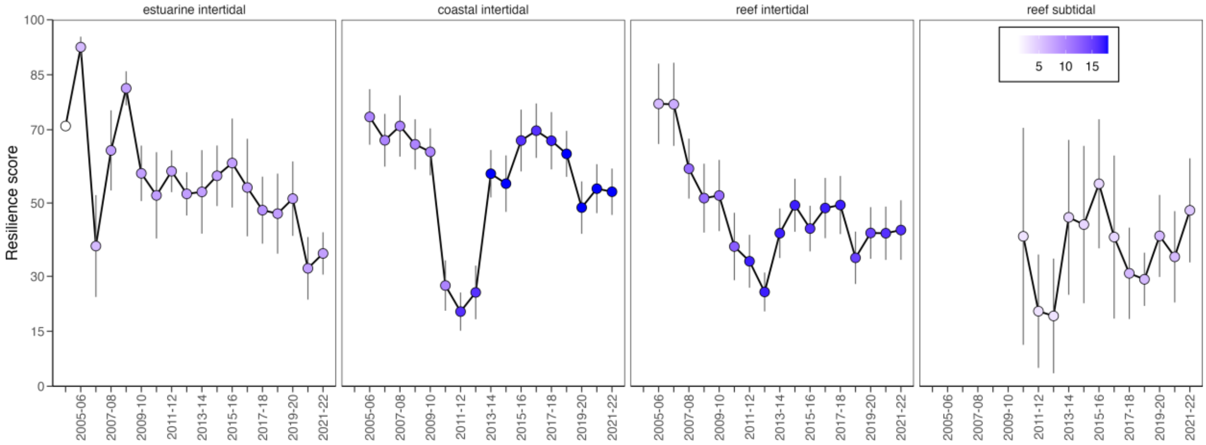


Figure 21. Trends in resilience score summarised for each habitat type of the Reef. Blue shading of points indicates the number of sites contributing to the score. Vertical error bars represent standard error.

Resilience in 2021–22 was generally highest in the northern and central Reef, and lowest in the southern Reef in the Fitzroy and Burnett–Mary regions. Within the northern and central Reef, resilience was the highest in the Burdekin region, followed by the Wet Tropics which improved considerably. Resilience in Cape York and the Mackay Whitsunday regions was intermediate with strong improvement in the latter.

4.3.3 Epiphytes and macroalgae

Epiphyte cover on seagrass leaves during 2021–22 was above the overall inshore Reef long-term average at estuarine and reef intertidal, and seasonally variable at coastal intertidal and reef subtidal habitats (Figure 22). Epiphytes historically varied the most in estuarine habitats (by 50 per cent). Over the previous five years, epiphytes have mostly varied by a small amount (<20 per cent) around the long-term average in both intertidal coast and reef habitats.

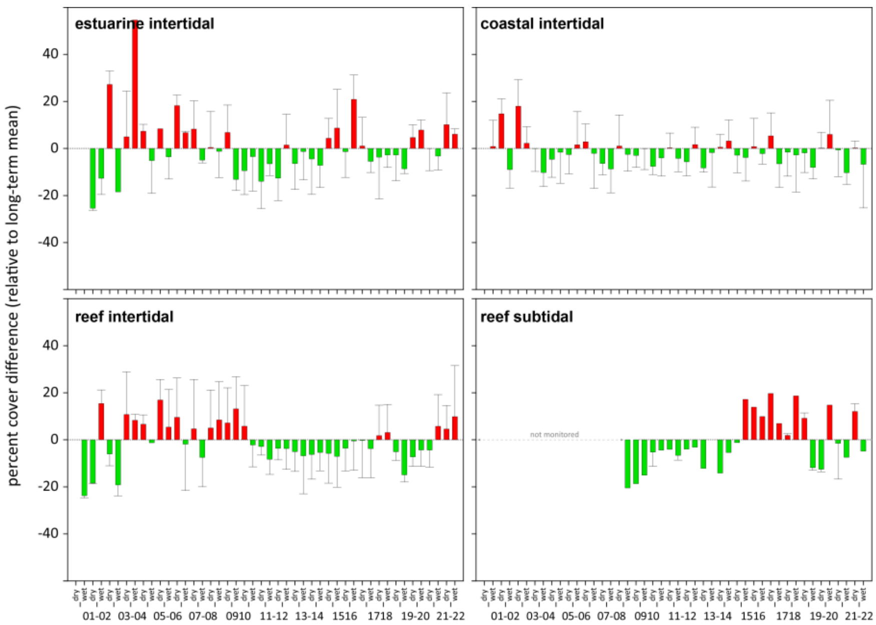


Figure 22. Epiphyte abundance (per cent cover) relative to the long-term average (the zero axis) for each Reef seagrass habitat (sites pooled, ± SE). Reef long-term average (2005 to 2021); estuarine = 25.3 ±5.7 per cent, coastal intertidal = 17.5 ±3.6 per cent, reef intertidal = 22.1 ±4.1 per cent, reef subtidal = 20.0 ±3.0 per cent.

Macroalgae abundance in 2021–22 followed the general trends of the previous 10 years in estuarine and coastal habitats, remaining below the overall inshore Reef long-term average for each of the habitats (Figure 23). Macroalgae abundance declined at reef intertidal sites for the third consecutive year, dipping below the long-term average in the late wet season of each year. Macroalgal abundance at reef subtidal sites returned to below the long-term average for the duration of 2021–22.

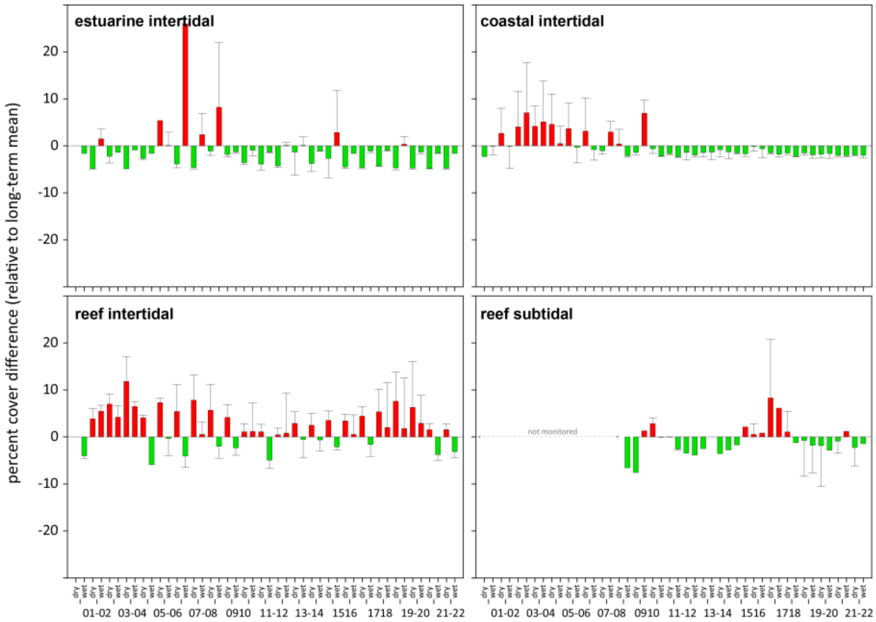


Figure 23. Macroalgae abundance (per cent cover) relative to the long-term average for each inshore Reef seagrass habitat. (sites pooled, ± SE). Reef long-term average ; estuarine = 2.0 ±1.0 per cent, coastal intertidal = 2.3 ±1.2 per cent, reef intertidal = 7.0 ±1.9 per cent, reef subtidal = 6.7 ±2.0 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 at each monitoring location
- sediment grain size composition at each monitoring site
- tables detailing statistical analysis.

5.1 Cape York

5.1.1 2021–22 Summary

Wet season rainfall and annual river discharge were around the long-term average for the region and exposure of the seagrass sites to turbid water types I and II was below average. The most significant environmental pressure on the region was that within-canopy water temperatures were above average for the tenth consecutive year and were 1.4ºC above the long-term average.

Seagrass condition is assessed only in the late dry in Cape York, which was before the summer when the highest temperatures occurred. Seagrass meadow condition across the Cape York NRM region in 2021–22 was similar to 2020–21. The increase was due to higher scores in both the abundance and resilience indicators. For the indicators:

- abundance score was moderate
- resilience score was moderate.

Seagrass abundance (per cent cover) in 2021–22 was similar to the previous period overall. Seagrass abundance increased considerably at coastal subtidal sites, but declined at reef subtidal sites and some of the coastal and reef intertidal sites.

The resilience score was moderate overall. Low scores occurred at one site at Shelburne Bay because there was a high proportion of colonising species and at Piper Reef where abundances were below thresholds and indicative of low resilience. Resilience was moderate to high at other sites. Reproductive structures continue to be rarely observed in Cape York in 2021–22 for the second consecutive year, which may hinder replenishment of the declining seed banks and weaken capacity to recover from seeds in the near future.

The number of sites, commission date and duration of monitoring at individual sites affects the long-term trends for the region. Prior to 2011–12, there was only one location monitored while trends after this time include a number of sites and habitat types. Elevated discharge in 2010–11 and 2018–19 led to declines in seagrass condition. The coastal and reef subtidal habitats have highly variable seagrass abundances and succumbed to elevated discharge after 2018–19. Post flood surveys were conducted in the growing season of the following year when the score dropped to poor again. The resilience of coastal habitats was also affected by the extreme weather and seagrass habitats across the region were still recovering in 2021–22.

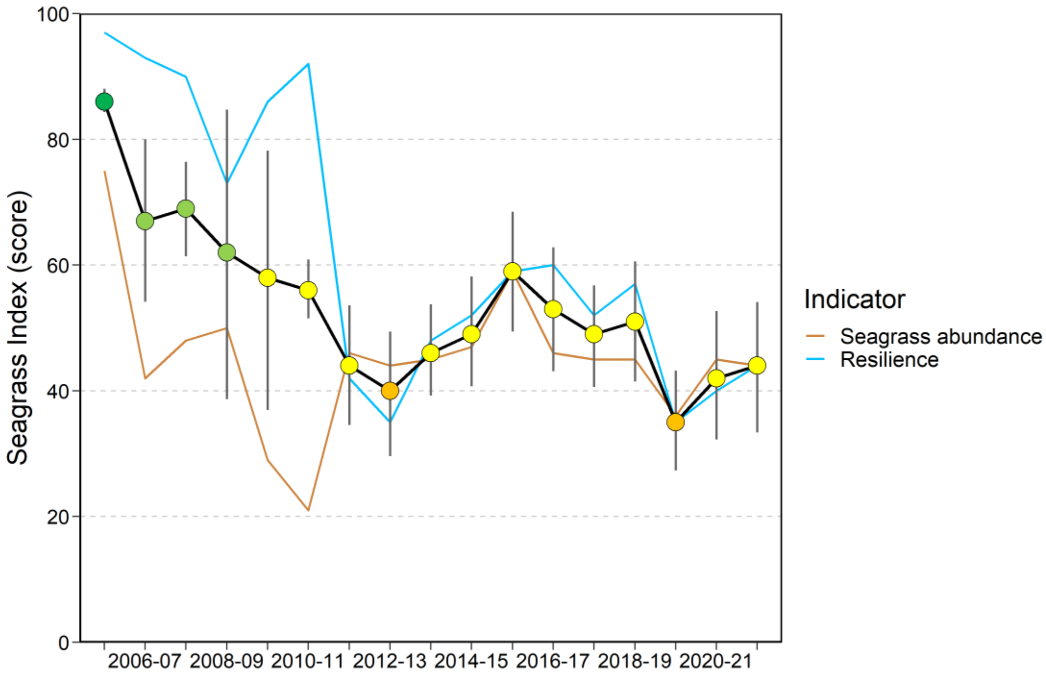


Figure 24. Temporal trend in seagrass condition index (± SE) with contributing indicator scores for the Cape York NRM region (averaged across habitats and sites). Index scores scaled from 0–100 and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

5.1.2 Climate and environmental pressures

One tropical cyclone directly affected the Cape York region during the 2021–22 wet season. Tropical cyclone Tiffany was a small system which formed in the northern Coral Sea on 8 January and developed quickly to category 1 cyclone strength in the afternoon of 9 January over waters to the northeast of Cooktown (Courtney and Boterhoven 2022). Tiffany intensified to category 2 during 9 January near Cape Melville, but rapidly weakened as it moved over Princess Charlotte Bay before crossing the coast late on 10 January at category 1 intensity (Courtney and Boterhoven 2022). The system brought high rainfall across the Cape York Peninsula near the track (Courtney and Boterhoven 2022).

Wet season rainfall across the basins of Cape York was similar to the long-term average for the region. Annual discharge from rivers in the Cape York region were also around the long-term average. There were above-average (1.5 times above the median) discharges from the Pascoe and Lockhart Rivers due to a period of elevated discharge late in the wet season.

Exposure to water types I and II was below the long-term average in Cape York. The frequency of exposure ranged from 52 per cent to 100 per cent of wet season weeks at seagrass monitoring sites (Figure 25a) (Figure 7 and Figure 8). The inshore waters of Cape York had predominantly water type II over the wet season in December-April (Figure 25b). Bathurst Bay sites (BY1 and BY2) had the highest exposure to turbid primary water, consistent with previous years. Reef habitats at Piper Reef (FR) and Stanley Island (ST) had the lowest level of exposure to water types I and II amongst the inshore seagrass monitoring sites.

Daily light (mol m^{-2} d^{-1}) reaching the top of the seagrass canopy is generally very high at all Cape York sites (long-term average = 16.4 mol m^{-2} d^{-1}) (Figure 98). In 2021–22, daily light (15.9 mol m^{-2} d^{-1}) was lower than the long-term average (Figure 25d). This was because daily light at Stanley Island (14.9 mol m^{-2} d^{-1}) was well below the long-term average (19.6 mol m^{-2} d^{-1}). There was insufficient data from Shelburne Bay to calculate an annual mean. Cape York sites are surveyed only once per year, and the instruments are not usually able to function for a full year due to battery life and inevitable fouling. However, there was almost a full year of data at Stanley Island in 2021–22 (350 days), so this does not explain the low light levels in 2021–22.

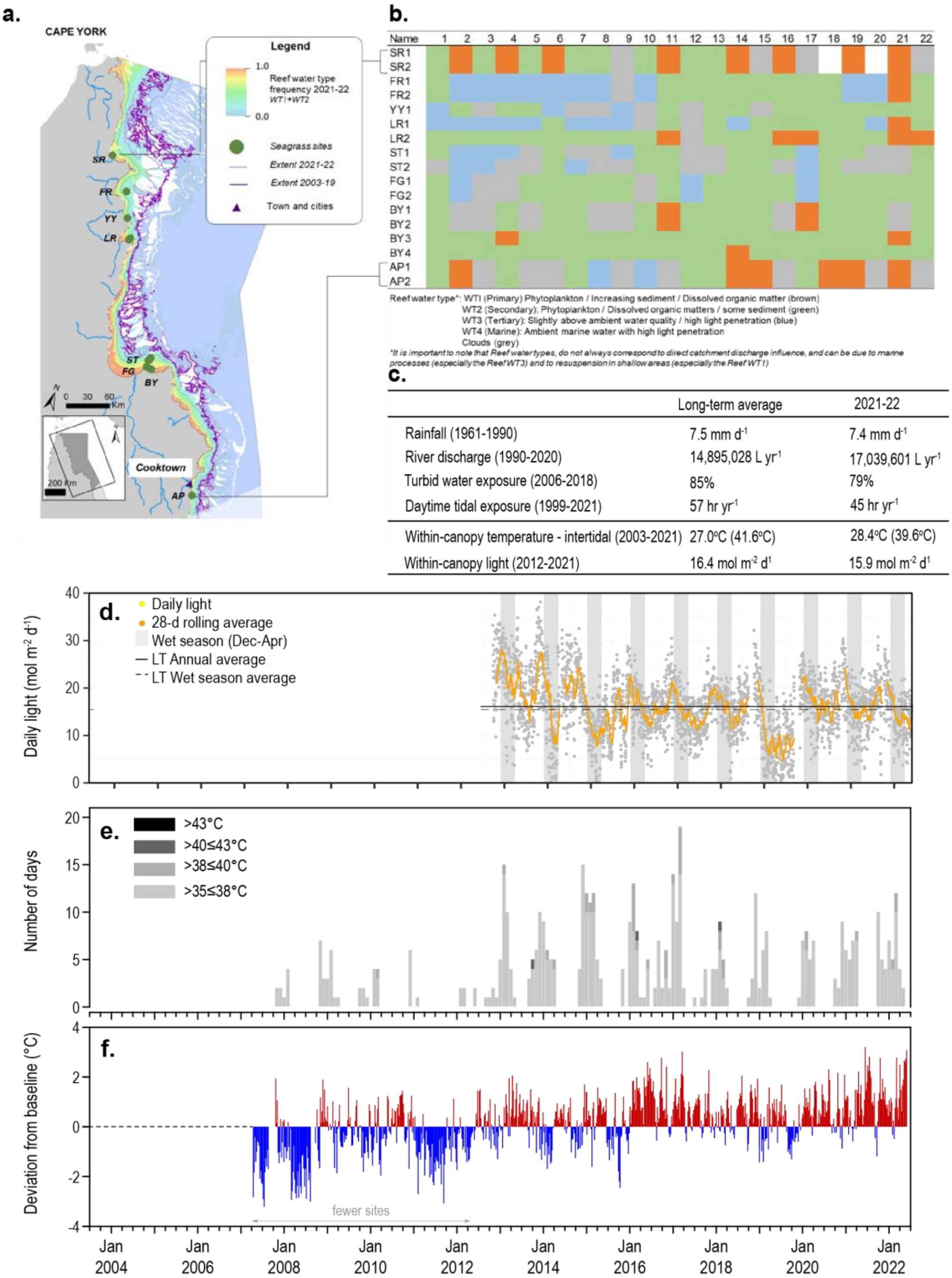


Figure 25. Environmental pressures in the Cape York region including: a. frequency of exposure to primary and secondary water from December 2021 to April 2022 ranging from frequency of 1 (orange, always exposed) to 0 (pale blue, never exposed) (white = no data), also showing the long-term average (2003–2018) exposure boundary (purple line), and the first (blue line) and third quartile (white line) of the long-term average (from Moran *et al.* 2023), b. wet season water type at each site; c. average conditions and max temperature over the long-term and in 2020–21; 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 at intertidal sites.

Most notably, 2021–22 was the warmest year of intertidal within-canopy temperatures since monitoring was established in the region (Figure 25c). Maximum within-canopy temperatures exceeded 35°C for a total of 49 days (in total among all sites where temperature is monitored) during 2021–22 (Figure 25e), with the highest temperature recorded at 39.6°C (FR2, 3pm 10Mar22). Daytime tidal exposure (hours water has drained from the meadow) was below the Cape York long-term median for the second consecutive year (Figure 25c, Figure 90), which may have provided some respite from the elevated temperatures.

In the Cape York NRM region, there was little change in reef habitat sediments, which remained dominated by sands and coarser sediments. However, coastal habitats which were dominated by fine sand, had a greater proportion of mud in 2021–22, particularly at both sites located within Bathhurst Bay located in vicinity of the Normanby River mouth (Appendix 2, Figure 105, Figure 106).

5.1.3 Inshore seagrass and habitat condition

There are 17 seagrass monitoring sites in Cape York from 9 locations (Table 13). Four seagrass habitat types were assessed across the Cape York region in 2021–22, with data from 16 of the 19 long-term monitoring sites (Table 13, Table 20).

Table 13. 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 5 and Table 6. Open square indicates not measured in 2021–22, blank cells indicate data not usually collected/measured at site. † drop camera sampling (RJFMP), *Seagrass-Watch.

Habitat	Site		abundance	composition	extent	reproductive effort	seed banks	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	■	■					■	■
	MA1†	Margaret Bay	■	■					■	■
	MA2†	Margaret 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 Beach (Weymouth Bay)	□	□			□	□	□	□
Reef subtidal	FG1†	Flinders Island (Flinders Group)	■	■					■	■
	FG2†	Flinders Island (Flinders Group)	■	■					■	■

5.1.3.1 Seagrass index and indicator scores

During the 2021–22 reporting period, the seagrass condition index score for the Cape York region improved slightly since the previous reporting period, with the overall grade remaining **moderate** (Figure 26).

The abundance indicator was on a mildly declining trend from 2015–16 to 2021–22, and declined only slightly between 2020–21 and 2021–22 (Figure 26). Losses occurred at reef subtidal habitats and some reef intertidal habitats where sites lost close to half their percentage cover. There were slight improvements in the resilience indicator. The improvement in the resilience score was partly a consequence of higher reproductive effort and seed banks in coastal habitats, e.g. Bathurst Bay (Figure 26).

Both indicators remain in a moderate state, with scores in 2021–22 marginally below long-term averages. Overall, the Cape York seagrass condition index remains well below the 2005–06 baseline and in 2020–21 was the fourth lowest over the last decade.

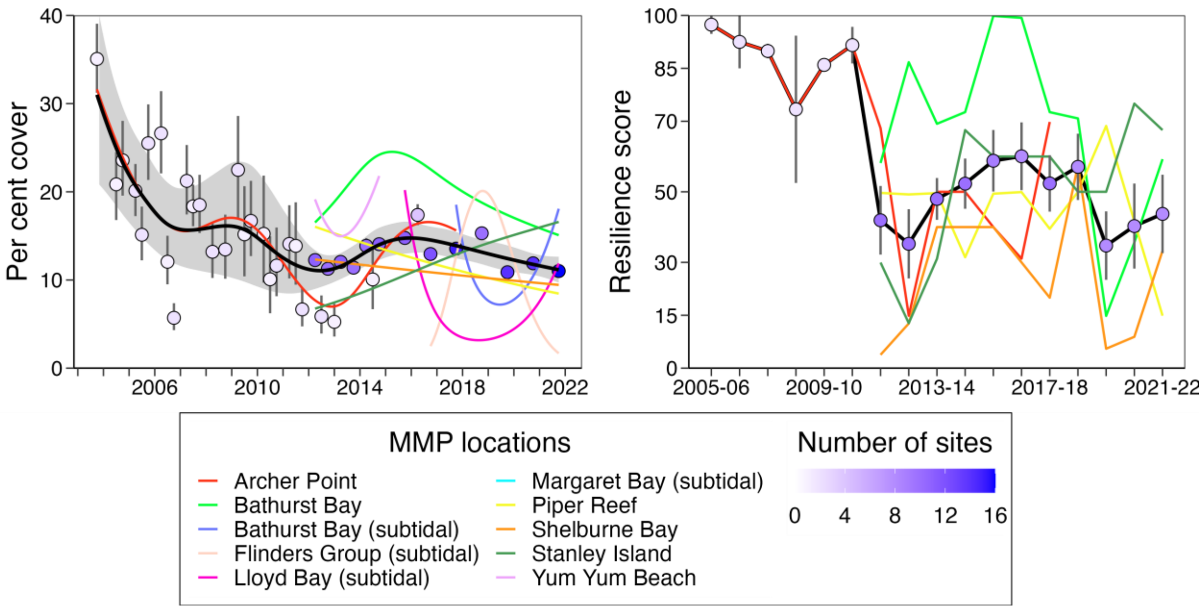


Figure 26. Temporal trends in the Cape York seagrass indicators used to calculate the seagrass condition index: a. average (circles, ±SE) seasonal abundance (per cent cover) and GAM plots of seagrass abundance trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); b. average annual resilience score (±SE) and trends for each location (coloured lines). Colour of circles represents the number of sites assessed to calculate the average.

An examination of the long-term trends in abundance 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 compared to the highest levels recorded for the region (Figure 26). Archer Point, which was the only location monitored prior to 2012–13, has not been included in the resilience score since October 2017, when monitoring continued only as part of Seagrass-Watch due to logistical difficulties.

5.1.3.2 Seagrass abundance, composition and extent

The deterioration in seagrass abundance in 2021–22 is a consequence of declines in per cent cover at all reef intertidal and subtidal sites and one of each of the replicate sites at Bathurst and Lloyd Bays (Figure 27). The majority of these sites are adjacent to large river basins (Olive Pascoe, Lockhart, Stewart and Normanby), which, in the previous wet season, received above average rainfall and discharges 2 to 3 times above long-term median for most rivers (Olive Pascoe, Lockhart, and Stewart). The declines in abundance are likely the legacy of those pressures, as these sites were only assessed in September 2021, prior to the 2021–22 wet season. These losses could be further exacerbated at sites in the Flinders Group and Bathurst Bay in late 2022, as a follow-on impact from TC Tiffany in the 2021–22 wet season.

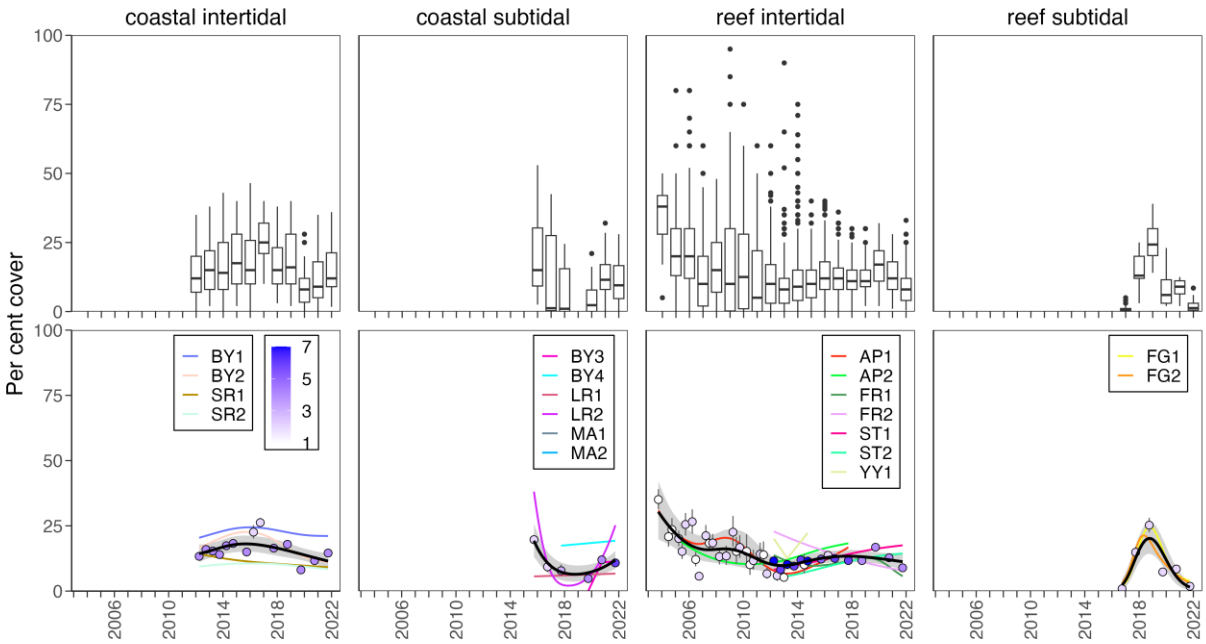


Figure 27. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends for each habitat monitored in the Cape York region from June 2005 to May 2022. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero indicates 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. GAM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

An examination of the long-term trend in seagrass abundance shows seagrass per cent cover progressively decreased at reef intertidal habitats across Cape York from 2003 to 2012, after which there was a slight improvement, particularly at Stanley Island, but abundances at the reef intertidal sites remain low (Figure 27, Table 22). Coastal intertidal and subtidal habitats which have only been monitored since 2012 and 2015 respectively, and over the last decade, apart from losses at SR1, show no long-term trend (Figure 27, Table 22).

In 2021–22, the proportion of species displaying colonising species traits (largely *Halophila ovalis*) were higher than the previous reporting year in all Cape York habitats, except reef subtidal which declined. With the exception of intertidal reef habitats, the proportions of colonising species were above the Reef long-term averages for all other habitats in 2021–22 (Figure 28).

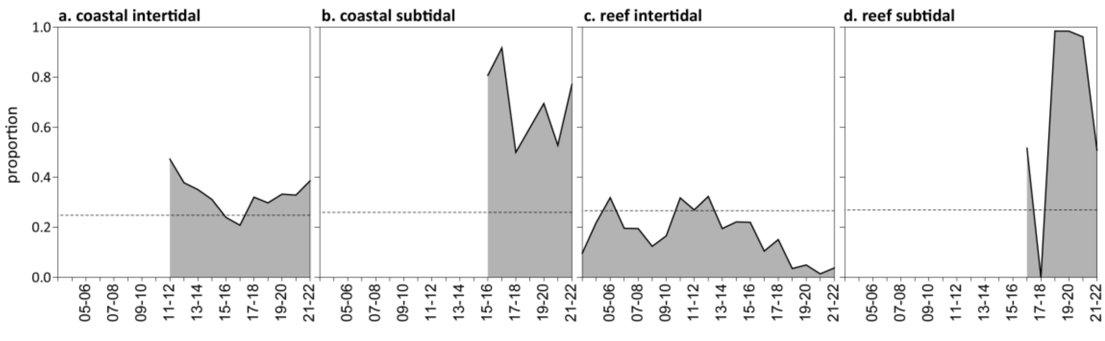


Figure 28. Proportion of seagrass abundance composed of species displaying colonising traits in each inshore habitat in the Cape York region.The dashed line represents Reef long-term average for each habitat type.

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). Only intertidal meadows are mapped across the Cape York region and prior to 2012, mapping only occurred at the reef intertidal meadows of Archer Point (Figure 29). Over the last decade, additional reef and coastal meadows in the Cape York region were included. Overall, relative meadow extent was reasonably stable until 2016, after which it has increased at reef habitats and fluctuated between years in coastal intertidal habitats (Figure 29), due primarily to changes in drainage channels.

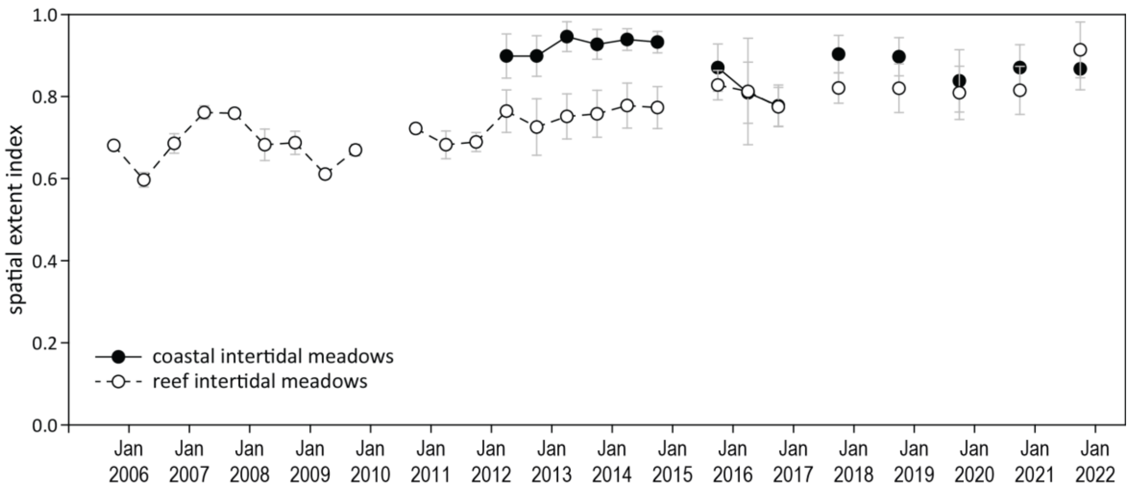


Figure 29. Change in relative spatial extent (± SE) of seagrass meadows within monitoring sites for each intertidal coastal and reef habitat and monitoring period across the eastern Cape York NRM region.

5.1.3.3 Seagrass reproductive status

Total reproductive effort is only monitored at intertidal meadows in Cape York. Reproductive structures were only reported at half of the eight sites examined in 2021–22; one location in each habitat. Historically, from 2006 to 2012, reproductive effort in reef intertidal habitats was recorded only at Archer Point, which has not been assessed since 2017. Reproductive effort is now based on sites introduced in 2012, which have consistently low numbers of reproductive structures. Reproductive effort has progressively declined at coastal habitats after reaching its peak in late 2016, and appears to have stabilised over the last 2 years (Figure 30).

Seed banks are also only measured at intertidal sites, which are dominated by *H. uninervis* across Cape York. Seeds are typically low in density in reef intertidal habitats, and in 2021–22 were only reported from Stanley Island where *H. uninervis* occurs (Table 5). A seed bank has persisted in the coastal meadows of Bathurst Bay for the last decade, and seed densities increased in 2021–22 relative to the previous reporting period (Figure 30). The low reproductive effort at Shelburne Bay for the third year in a row, will hinder replenishment of the seed banks, rendering most meadows vulnerable to further disturbances because of their limited capacity to recover from seed (i.e. low resilience).

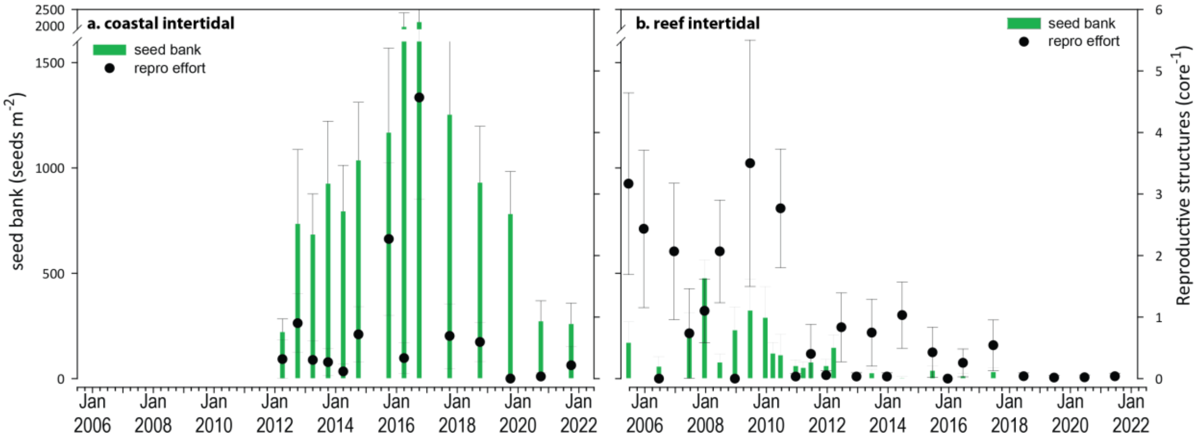


Figure 30. Seed banks and reproductive effort at inshore intertidal coastal (a) and reef (b) habitats in the Cape York region, for late dry season, 2005–22(species and sites pooled). Seed banks (green bars, ± SE) presented as the total number of seeds per m^2 sediment surface. Reproductive effort (dots, ± SE) presented as the average number of reproductive structures per core. NB. Reproductive effort was also assessed in the late wet season from 2008 to 2016.

5.1.3.4 Resilience

The resilience score is calculated for locations where reproductive effort is assessed. In Cape York, this is at intertidal coastal and reef habitats. In 2021–22, the resilience score was moderate overall.

At coastal sites, the score increased considerably in 2021–22 compared to the previous year. At Bathurst Bay, abundance was stable and there were reproductive structures present. The reproductive effort was predominantly by colonising species but at BY1 there were reproductive structures of foundational species and so it was in the highest category for resilience. At Shelburne Bay, there were no reproductive structures present, but at SR2 there are persistent species (*T. hemprichii*) present, and there had been reproductive structures observed in the past three years. By contrast at SR1, colonising species dominated and there were no reproductive structures in 2021–22 or recent history of reproduction.

Resilience declined slightly at reef intertidal sites due to declines in the score at Piper Reef (FR). Abundance was below the resilience threshold at both sites, and no reproductive structures were observed placing them in the lowest category. Resilience remains higher at Stanley Island where abundance was improving, persistent species were present and reproductive structures of foundational species were observed at ST1.

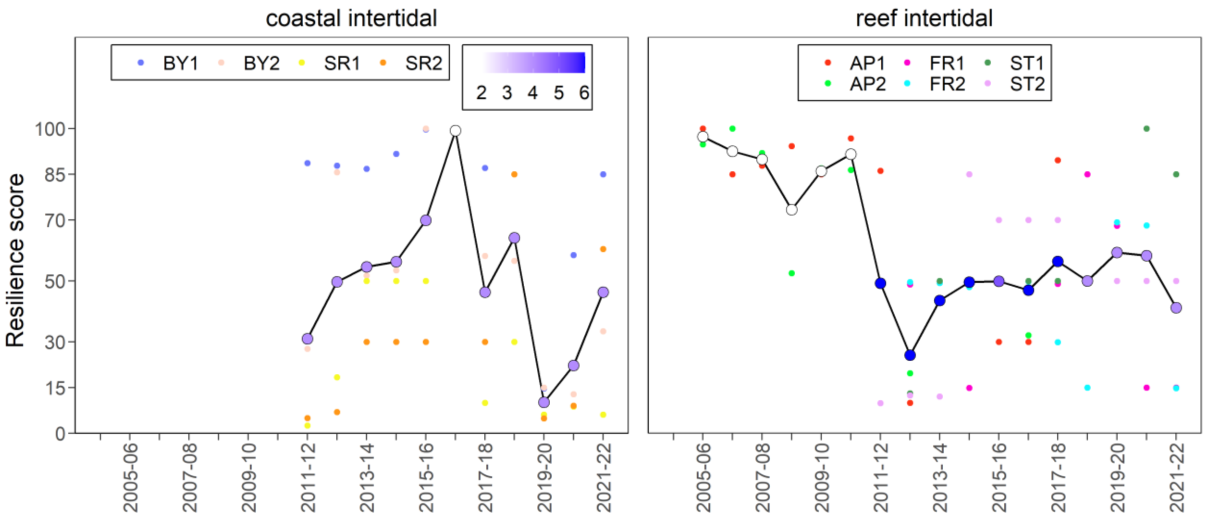


Figure 31. Temporal trend in the resilience score for each habitat monitored in the Cape York NRM region from 2005–2022. Coloured small points represent different sites. Shades of blue for the larger points indicate the number of sites that contribute to the score.

5.1.3.5 Epiphytes and macroalgae

Epiphyte cover on seagrass leaf blades at intertidal coastal habitats increased marginally above the long-term average for the first time in nearly a decade, whereas at reef habitats epiphyte cover has remained below for the fourth consecutive year (Figure 32). Overall, the low epiphyte covers are unlikely to have any significant impact on seagrass growth.

Per cent cover of macroalgae continues to vary between habitats. Macroalgae cover at intertidal habitats continued below the long-term average at coastal sites for the fifth consecutive year (Figure 32b), whereas it has remained above at reef sites for the last decade (Figure 32). At intertidal reef habitats, macroalgae are growing attached to coral rubble in the meadow, and not considered to be at levels sufficient to impact seagrass. Macroalgae is variable at coastal subtidal habitats, increasing to its highest level in 2021–22. Macroalgae at reef subtidal sites continued to remain below the overall inshore Reef long-term average.

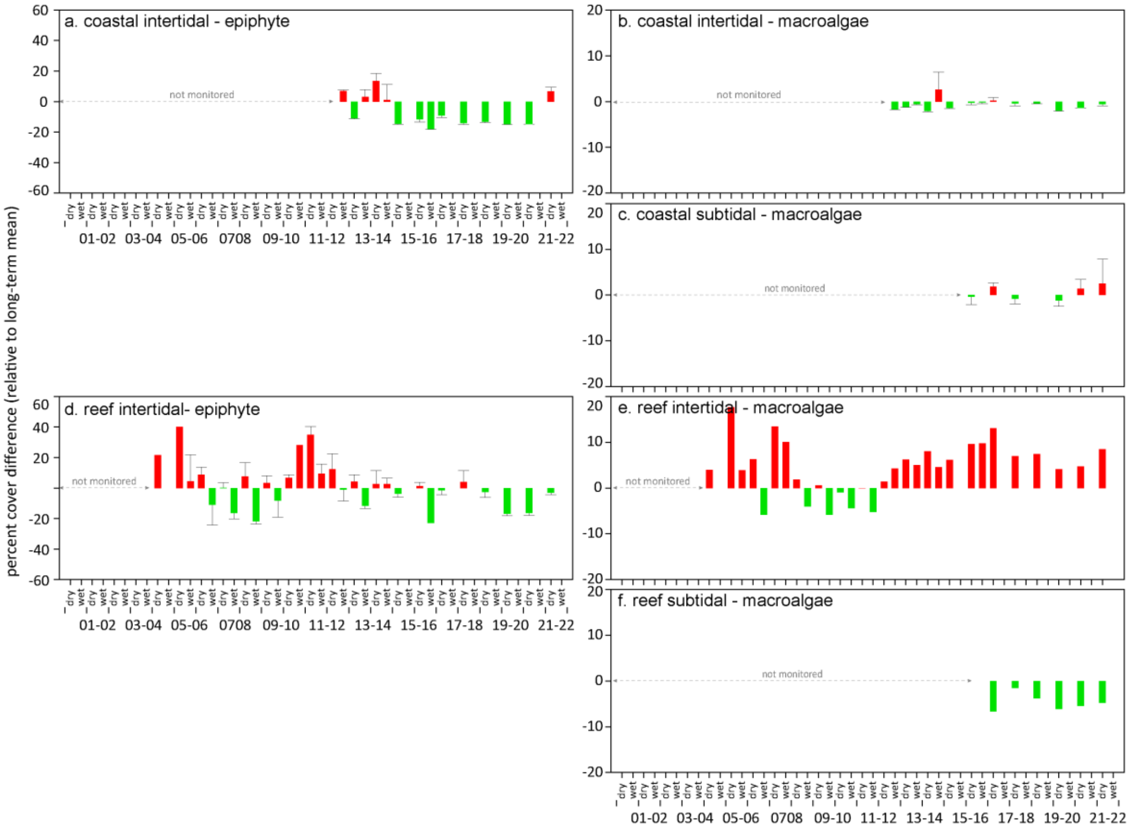


Figure 32. Deviations in mean epiphyte and macroalgae abundance (per cent cover) at monitoring habitats in the Cape York region, relative to the Reef long-term average (sites pooled, ± SE).

5.2 Wet Tropics

5.2.1 2021–22 Summary

Environmental conditions were relatively benign in 2021–22 in the northern Wet Tropics as rainfall and river discharge were similar to the long-term median, exposure to turbid water was lower than average and daily light was higher than average. The most significant environmental pressure was within-canopy water temperature which was 1ºC above average for the year, and the maximum temperature reached 45.5ºC which was 4ºC above the previous maximum.

Seagrass meadows within the Wet Tropics showed an overall improvement in the seagrass condition index in 2021–22. Seagrass condition in the northern Wet Tropics NRM region increased and was moderate (Figure 33). Seagrass condition improved and remained poor in the southern Wet Tropics, but it on the cusp of being rated moderate, and is the highest score recorded for the sub-region (Figure 33). The combined regional condition was **moderate** (Figure 33).

Contributing indicators in the north were:

- abundance was good
- resilience was moderate.

Contributing indicators in the south were:

- abundance was poor
- resilience was moderate.

In the northern Wet Tropics sites, seagrass abundance improved across the region in 2021–22 relative to the previous period largely because of increasing trends at subtidal reef sites, and mild climatic conditions across the sub-region. However, resilience declined in the north due to small declines in both coastal and reef intertidal habitats.

In the southern Wet Tropics, seagrass abundance declined slightly but was the third highest score for the sub-region. The decline was due to reductions in abundance in the reef subtidal habitat. Overall abundance was low compared to the northern sub-region, and abundances significantly declined over the long-term at coastal intertidal sites. The declines were a legacy of losses that occurred from 2009 to 2011, the result of multiple years of severe weather, above-average rainfall and elevated discharge. Recovery of seagrass meadows post 2011 was challenged, particularly in the south, by unstable substrates, chronic poor water quality compared to the north (high turbidity, light limitation) and limited recruitment capacity.

Resilience was declined overall in the northern Wet Tropics due to declines in reef intertidal and coastal habitats. The largest contributing factor to low scores at sites in the north was the dominance of colonising species at the reef intertidal and subtidal sites at Low Isles. Seed banks declined in coastal habitats in the north in 2020–21 and there were no seeds at reef intertidal or subtidal habitats. In the south, resilience increased and was the highest level recorded. This was due predominantly to large increases into the resilience score at reef intertidal sites where there were reproductive structures of foundational species for the first time since 2017–18.

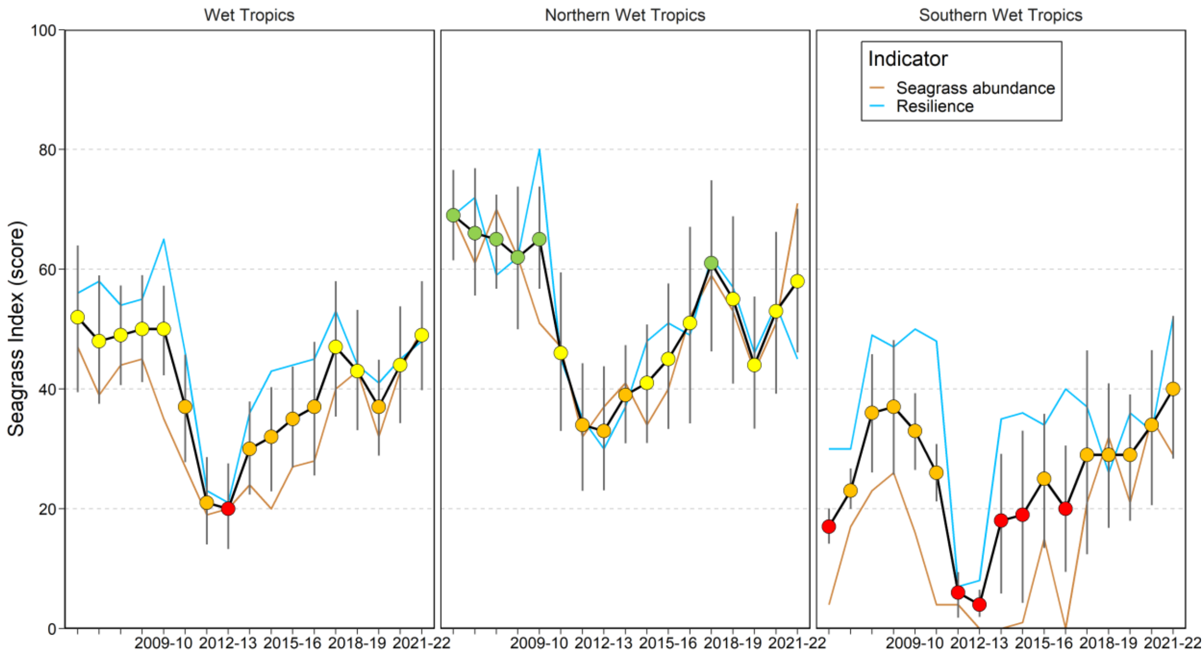


Figure 33. Report card of seagrass index and indicators for the Wet Tropics NRM region, including northern and southern sections (average across habitats and sites). Values are indexed scores scaled 0–100 (± SE) and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

5.2.2 Climate and environmental pressures

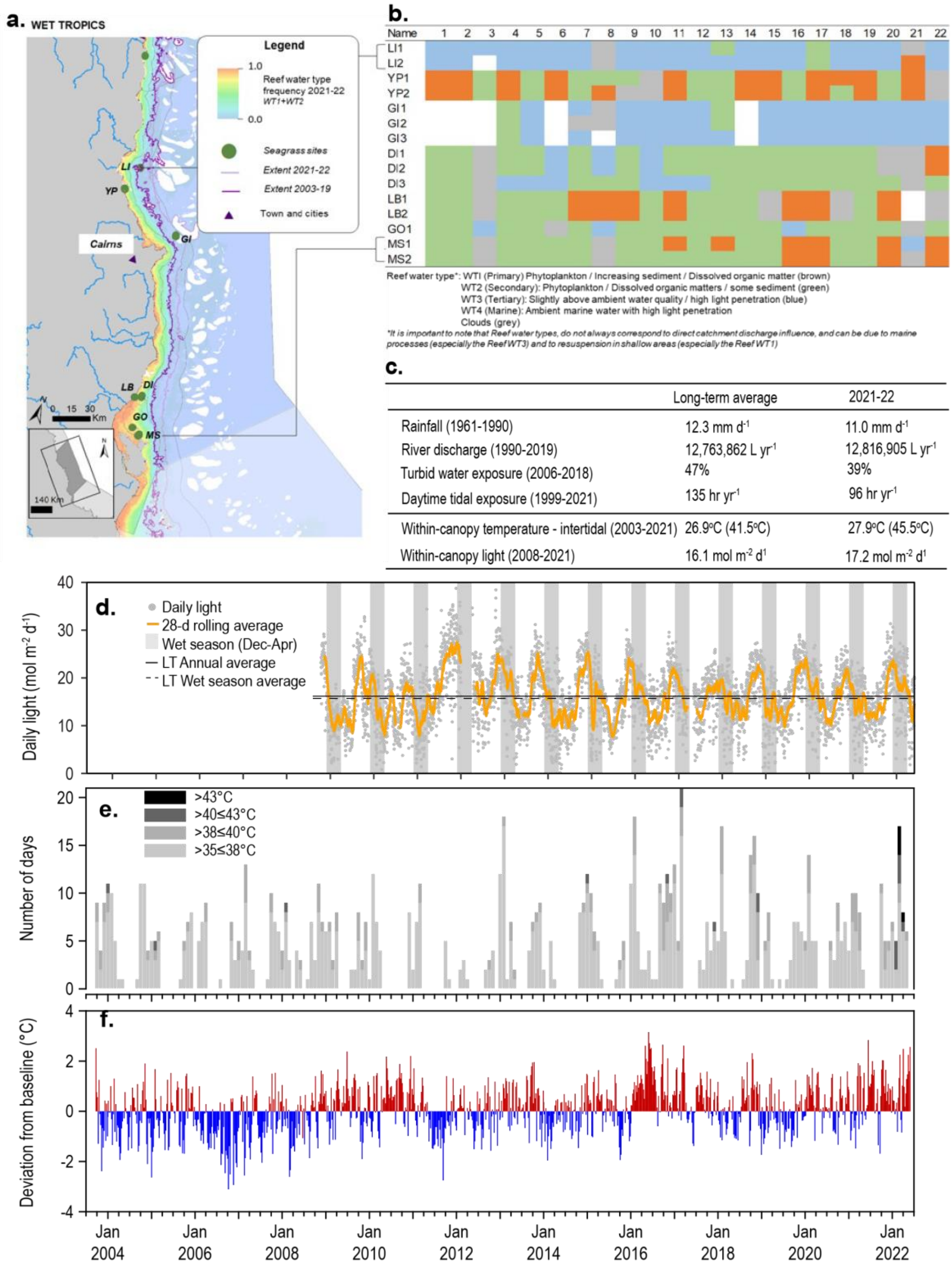
There was one tropical cyclone to affect the Wet Tropics region in 2021–22. Tropical cyclone Seth moved south east crossing the coast near Cairns as an ex-tropical cyclone in early January. Annual rainfall was slightly lower than average and river discharge was average in the northern Wet Tropics in 2021–22 across the region.

Exposure to primary or secondary turbid water was lower than the long-term average across the northern Wet Tropics during 2021–22 (Figure 34a, b). Sites were primarily exposed to water type II except at Yule Point where there was more exposure to water type I (Moran *et al.* 2023). Daily light levels at the intertidal sites (17.2 mol m^{-2} d^{-1} in 2020–21) were higher than the long-term average in the northern Wet Tropics (Figure 34c, d).

Intertidal within-canopy temperatures in the northern Wet Tropics were above the long-term average in intertidal habitats for the second consecutive year in 2021–22 (Figure 34e). Maximum intertidal within-canopy temperatures exceeded 35°C for a total of 64 days during 2021–22, including 11 days where maximum temperatures exceeded 40°C and the highest temperature ever for the region was recorded at 35.5°C (YP2, 3pm 23Mar21). In fact, there were six days between February and April 2022 where maximum temperatures were above the long-term maximum, making 2021-22 the hottest reporting period in the last five years.

Daytime tidal exposure in the north was below the long-term median (Figure 34c, Figure 91, Figure 92), which may have provided some respite from the elevated temperatures, particularly in coastal habitats.

Overall, the main pressures affecting seagrass habitats in the northern Wet Tropics in 2021–22 were above average temperatures and temperature extremes.



	Long-term average	2021-22
Rainfall (1961-1990)	12.3 mm d^{-1}	11.0 mm d^{-1}
River discharge (1990-2019)	12,763,862 L yr^{-1}	12,816,905 L yr^{-1}
Turbid water exposure (2006-2018)	47%	39%
Daytime tidal exposure (1999-2021)	135 hr yr^{-1}	96 hr yr^{-1}
Within-canopy temperature - intertidal (2003-2021)	26.9°C (41.5°C)	27.9°C (45.5°C)
Within-canopy light (2008-2021)	16.1 mol m^{-2} d^{1}	17.2 mol m^{-2} d^{1}

Figure 34. Environmental pressures in the northern Wet Tropics region including: a. frequency of exposure to primary and secondary water from December 2021 to April 2022 ranging from frequency of 1 (orange, always exposed) to 0 (pale blue, never exposed) (white = no data), also showing the long-term average (2003–2018) exposure boundary (purple line), and the first (blue line) and third quartile (white line) of the long-term average (from Moran *et al.* 2023); b. wet season water type at each site; c. average conditions and max temperature over the long-term and in 2020–21; 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; and f. deviations from 13-year mean weekly temperature records at intertidal sites.

Annual rainfall and river discharge were lower than average across the southern Wet Tropics during 2021–22 during the wet season (Figure 5). However, the largest discharge events in the region occurred late in April, followed by another in early May, after the ‘wet season’. Exposure to primary or secondary turbid water occurred 89 per cent of weeks during the wet season, which was a lower level of exposure than average (99 per cent) (Figure 35a, c). There was less frequent exposure to primary water and more exposure to secondary water at coastal sites including Lugger Bay (LB1 and LB2) and Missionary Bay (MS1 and MS2) compared to previous years (Figure 35b).

Light was measured at Dunk Island in the southern Wet Tropics and the annual average (14.3 mol m^{-2} d^{-1}) was lower than the long-term average (15.9 mol m^{-2} d^{-1}) (Figure 35d, Figure 100). Daily light reached a maximum in late November, and declined sharply in the December, at the start of the wet season (Figure 35d). Daily light was lower than the wet season average for most of the wet season.

In the southern Wet Tropics, within-canopy temperatures are only measured at Dunk Island where in 2021–22 they were above the long-term average (Figure 35b). Maximum intertidal within-canopy temperatures during 2021–22 exceeded 35°C over eight days, the most ever in a reporting period, which also included the second highest temperature ever recorded at 39.6°C (DI2, 3:30pm 06Oct21) (Figure 35e, f). Daytime tidal exposure was below the long-term average for the second consecutive year (Figure 35b, Figure 91, Figure 92), which may have provided some respite from the elevated temperatures.

Overall, the main pressures affecting seagrass habitats in the southern Wet Tropics in 2021–22 were similar to those in the northern with above average temperatures and temperature extremes.

In 2021–22, sediments at the monitoring sites appeared similar to the long-term average and the proportion of fine sediments (i.e. mud) was well below the overall inshore Reef long-term average across all habitats. The slight increase in mud that was noted at one of the coastal sites (YP2) in the north appears to have dissipated (Figure 107, Figure 108). Across the Wet Tropics region, coastal sediments were composed primarily of fine sand, while reef habitats were composed of sand and coarser sediments (Figure 107, Figure 108).

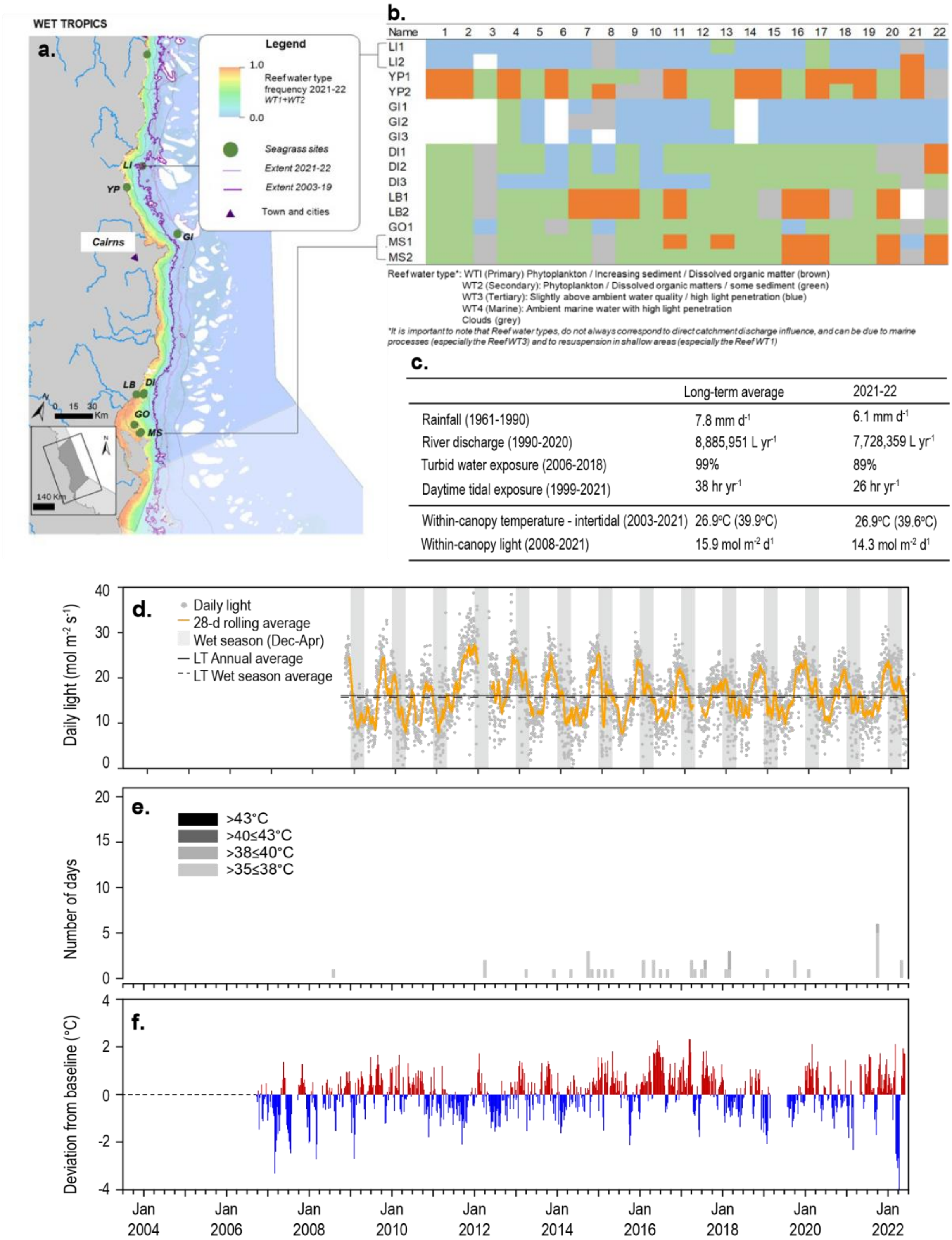


Figure 35. Environmental pressures in the southern Wet Tropics region including: a. frequency of exposure to primary and secondary water from December 2021 to April 2022 ranging from frequency of 1 (orange, always exposed) to 0 (pale blue, never exposed) (white = no data), also showing the long-term average (2003–2018) exposure boundary (purple line), and the first (blue line) and third quartile (white line) of the long-term average (from Moran *et al.* 2023); b. average conditions and max temperature over the long-term and in 2020–21; 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; and f. deviations from 13-year mean weekly temperature records at intertidal sites.

5.2.3 Inshore seagrass and habitat condition

Three seagrass habitat types were assessed across the Wet Tropics region with data from 14 sites (Table 14).

Table 14. 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 2021–22, blank cell indicates data not usually collected/measured at site. † drop camera sampling (RJFMP), *Seagrass-Watch. For site details see Table 5 and Table 6.

Sub region	Habitat	Site		abundance	composition	extent	reproductive effort	seed banks	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	■	■	■	■		■	■	■

5.2.3.1 Seagrass index and indicator scores

In the 2021–22 monitoring period, the seagrass condition index for the overall Wet Tropics region improved and was moderate (Figure 33). Both indicators increased when averaged across the Wet Tropics and the abundance score was the highest level recorded for the Wet Tropics. There were differences in the trends of the indicators between regions, though both showed overall improvement in the Index.

In the northern Wet Tropics, seagrass abundance increased from moderate to good and was the highest ever recorded. There were increases in abundance at all locations except at Yule Point and the subtidal habitat at Low Isles. The largest improvement was in subtidal habitat at Green Island (Figure 36). The long-term trend in seagrass per cent cover shows a period of decline starting in 2008–09 when there were Reef-wide declines associated with extreme weather. However, the Wet Tropics has had relatively stable abundance compared to other regions and has recovered to within pre-2008 levels though there were fewer sites in the earlier records.

Resilience in the northern Wet Tropics declined in 2021–22 and is the fourth lowest score since records began (Figure 36). This was driven by declines in resilience in the intertidal reef and coastal habitats. This indicates that although the abundance is high, the habitats may be vulnerable to further pressures.

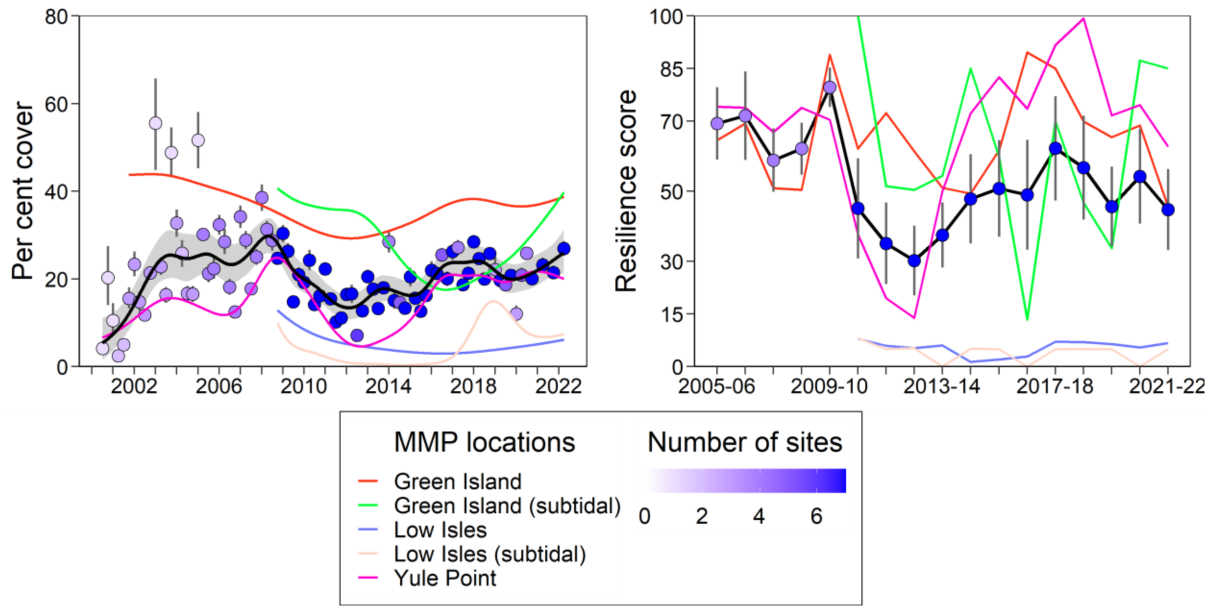


Figure 36. Temporal trends in the northern Wet Tropics seagrass indicators used to calculate the seagrass condition index: a. average (circles, ±SE) seasonal abundance (per cent cover) and GAM plots of seagrass abundance trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); b. average annual resilience score (±SE) and trends for each location (coloured lines). Colour of circles represents the number of sites assessed to calculate the average.

In the southern Wet Tropics, the seagrass condition index improved and reached the highest level since monitoring began in 2005 (Figure 37). This was driven by improvements in resilience, which was also at the highest level observed and was moderate. Both the abundance and resilience indicators have been highly variable since 2012–13, often with what appears as an annual lag from abundance to resilience (Figure 33). Abundance declined in 2021–22 and remained poor in the southern Wet Tropics.

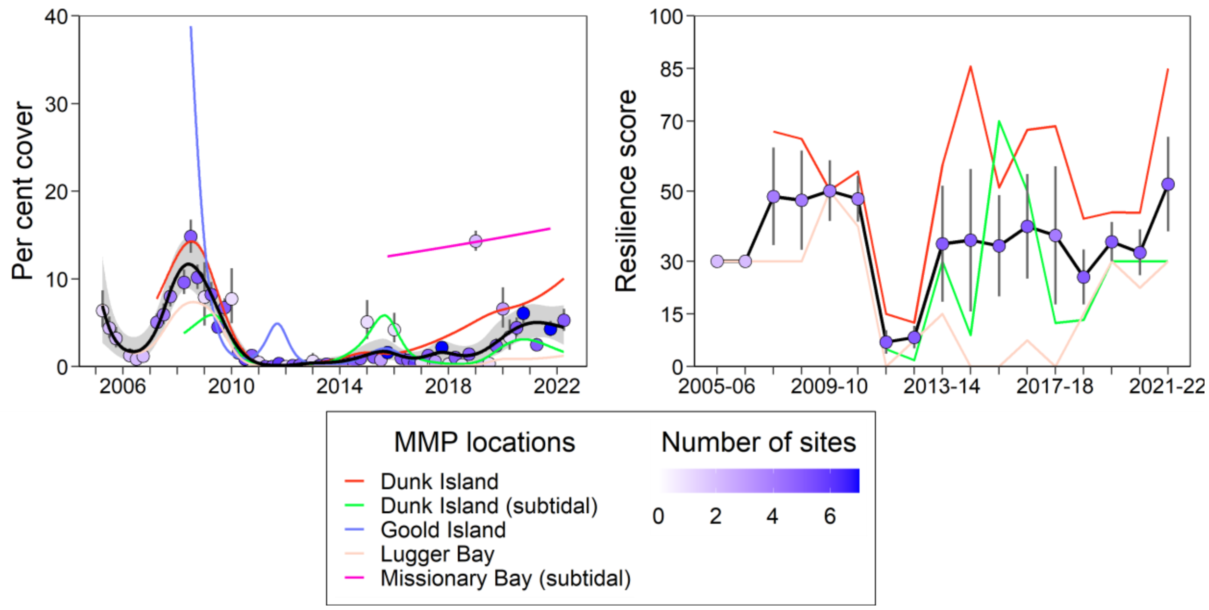


Figure 37. Temporal trends in the southern Wet Tropics seagrass indicators used to calculate the seagrass condition index: a. average (circles, ±SE) seasonal abundance (per cent cover) and GAM plots of seagrass abundance trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); b. average annual resilience score (±SE) and trends for each location (coloured lines). Colour of circles represents the number of sites assessed to calculate the average.

5.2.3.2 Seagrass abundance, community and extent

Seagrass meadows remain more abundant (higher per cent cover) across all habitats in the northern than the southern Wet Tropics (Figure 38, Figure 39). In the northern Wet Tropics, seagrass abundance over the long-term is higher at intertidal reef (28.0 ±2.1 per cent) than subtidal reef (17.1 ±2.4 per cent) or coastal habitats (15.1 ±1.6 per cent). In 2021–22, seagrass abundances improved overall in the northern Wet Tropics (Figure 38). Despite seagrass abundances at the intertidal coastal meadows at Yule Point remaining steady and above the long-term average for the 7th consecutive year, the sub-regional increase in abundance was driven by improvements across reef habitats in 2021–22. At Low Isles, seagrass abundances improved intertidally to the highest in a decade, while subtidally they were the highest since 2019 (Figure 38). At Green Island the intertidal abundances remained relatively stable, however subtidal abundances were the highest since monitoring was established (Figure 38).

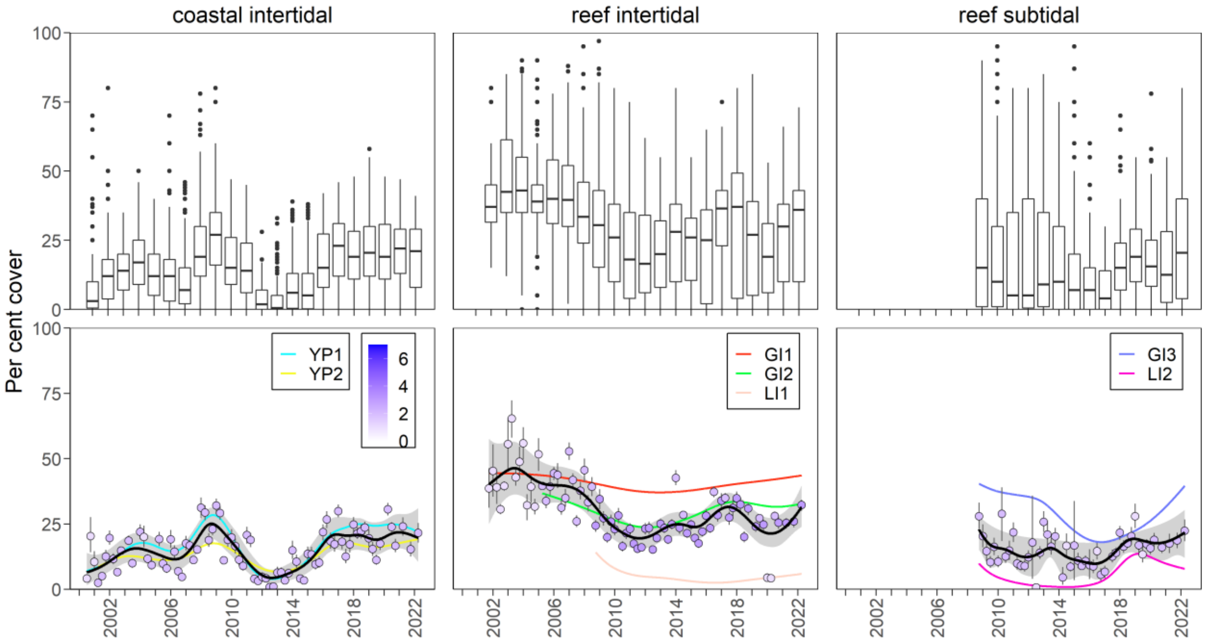


Figure 38. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the northern Wet Tropics NRM region from 2001 to 2022. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero 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. GAM plots (bottom), show trends for each habitat and coloured lines represent individual site trends

In the southern Wet Tropics, although long-term seagrass abundance is higher at intertidal reef (4.7 ±1.0 per cent) than at subtidal reef (2.0 ±0.8 per cent) or intertidal coastal habitats (1.8 ±0.6per cent), the abundances were 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 in early 2011. At coastal habitats in Lugger Bay, complete loss was sustained for years and 2021–22 marks the 13th consecutive year that abundances have been well below pre-2011 levels (Figure 39). Although recovery has been 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 years. Similarly, abundances improved at the reef habitats, with both intertidal and subtidal abundances having recovered to levels similar to the onset of monitoring in 2006 and remaining above the long-term average for the third consecutive year. Intertidal reef seagrass abundance remains on an increasing trajectory since 2012–13, with abundances in 2021–22 being the highest since 2009.

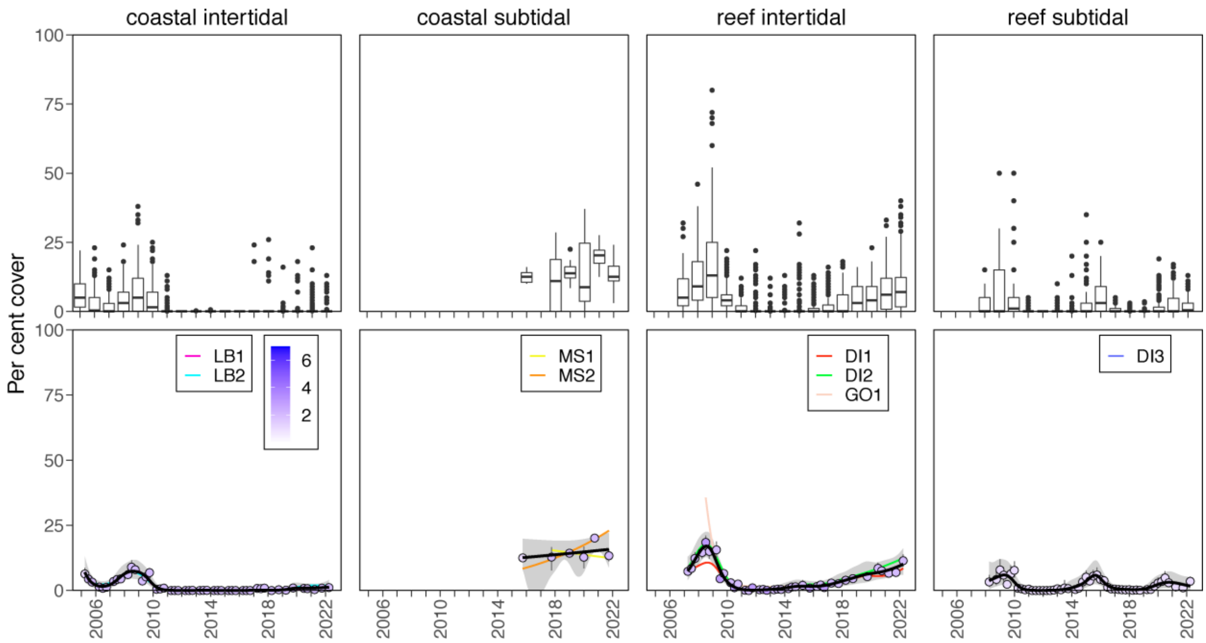


Figure 39. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the southern Wet Tropics NRM region from 2001 to 2022. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero 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. GAM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

The proportion of seagrass species displaying colonising traits in the northern Wet Tropics has remained above the long-term average for reef habitats in 2021–22 (Figure 40). At coastal intertidal habitats (Yule Point), the proportion of colonising species has declined relative to the previous period, returning to below the long-term average suggesting abatement of the physical disturbances experienced in 2020–21.

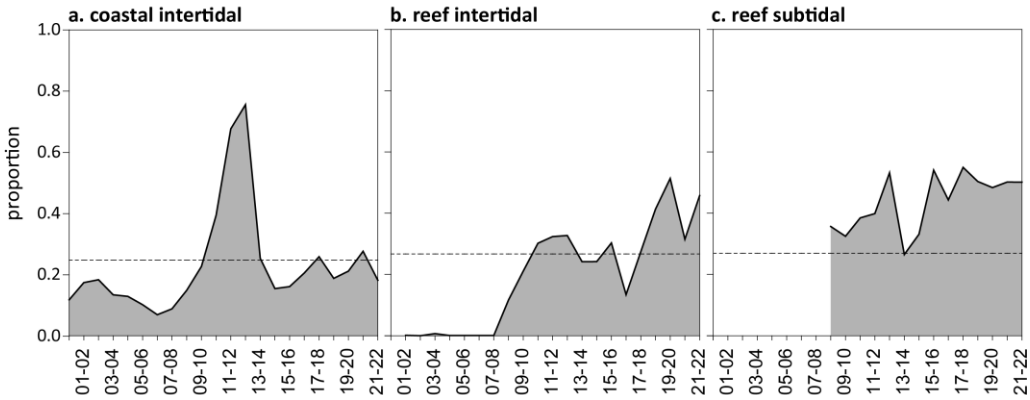


Figure 40. Proportion of seagrass abundance composed of colonising species at inshore habitats in the northern Wet Tropics region, from the 2000–2001 to the 2021–22 reporting periods. The dashed line represents the overall inshore Reef average for each habitat type.

In the southern Wet Tropics, the proportion of seagrass species displaying colonising traits remains variable across habitats (Figure 41). Coastal habitats appear unchanged, remaining dominated by opportunistic species, with a higher proportion of colonising species in the subtidal. Colonising species remained in low proportions in reef habitats, however they increased intertidally while decreasing subtidally.

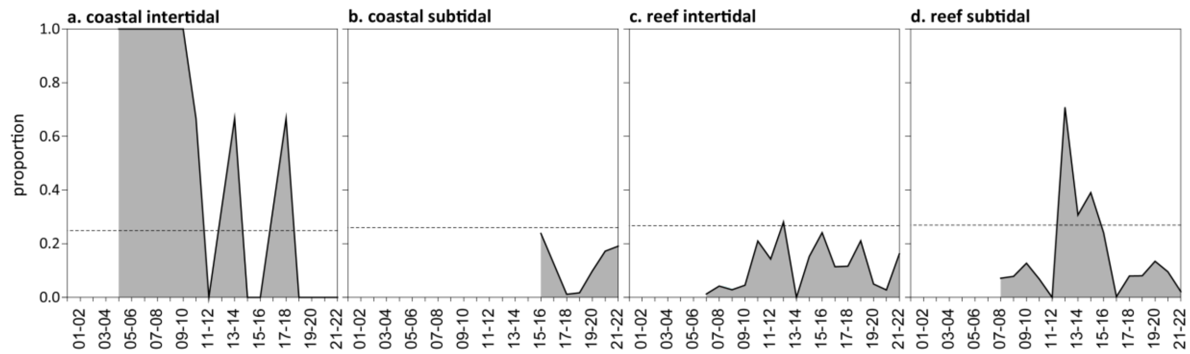


Figure 41. Proportion of seagrass abundance composed of colonising species at inshore habitats in the southern Wet Tropics region, from the 2000–2001 to the 2021–22 reporting periods. The dashed line represents the Overall inshore Reef average for each habitat type.

Seagrass meadow spatial extent within all monitoring sites continues to fluctuate within and between years. At intertidal coastal habitats in the northern Wet Tropics, meadow relative extent has not improved since the previous reporting period (Figure 42), where a slight decline was observed due to increasing prevalence of scars within the meadows (pers. obs.). Nevertheless, the overall extent has remained above the long-term average for the seventh consecutive year (Figure 42). In contrast, intertidal and subtidal Reef habitats have continued to recover from losses experienced in early 2020, and are now at their most extensive in over five years (Figure 42).

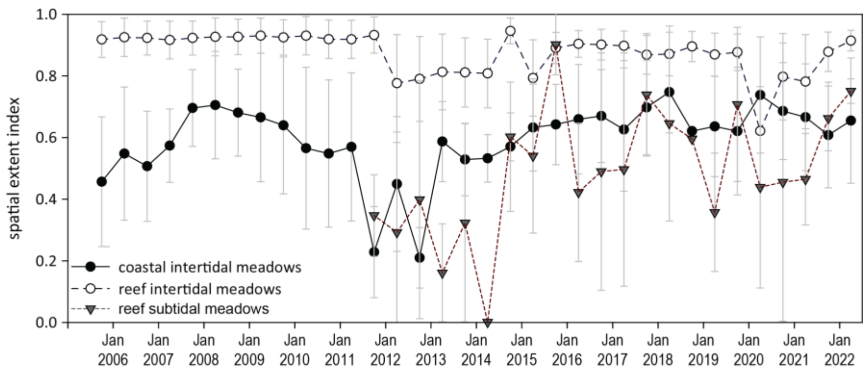


Figure 42. Change in relative spatial extent (±SE) of seagrass meadows within monitoring sites for each habitat and monitoring period across the northern Wet Tropics NRM region.

In the southern Wet Tropics, seagrass meadows across all habitats were lost in early 2011 as a consequence of Tropical cyclone Yasi (Figure 43). Since then, intertidal reef meadows have progressively improved, reaching their greatest post–2011 extent in 2020–21, but with little change over the last 12 months (Figure 43). Subtidal reef meadows have fluctuated greatly over the last decade, showing significant recovery in the previous reporting period, but with little change in 2021–22 (Figure 43). At intertidal coastal habitats, the meadows have had a severely protracted recovery since 2011, with colonisation delayed until mid-2018 (Figure 43), after which the isolated patches have struggled to expand and coalesce in a highly dynamic environment with mobile sediments (Pers. Obs.).

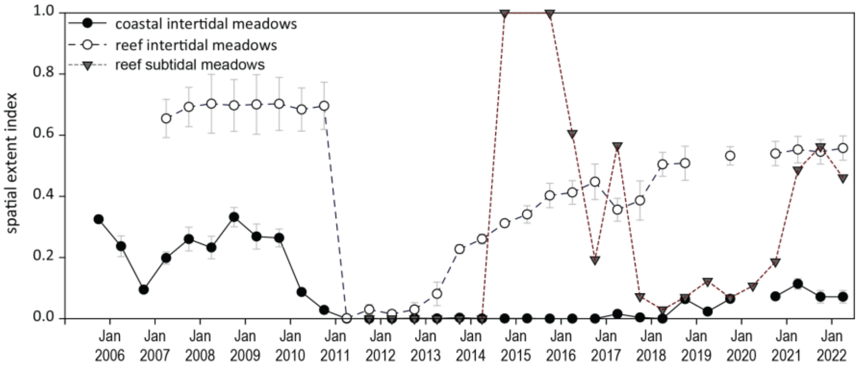


Figure 43. Change in relative spatial extent (±SE) of seagrass meadows within monitoring sites for each habitat and monitoring period across the southern Wet Tropics NRM region.

5.2.3.3 Seagrass reproductive status

Reproductive effort varies across habitats in the Wet Tropics, and is consistently higher in the northern sub-region than the south. In general, reproductive effort and seed density have been buoyed in the Wet Tropics in the last five years, though with some variability among habitats and regions. In the northern Wet Tropics, reproductive effort in coastal intertidal habitats (Yule Point) has remained below the long-term average for the third consecutive year and during 2021–22 declined slightly relative to the previous reporting period. Conversely, the number of reproductive structures improved slightly in reef habitats and was at or marginally above the long-term average (Figure 44). Nevertheless, over the last decade, the number of reproductive structures reported in coastal habitats has been consistently higher than reef habitats, and over the long-term it is greater by a factor of approximately 50 fold.

Seed density was below the long-term average and at the lowest level in six years, likely a consequence of lower reproductive effort. To date, seed banks have remained very low across the region in reef habitats (Figure 44). The absence of seeds in the reef meadows examined in 2021–22, is likely the result of the greatly depressed reproductive effort over the previous two years. Other 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).

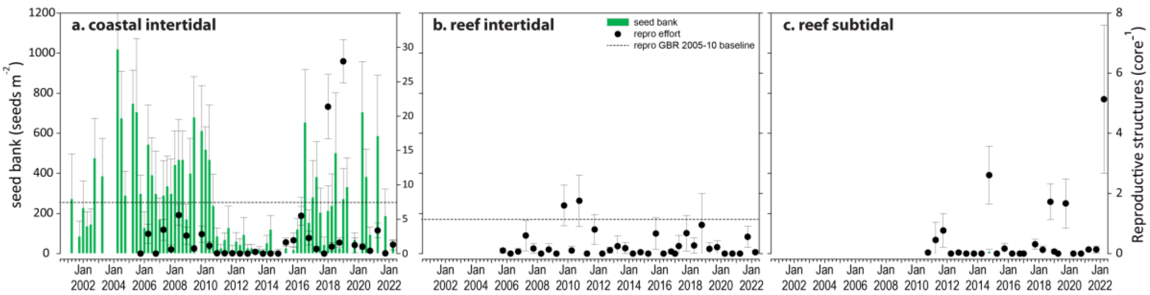


Figure 44. Seed bank and reproductive effort at inshore coastal intertidal and reef intertidal and subtidal habitats in the northern Wet Tropics region, 2001 to 2022.Seed banks presented as the total number of seeds per m^2 of sediment surface (green bars ±SE). Reproductive effort presented as the average number of reproductive structures per core (species and sites pooled) (dots ±SE). Y-axis labels are different in panel a to those in panels b and c.

In the southern Wet Tropics, sexually reproductive structures and seed banks were absent from coastal intertidal meadows for the 9th consecutive year and absent from reef intertidal and subtidal habitats for the first time in six year (Figure 45). 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.

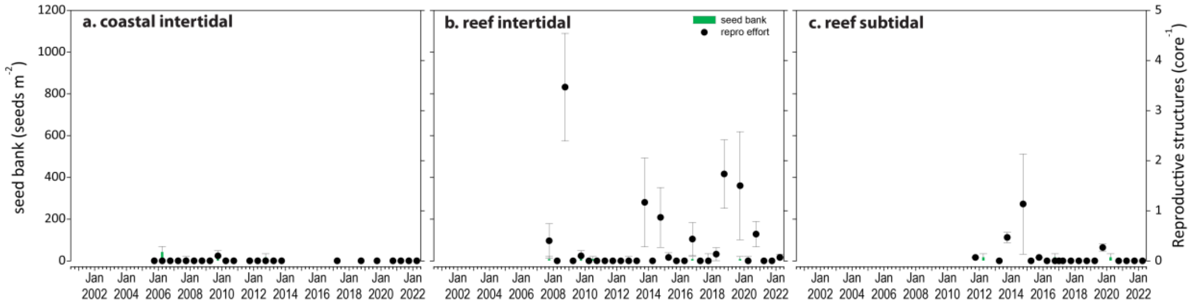


Figure 45. Seeds banks and reproductive effort for inshore coastal intertidal and reef intertidal and subtidal habitats in the southern Wet Tropics region for the late dry and late wet season, 2001 to 2022.Seed banks presented as the total number of seeds per m^2 sediment surface (green bars ±SE). Reproductive effort presented as the average number of reproductive structures per core (species and sites pooled) (dots ±SE).

5.2.3.4 Resilience

Resilience was moderate overall in the northern Wet Tropics, but varied among habitat and site (Figure 46). At Yule Point coastal sites, meadow condition was above critical thresholds for abundance and composition, and although reproductive structures were present at YP2, there were fewer than in recent years and there were none at YP1.

At reef intertidal sites at Green Island, meadow condition was above critical thresholds for abundance and composition, but reproductive structures were absent again in 2021–22 but they had been present in the previous three years. At Low Isles, colonising species continue to dominate the species composition, resulting in a low resilience score.

There were large differences in resilience at reef subtidal sites. The Green Island meadow condition was above critical thresholds for abundance and composition and there were reproductive structures of foundational species in 2021–22. At Low Isles, the meadow had continued to be comprised of only colonising species resulting in a low resilience score and rendering the meadow highly vulnerable to even short-term disturbances such as elevated discharge.

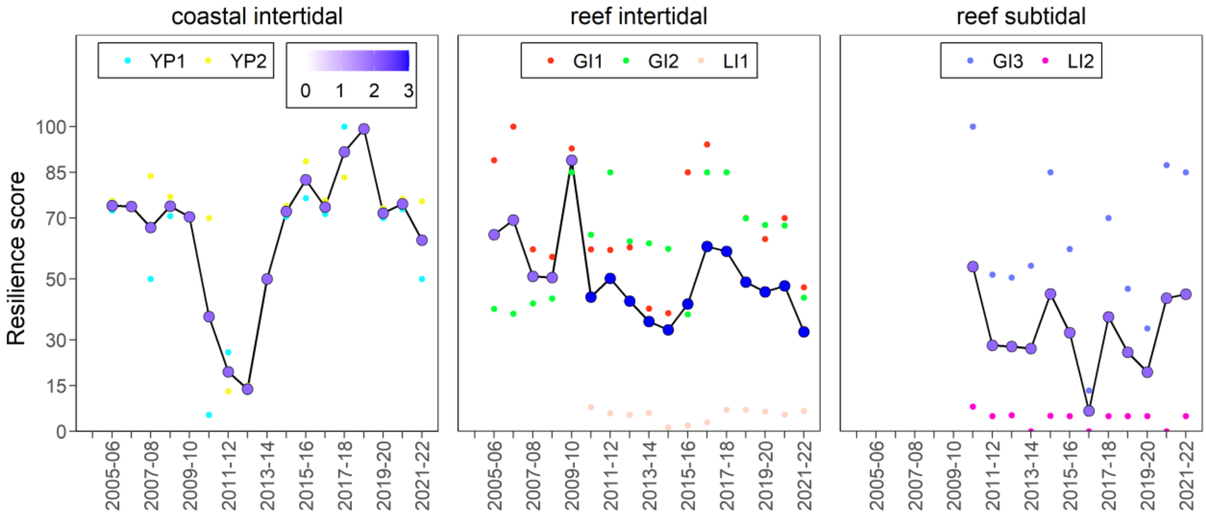


Figure 46. Resilience score for each habitat type in the northern Wet Tropics. Coloured small points represent different sites. Shades of blue for the larger points indicate the number of sites that contribute to the score.

In the southern Wet Tropics, resilience was moderate overall for the first time since 2008–09 (Figure 47). At the coastal intertidal sites at Lugger Bay, the meadow was above critical per cent cover thresholds and comprised of only opportunistic species but they were not observed to be flowering and there was no recent history of flowering at the site.

At reef intertidal sites at Dunk Island, meadow condition was above critical thresholds for species composition and per cent cover, there were reproductive structures for the first time in four years and persistent species were present placing them in the highest category for resilience and resulting in the second highest score for the habitat and region. While there were historically higher levels of reproduction at the site (Figure 45), the large historical values were mainly colonising species which do not contribute towards the residence score in category 2. At the reef subtidal site meadow condition was above critical thresholds for species composition and per cent cover but there were no reproductive structures observed again in 2021–22 or in the previous three years.

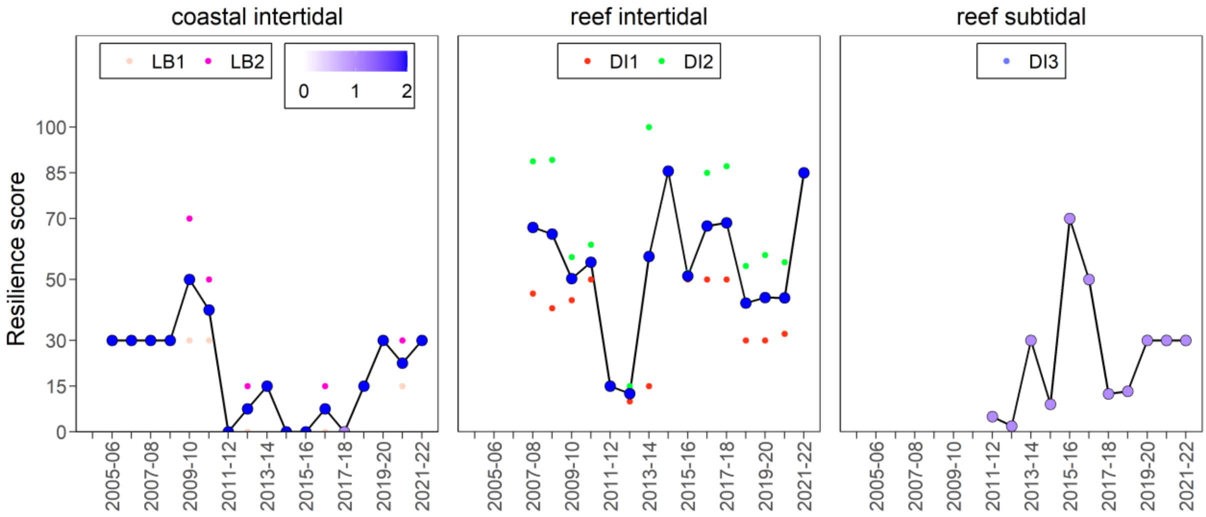


Figure 47 Resilience score for each habitat type in the southern Wet Tropics. Coloured small points represent different sites. Shades of blue for the larger points indicate the number of sites that contribute to the score.

5.2.3.5 Epiphytes and macroalgae

Epiphyte cover on seagrass leaves in the northern Wet Tropics, remained above the overall inshore Reef long-term average in all habitats in 2021–22 (Figure 48).

Macroalgae cover remained below the Reef long-term average in coastal habitat and reef subtidal habitats in both the wet and dry season for the fifth consecutive year (Figure 48). Macroalgae cover is typically higher in reef intertidal habitats, as it attaches to coral rubble, and has remained above the long-term average for over a decade (Figure 48); only dropping below during the occasional wet season as a consequence of increased freshwater and reduced light. In 2021–22, macroalgae cover in reef intertidal habitats was slightly higher than the previous period but lower that has been reported earlier (Figure 48).

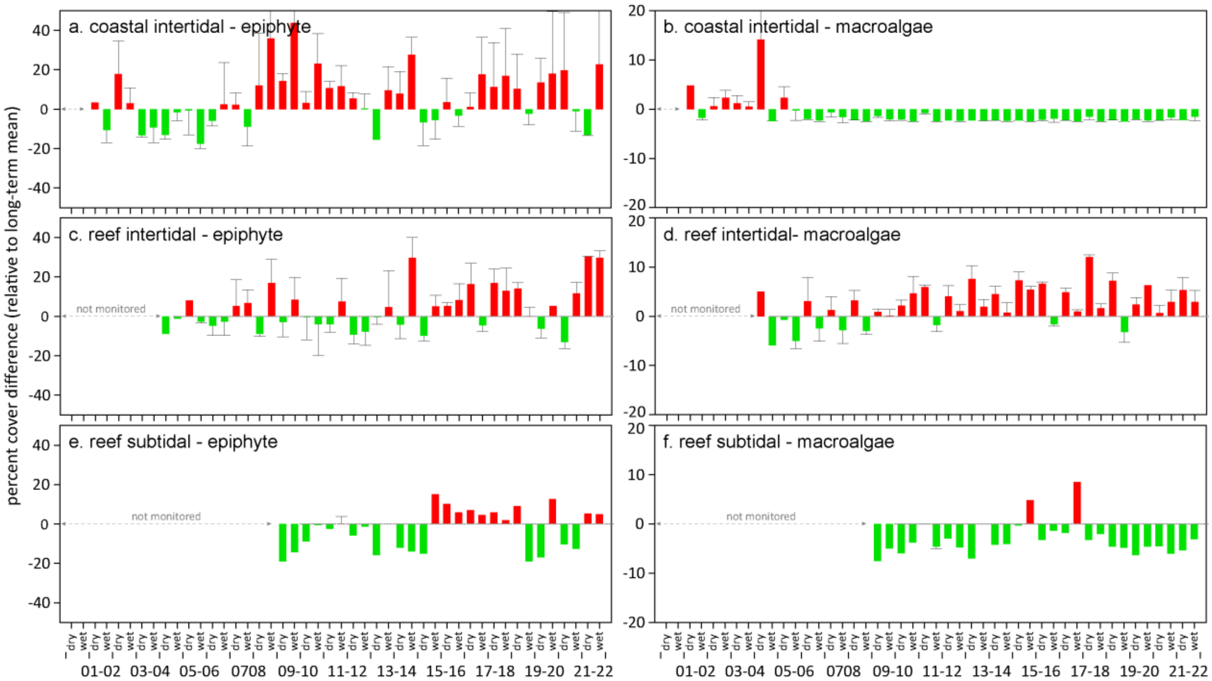


Figure 48. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term average for each inshore seagrass habitat in the northern Wet Tropics region, 2001–2022 (sites pooled, ±SE).

In the southern Wet Tropics, epiphyte cover in reef habitats was below the Reef long-term average, decreasing intertidally in 2021–22 relative to the previous period (Figure 49d, f). Similarly, epiphyte cover in coastal habitats is generally low, however it increased above the long-term average in the late dry 2021 (Figure 49a).

Macroalgae cover is generally low and/or below the Reef long-term average in all habitats except reef subtidal in the southern Wet Tropics (Figure 49). Macroalgae cover at the reef subtidal site has varied greatly over the last decade and declined in 2020–21 after reaching its highest cover in the previous reporting period (Figure 49g).

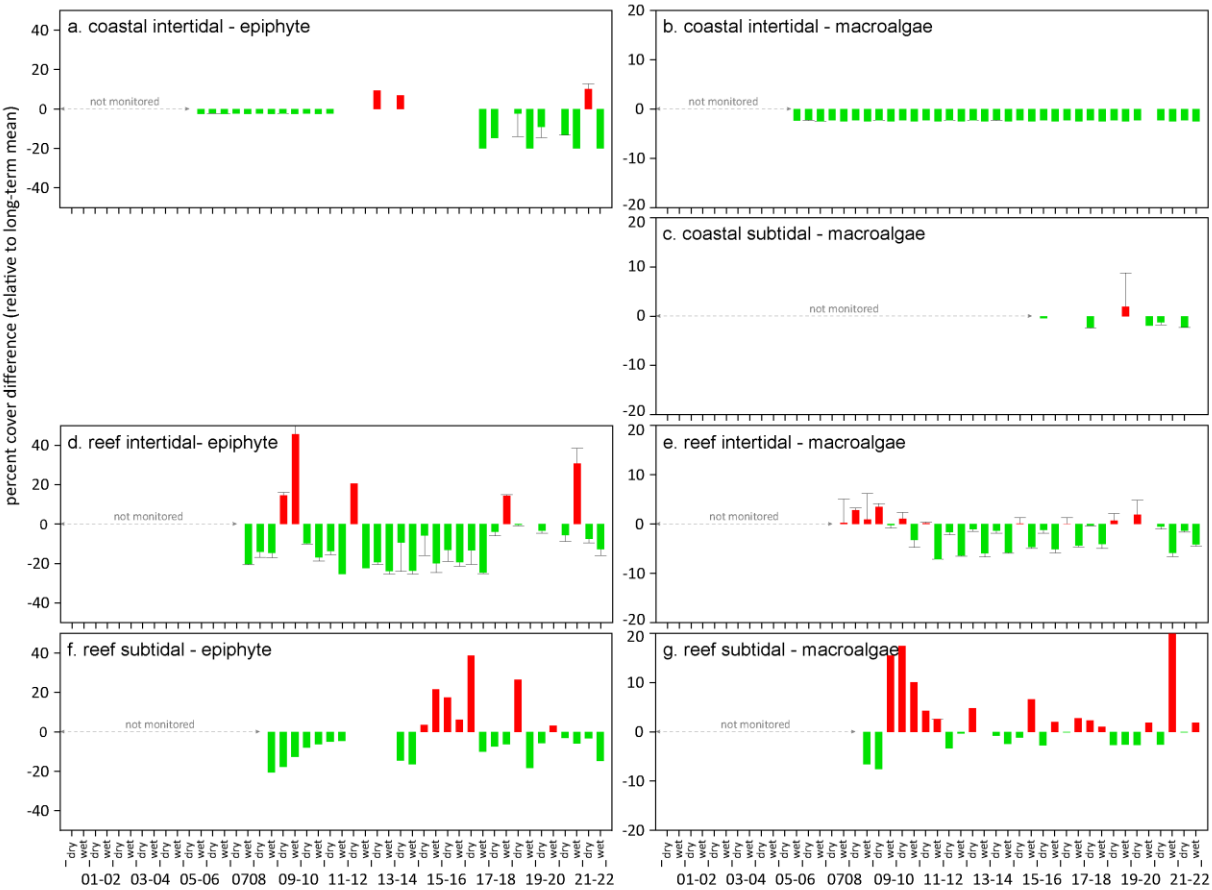


Figure 49. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term average for each inshore seagrass habitat in the southern Wet Tropics region, 2001–2022 (sites pooled, ±SE).

5.3 Burdekin

5.3.1 2021–22 Summary

In 2021–22, wet season rainfall was below average but there were late rainfall events after the wet season and so annual river discharge was around the long-term median for all of the basins in the Burdekin region (Figure 51, Table 11). Annual average water temperature was 0.8°C higher than the long-term average.

The condition of seagrass meadows across the Burdekin NRM region 2021–22 was unchanged overall and remained **moderate** (Figure 50). Condition indicators contributing to this were:

- abundance score was moderate
- resilience score was moderate.

Seagrass abundance marginally increased relative to the previous period but remains lower than historical records. The low abundances at some sites were likely the legacy from the 2019 wet season 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.

Seagrass resilience reduced marginally in 2021–22 compared to the previous reporting period and remained moderate. In coastal habitats, the resilience score was stable. Patterns were inconsistent among habitat types. In coastal intertidal habitat reproductive effort declined but remained at average levels and seed density in the seed bank was the highest on record. This occurred late in the wet season. Reproductive effort and seed banks remained very low in reef intertidal and were absent subtidal habitats.

Since monitoring was established, seagrass meadows of the Burdekin region have demonstrated high resilience particularly through their capacity for recovery. This may reflect a conditioning to disturbance (large 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.

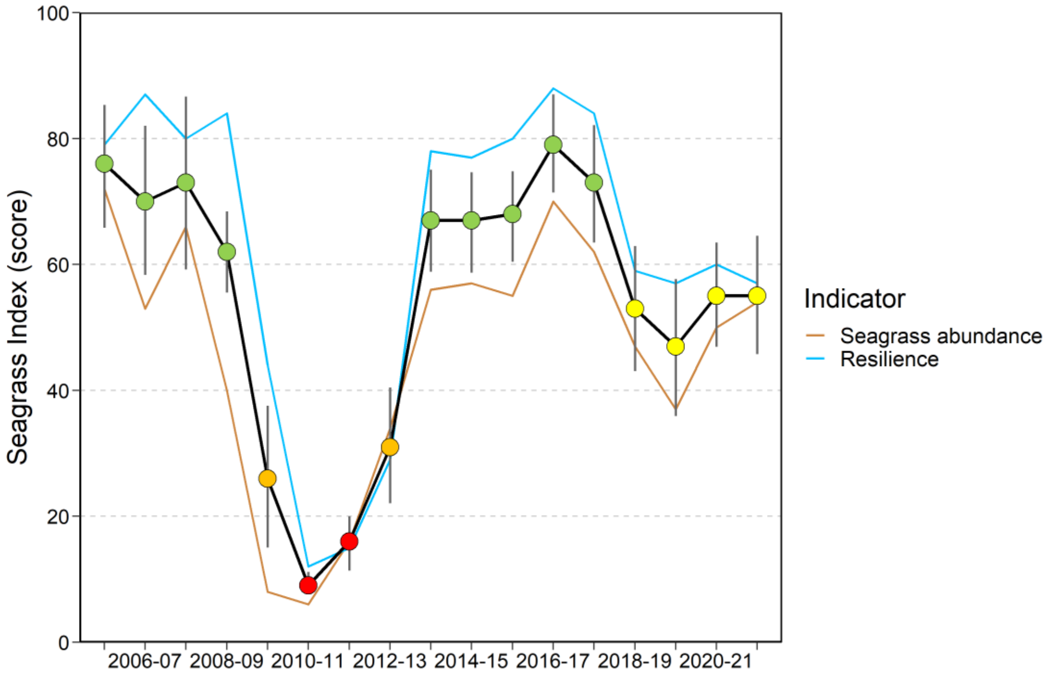


Figure 50. Report card of seagrass status indicators and index for the Burdekin NRM region (averages across habitats and sites). Values are indexed scores scaled from 0–100 (± SE) and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

5.3.2 Climate and environmental pressures

Tropical cyclones did not affect the Burdekin NRM in 2021–22. Wet season rainfall across the Burdekin catchments was below the long-term average, but there was elevated rainfall in May 2022. Because of this, annual river discharge was around the long-term median for the region (1.2 times above). Inshore seagrass sites in the region are exposed to turbid waters (water types I and II) in all weeks of the wet season. In 2021–22, exposure to turbid water was around the long-term average with coastal sites (BB, SB and JR) exposed to water type I while reef sites at Magnetic Island were exposed predominately to water type II for most of the wet season (Figure 51a, b).

Daily light levels at intertidal locations in the Burdekin region were 11.9 mol m^{-2} d^{-1} on average in 2021–22, and therefore higher than the long-term average (11.4 mol m^{-2} d^{-1}) (Figure 51c, d). However, the trend in 2021–22 varied among locations, and there was limited data available for the year from all of the coastal sites. Daily light levels at the reef intertidal sites were higher than average at Cockle Bay (MI2), but lower than average at Picnic Bay (MI1). In 2020–21, the regional trend in light was unusual, as light levels were above the wet season average for most of the wet season, but this was affected by the limited data available from the typically turbid and low light coastal sites. Daily light levels declined just after the wet season in May, when there was a period of elevated rainfall in the catchments (Figure 51d).

After a slightly cooler 2020–21, intertidal within-canopy temperatures increased this year to above the long-term average and were on average the warmest since monitoring was established (Figure 51c, f). Maximum intertidal within-canopy temperatures exceeded 35°C for a total of 34 days during 2021–22, with 2 days reporting maximums above 40°C and the second highest temperature ever recorded for the region at 43.2°C (MI1, 4pm 16May22); the highest extreme temperature in 14 years (Figure 51e, f). Daytime tidal exposure was below the long-term median at all sites for the 6th consecutive year (Figure 51c, Figure 93, Figure 94), which may have provided some respite from the elevated temperatures.

The proportion of mud at Jerona (Barratta Creek) coastal meadows remains much higher than Townsville meadows (Bushland Beach and Shelley Beach) and has persisted well above the Reef long-term average (Figure 110). Post 2011, Townsville coastal meadows have been dominated by fine sediments, and although the proportion of mud fluctuated at Bushland Beach between 2018 and 2020, over the last couple of years it has stayed below the long-term average (Figure 110). 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 five years (Figure 111, Figure 112).

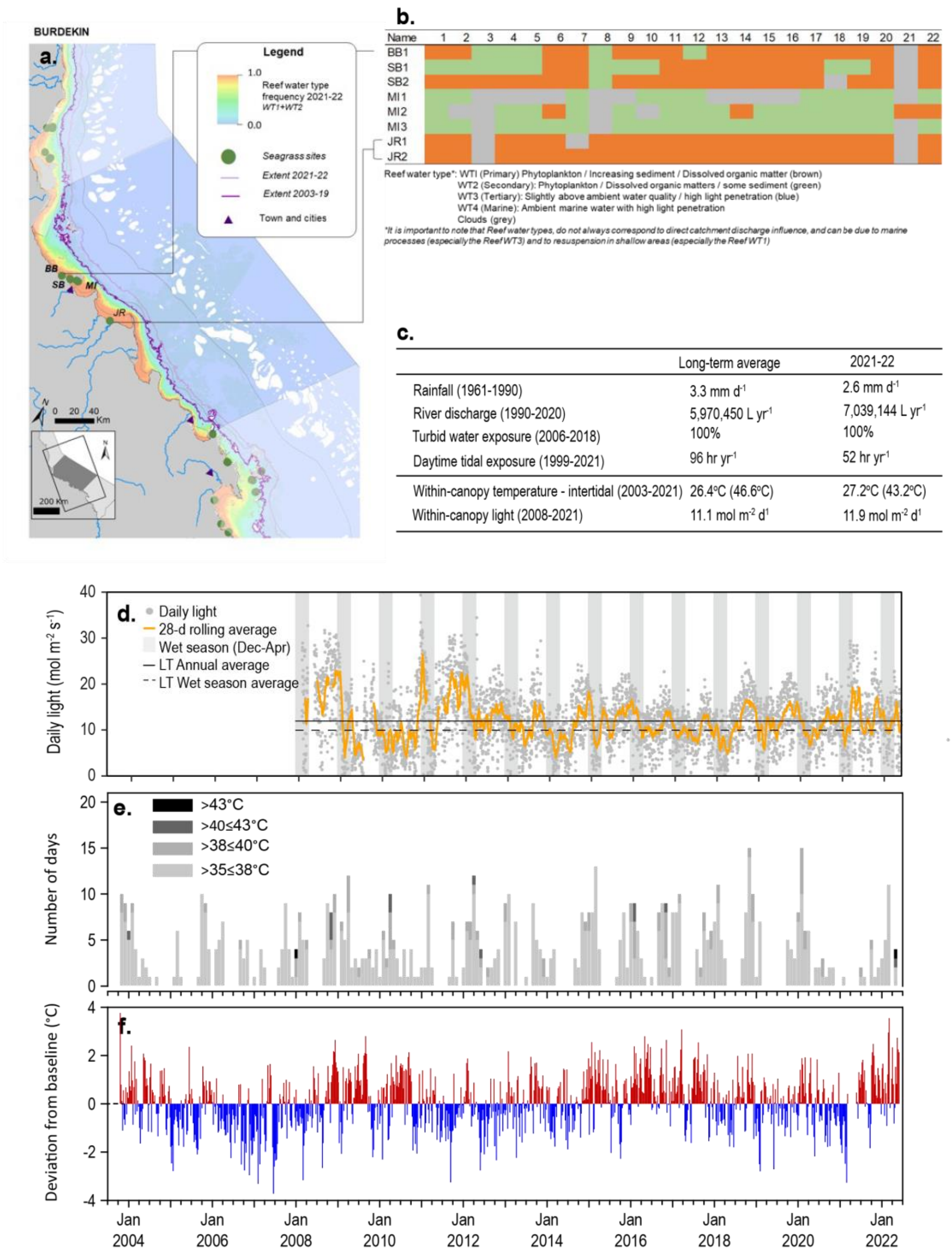


Figure 51. Environmental pressures in the Burdekin region including: a. frequency of exposure to primary and secondary water from December 2021 to April 2022 ranging from frequency of 1 (orange, always exposed) to 0 (pale blue, never exposed) (white = no data), also showing the long-term average (2003–2018) exposure boundary (purple line), and the first (blue line) and third quartile (white line) of the long-term average (from Moran *et al.* 2023); b. wet season water type at each site; c. average conditions and max temperature over the long-term and in 2021–22; 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 13-year mean weekly temperature records at intertidal sites.

5.3.3 Inshore seagrass and habitat condition

Three seagrass habitat types were assessed across the Burdekin region in 2021–22, with data from 10 sites (Table 15, Table 20).

Table 15. List of data sources of seagrass and environmental condition indicators for each seagrass habitat type in the Burdekin NRM region. Blank cell indicates data not usually collected/measured at site *Seagrass-Watch. For site details see Table 5 and Table 6.

Habitat	Site code and location		abundance	composition	distribution	reproductive effort	seed banks	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 2021–22 monitoring period, the seagrass condition index for the Burdekin region was unchanged and remained **moderate** (Figure 50). The grade continued to appear a legacy of the previous monitoring periods, which were influenced by region-wide above average wet season rainfall and river discharge in early 2019, and have carried into the 2021–22 reporting period. The seagrass Index in the Burdekin NRM is highly variable and it responds rapidly to changing pressures. It is the only region to have scores that varied from good to very poor since monitoring began in 2005.

Both indicators changed little in 2021–22 compared to the previous year. Abundance increased and resilience deceased slightly, contributing to an overall steady score. Examination of the indicators 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 habitats in 2021–22 would appear to be improving overall, but some sites remain well below historical maxima (Figure 52). Furthermore, reef intertidal sites have low resilience.

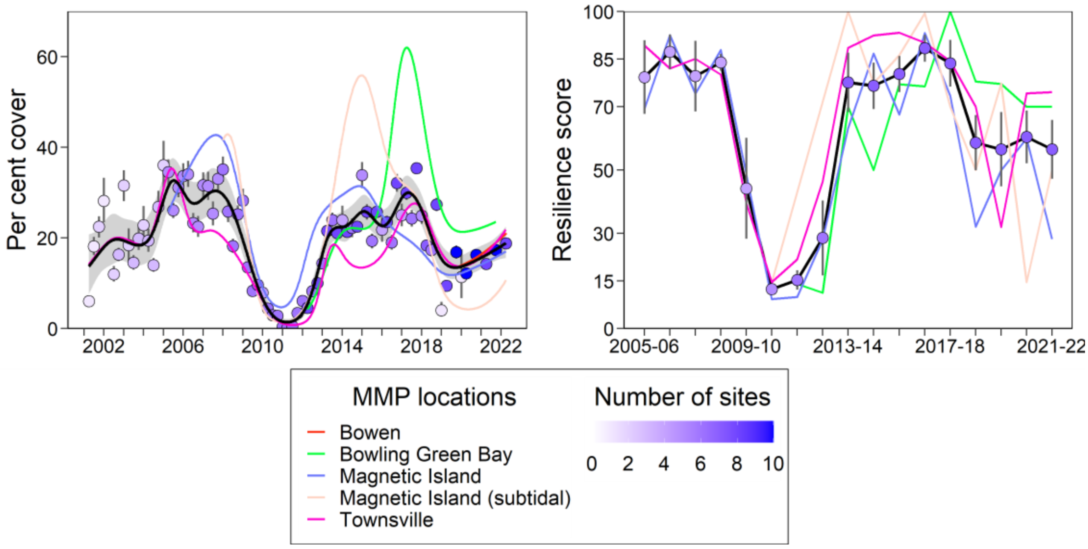


Figure 52. Temporal trends in the Burdekin seagrass indicators used to calculate the seagrass condition index: a. average (circles, ±SE) seasonal abundance (per cent cover) and GAM plots of seagrass abundance trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); b. average annual resilience score (±SE) and trends for each location (coloured lines). Colour of circles represents the number of sites assessed to calculate the average.

5.3.3.2 Seagrass abundance, composition and extent

Seagrass abundance in the Burdekin region has shown a pattern of loss and recovery over the duration of the MMP. 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, recovery has varied between habitats, with seagrass abundance progressively declining at reef (intertidal and subtidal) habitats since 2015. In 2017–18, coastal habitats increased to their highest abundance since 2001, immediately followed by large declines in 2018–19. Declines in abundances occurred across the region in 2018–19, with the largest losses in reef subtidal and coastal intertidal habitats. The onset of recovery occurred in coastal habitats within 12 to 18 months, with abundances continuing to improve in 2021–22 to above the long-term average for the first time in 3 years. Recovery at reef habitats has been more protracted, with little change in intertidal abundances over the last 5 years, and only a moderate improvement in subtidal abundances in 2021–22 for the first time in 3 years.

An examination of the long-term abundances across the Burdekin region indicates no significant regional trend (from first measure to 2021–22), although significant trends were detected at one of the coastal sites and one of the reef intertidal sites. The coastal site (JR2), near Jerona (Barratta Ck, Bowling Green Bay), has been monitored for nearly a decade, and predictably showed a significant increasing trend in abundance, as this coincides with the main recovery period after the 2010–11 regional losses. A significant long-term decline has occurred at Cockle Bay, Magnetic Island (reef intertidal, MI2) since monitoring began in 2005 (Table 22).

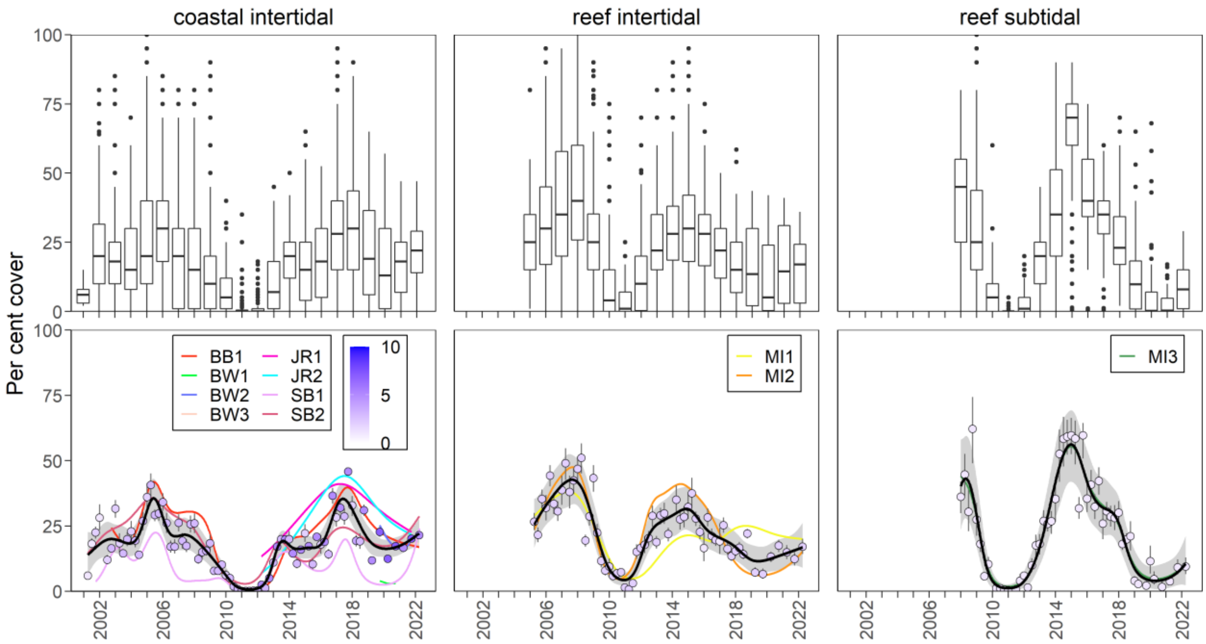


Figure 53. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the Burdekin NRM region from 2001 to 2022. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero indicates 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. GAM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

This year was the second year since 2014, that the proportion of species displaying colonising traits (e.g. *H. ovalis*) increased above the Reef long-term average at reef intertidal habitats in the region (Figure 54). The intertidal reef habitat at Cockle Bay (MI2) has been dominated by *Halophila ovalis* since early 2019 when the location was severely impacted by floodwaters. Colonising species are important for recovery following loss (Kilminster *et al.* 2015), however, the increased proportion of colonising species suggests some level of localised disturbance which is delaying recovery. Conversely, coastal and reef subtidal habitats remained dominated by opportunistic species (*H. uninervis, Z. muelleri, C. serrulata*). Opportunistic foundation species have a capacity to resist stress (survive, through reallocation of resources) caused by acute disturbances (Collier *et al.* 2012b), and therefore, current species composition in coastal and reef subtidal habitats provides greater overall resilience in Burdekin meadows.

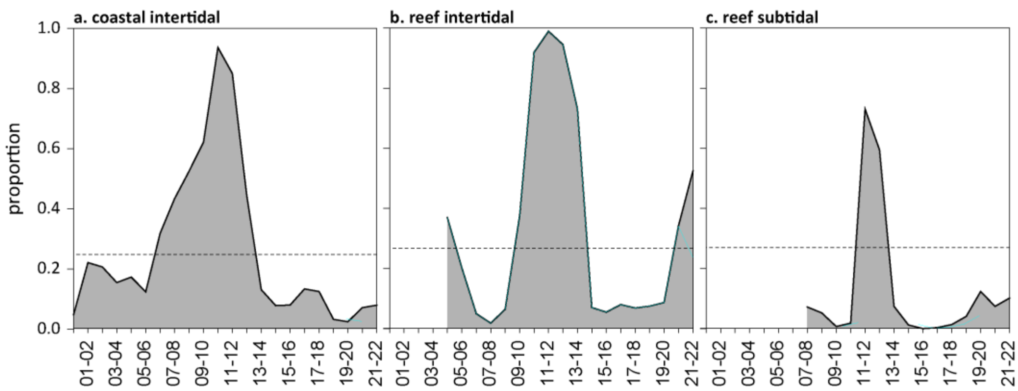


Figure 54. Proportion of seagrass abundance composed of colonising species at inshore habitats in the Burdekin region, 2001 to 2022. Dashed line represents Reef long-term average proportion of colonising species for each habitat type.

Meadow spatial extent continued to improve slightly in 2021-22 from the lowest level recorded in reef subtidal habitats in early 2020, towards extents prior the flood events in early 2019 (Figure 55). Intertidal meadows at coastal and reef sites changed little over the last 12 months, relative to the previous reporting period (Figure 55).

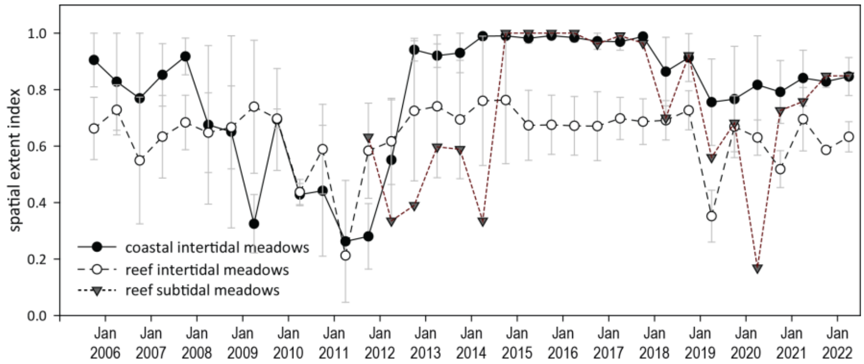


Figure 55. Change in spatial extent (± SE) of seagrass meadows within monitoring sites for each inshore intertidal habitat and monitoring period across the Burdekin region, 2005–2022.

5.3.3.3 *Seagrass reproductive status*

Over the long-term, reproductive effort has been 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 56). There was little change in overall reproductive effort in 2021–22 relative to the previous period or across coastal and reef intertidal habitats, with both remaining below the long-term average for the third consecutive year. Seed banks persisted across the region in 2021–22, however, seed densities greatly increased in coastal habitats (Figure 56a) while remaining relatively stable in reef habitats. Low reproductive effort in reef habitats will hinder replenishment of reduced seed banks, and seed banks are therefore likely to remain low in coming years. This may limit the capacity of meadows to recover from seed should reproductive effort and seeds banks continue to decline.

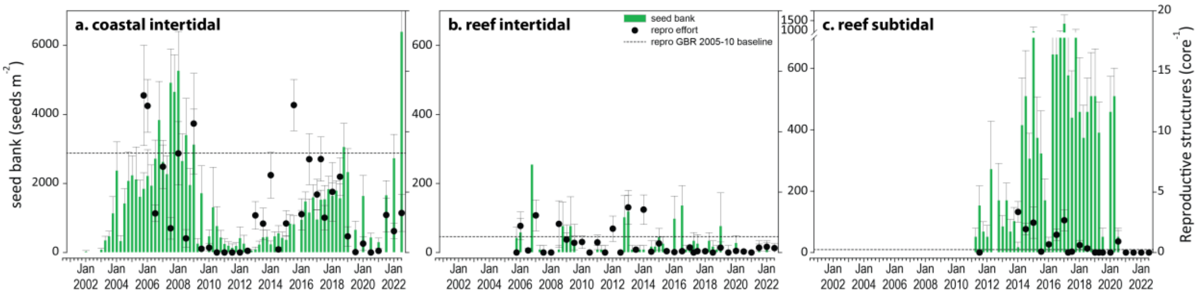


Figure 56. Seedbank and reproductive effort at inshore coastal intertidal and reef subtidal and intertidal habitats in the Burdekin region. Seed bank presented as the total number of seeds per m^2 sediment surface (green bars ±SE). Reproductive effort for the late dry season and late wet season presented 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 *Resilience*

The overall resilience score for the Burdekin was moderate, with large variability between habitats (Figure 57). At coastal intertidal sites, the resilience score was stable and high. Seagrass condition exceeded abundance and composition thresholds. At coastal sites there were reproductive structures present, but at low levels compared to historical levels so the resilience score was in the low range for sites meeting these criteria. At reef intertidal sites the resilience score declined. At MI2 colonising species dominated the habitat (85% of total cover) for the first time since 2012–13. This was not the case at MI1 but there were no reproductive structures present.

At the reef subtidal site the resilience score improved in 2021–22 from being very low in the previous period (Figure 57). Abundance increased to be above the per cent cover threshold. There were no reproductive structure present, but there had been within the previous three years.

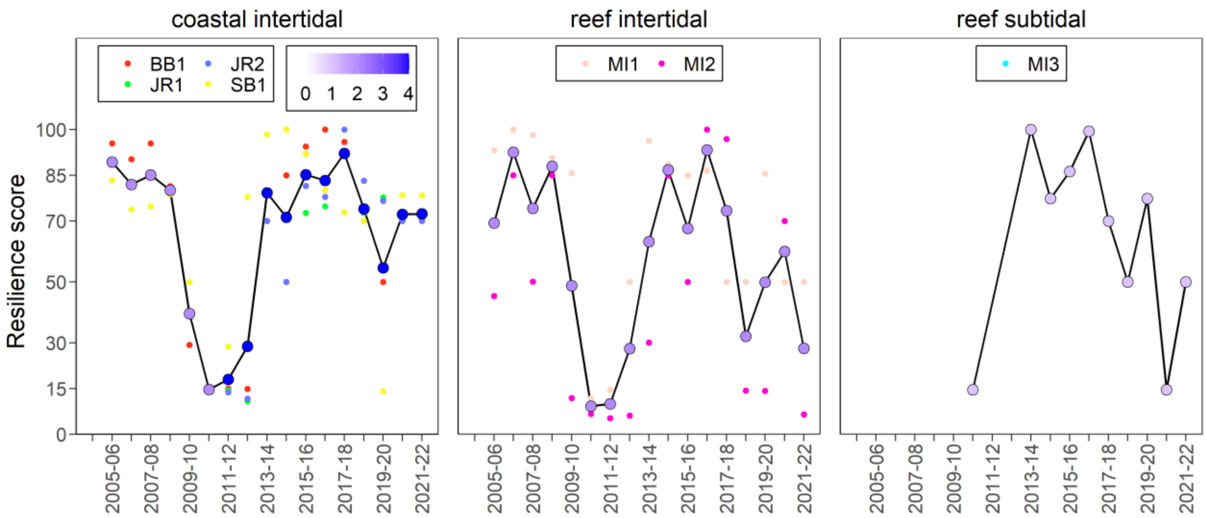


Figure 57. Resilience score in each habitat in the Burdekin, 2006 to 2022. Coloured small points represent different sites. Shades of blue for the larger points indicate the number of sites that contribute to the score.

5.3.3.5 Epiphytes and macroalgae

Epiphyte cover on seagrass leaf blades in 2021–22 was similar to the previous period, with increased abundance during the late dry, followed by declines in the late wet slightly lower at coastal meadows (Figure 58a). At reef habitats, cover varied, remaining above and below the inshore Reef average at intertidal and subtidal meadows, respectively (Figure 58c, e). Conversely, macroalgae abundance in 2020–21 remained low and below the long-term average for the second consecutive year across the region at all seagrass habitats (Figure 58).

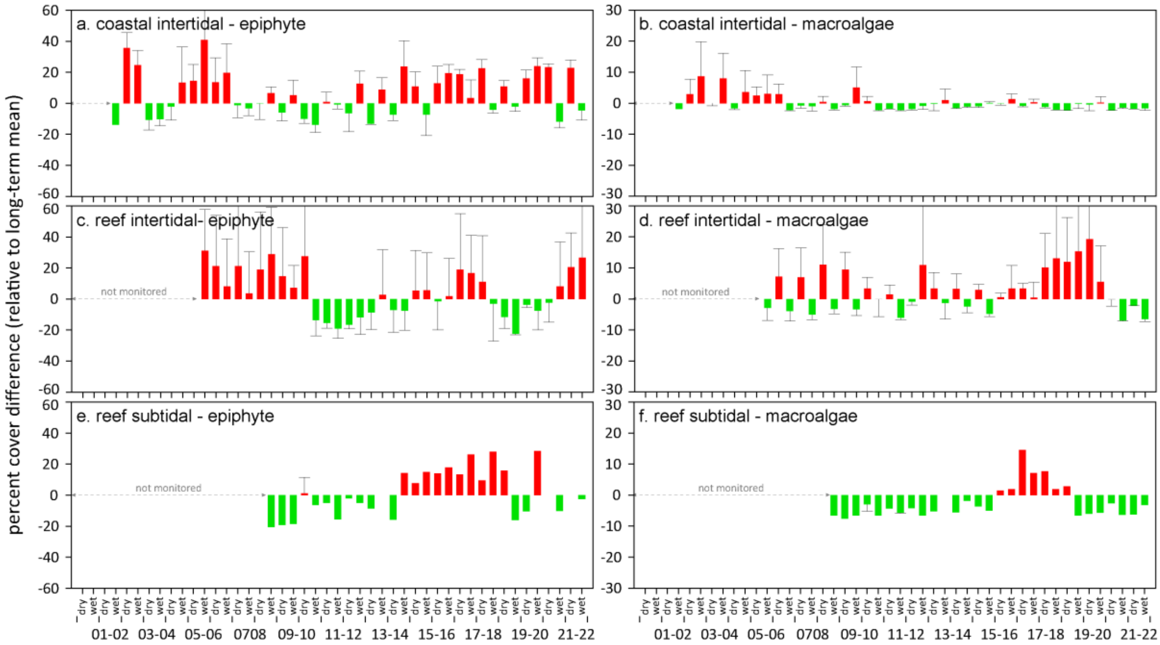


Figure 58. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term Reef average for each inshore seagrass habitat in the Burdekin region (sites pooled, ±SE).

5.4 Mackay–Whitsunday

5.4.1 2021–22 Summary

The 2021–22 monitoring period in the Mackay–Whitsunday region was relatively benign with environmental pressures around or below the long-term averages. It was characterised by wet season rainfall, annual discharge and turbid water exposure that was below the long-term average and daily light levels were higher than average (Figure 6, Table 11, Figure 51). Within-canopy temperature was 0.6°C above the long-term average.

Inshore seagrass meadows across the Mackay–Whitsunday NRM region improved in overall condition in 2021–22, and the condition grade increased to **moderate** (Figure 59). There was a small decline in both indicators. Indicators for the overall condition score were:

- abundance score was poor
- resilience was moderate.

Seagrass condition in the Mackay–Whitsundays has fluctuated between poor and moderate since 2011–12 which appears to be due to a range of environmental pressures.

The seagrass abundance score decreased slightly again in 2021–22, with losses at 40 per cent of sites relative to the previous period. There were small increases and small declines in abundance at sites within all habitat types, with overall declines in coastal intertidal and reef subtidal habitats on average.

The overall resilience score for the Mackay–Whitsunday region was moderate following a substantial improvement from poor in 2020–21. There were no sites where the resilience score declined in 2020–21, but there were increases at several sites. There were large improvements in resilience at reef intertidal habitat where reproductive structures were observed for the first time and also at subtidal habitats. Coastal habitats also improved slightly at Midge Point. Despite these improvements in the resilience score, seed banks declined to the lowest levels since 2010–11 at estuarine sites, since 2013–14 in coastal habitats and remained absent in reef habitats.

Up until 2016–17, the Mackay–Whitsunday regional seagrass condition had been improving from 2010–2011, when it reached its lowest level since monitoring commenced. After this time, the recovery trend abated and dropped to poor, as a consequence of cyclone Debbie in March 2017. Since then, the Index has fluctuated between poor and moderate with recovery not occurring across the region. When abundances increase, they have not persisted in most habitats. The exception is at reef intertidal habitats where abundance has been steadily rising since 2016–17. Overall, the long-term trend indicates that seagrass habitats in the region are failing to recover from past disturbances due to localised pressures and chronic changes but are not easily identifiable in all sites and habitats.

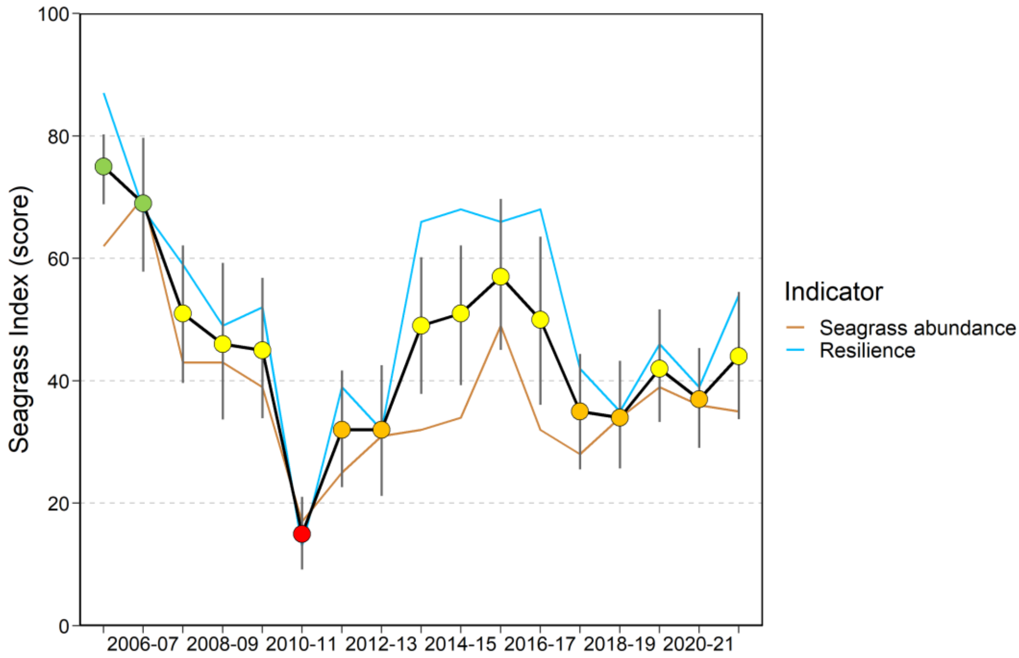


Figure 59. Report card of seagrass status indicators and index for the Mackay–Whitsunday NRM region (averages across habitats and sites). Values are indexed scores scaled from 0–100 (± SE) and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

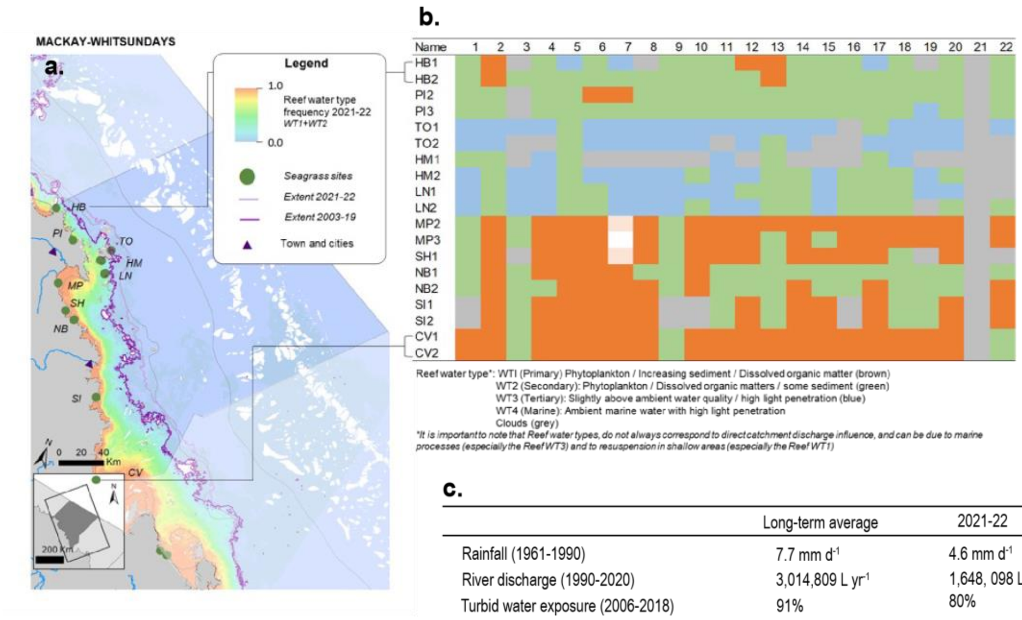
5.4.2 Climate and environmental pressures

Environmental conditions were relatively favourable for seagrasses in the Mackay–Whitsunday region in 2021–22. There were no cyclones to affect the region and rainfall and river discharge were also well below the long-term average for the third year in a row.

Exposure of inshore seagrass to turbid waters during the wet season were below the long-term average (Figure 60a, c). Exposure to either water type I or II was also variable among seagrass habitats (Figure 60b). Estuarine and coastal sites from Midge Point and south were not only exposed to turbid waters for the entire wet season, but were also exposed to primary waters for most of the wet season. North of Midge Point where reef habitats fringing the mainland (HB1 and HB2) and on offshore islands (HM1 and HM2, LN1 and LN2) are the dominant habitats surveyed, they were exposed to lower levels of turbid water, and predominantly water type II which is less turbid (Figure 8, Figure 60b).

Daily light was higher than the long-term average combined within the region (Figure 8, Figure 60c, Figure 102). At Lindeman Island (LI3) light has only been measured for two years and daily light was much higher in 2021–22 (13.6 mol m^{-2} d^{-1}) than the previous year (9.1 mol m^{-2} d^{-1}). At Sarina Inlet and Midge Point, daily light was around the long-term average (Figure 102).

The 2021–22 reporting period was the ninth consecutive year when intertidal within-canopy temperatures were above the long-term average (Figure 60c,f). Maximum intertidal within-canopy temperatures exceeded 35°C for a total of 42 days during 2021–22, with 4 days experiencing temperatures above 40°C and the highest at 41.3°C (SI2, 07Jan22) (Figure 60e, f). Daytime tidal exposure was similar to the long-term average in 2021–22 at all habitats and below the previous three reporting periods at estuarine habitats (Figure 60c, Figure 95), which may have provided some respite from desiccation stresses at these intertidal sites.



c.

	Long-term average	2021-22
Rainfall (1961-1990)	7.7 mm d^{-1}	4.6 mm d^{-1}
River discharge (1990-2020)	3,014,809 L yr^{-1}	1,648, 098 L yr^{-1}
Turbid water exposure (2006-2018)	91%	80%
Daytime tidal exposure (1999-2021)	49 hr yr^{-1}	76 hr yr^{-1}
Within-canopy temperature - intertidal (2003-2021)	25.4°C (42.7°C)	26.0°C (41.3°C)
Within-canopy light (2010-2021)	12.5 mol m^{-2} d^{1}	13.5 mol m^{-2} d^{1}

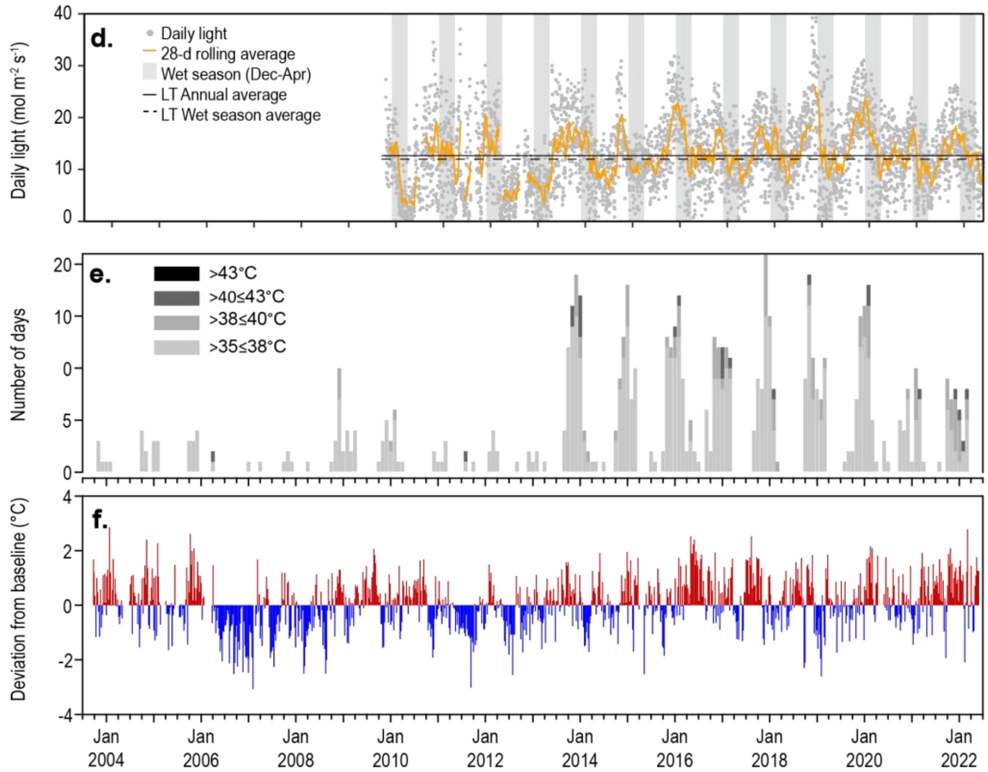


Figure 60. Environmental pressures in the Mackay–Whitsunday NRM region including: a. frequency of exposure to primary and secondary water from December 2021 to April 2022 ranging from frequency of 1 (orange, always exposed) to 0 (pale blue, never exposed) (white = no data), also showing the long-term average (2003–2018) exposure boundary (purple line), and the first (blue line) and third quartile (white line) of the long-term average (from Moran *et al.* 2023); b. wet season water type at each site; c. average conditions and max temperature over the long-term and in 2020–21; 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 at intertidal sites.

The proportion of fine grain sizes (fine sand and mud) increased in the sediments of estuarine and coastal seagrass monitoring sites in 2021–22, relative to the previous period

(Figure 113). Although the proportion of mud in estuarine sediments increased, it continued to remain below the overall inshore Reef long-term average. In comparison, the proportion of mud has varied across coastal habitats, fluctuating over the long-term within and between both meadows and years, while remaining above the long-term average at most sites (Figure 114). The proportion of fine grain sizes decreased in the sediments of the seagrass monitoring sites with distance from the coast, with reef habitats being composed predominately of fine to medium sand, with little change in 2021–22 relative to the previous period (Figure 115).

5.4.3 Inshore seagrass and habitat condition

Five seagrass habitat types were assessed across the Mackay–Whitsunday region this year, with data from 22 sites (Table 16, Table 20).

Table 16. List of data sources of seagrass and environmental condition indicators for each seagrass habitat type in the Mackay–Whitsunday NRM region. Blank cells indicate data not usually collected/measured at site. † drop camera sampling (QPWS), *Seagrass-Watch. For site details see Table 5 and Table 6.

Habitat	Site		abundance	composition	distribution	reproductive effort	seed banks	meadow sediments	epiphytes	macroalgae
estuarine 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	CH4†	Cid Harbour	■	■					■	■
	CH5†	Cid Harbour	■	■					■	■
	LN1	Lindeman Is	■	■	■	■		■	■	■
	TO1†	Tongue Bay	■	■					■	■
	TO2†	Tongue Bay	■	■					■	■
	WB1†	Whitehaven Bch	■	■					■	■
	WB2†	Whitehaven Bch	■	■					■	■

5.4.3.1 Seagrass index and indicator scores

In the 2021–22 monitoring period, the Mackay–Whitsunday region seagrass condition index increased from the previous year, increasing back to a **moderate** grading (Figure 61).

The improvement was due to a rise in the resilience score which also increased from poor to moderate, driven by large increases in reef habitats. By contrast, the abundance score remained poor, with variations in abundance trends among habitats and sites.

The Index has been varying between poor and moderate since 2011–12 when it recovered from the impacts of the 2010–11 extreme weather events. In 2016–17 the improving trend abated and abundance declined as a consequence of Tropical cyclone Debbie (Figure 61). The following year both abundance and resilience declined, and in 2018–19 reached its lowest level since 2012–13, driven by declining resilience. Despite generally moderate environmental conditions, the seagrass Index has not been on a consistently improving trajectory. However, the rise in resilience score is appositive sign that with moderate environmental conditions further recovery may be possible.

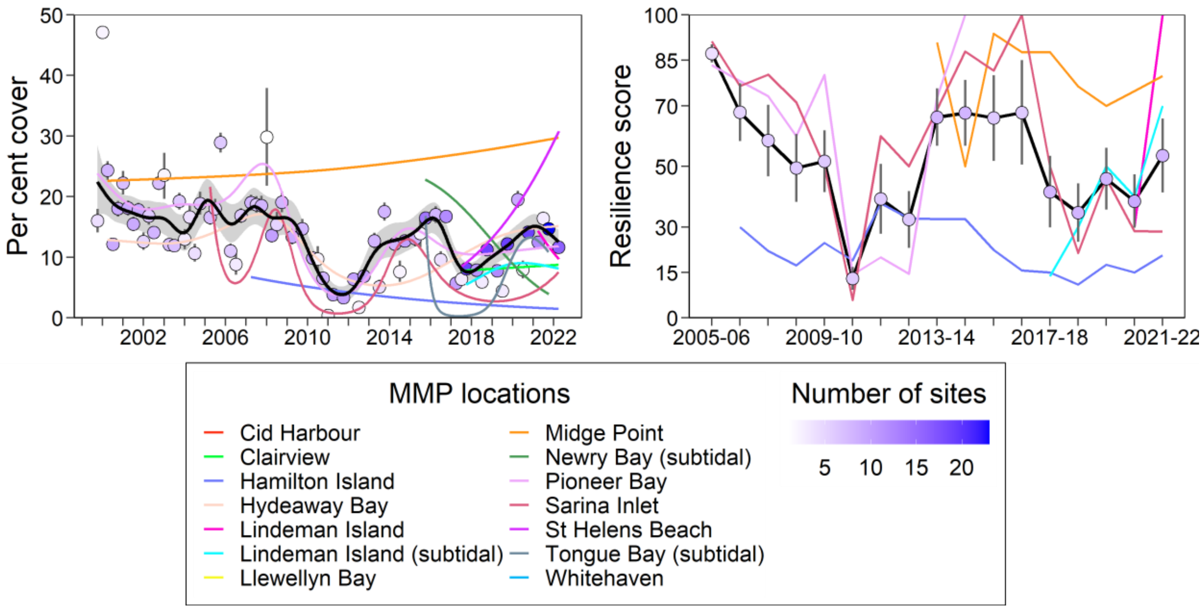


Figure 61. Temporal trends in the Mackay–Whitsunday seagrass indicators used to calculate the seagrass condition index: a. average (circles, ±SE) seasonal abundance (per cent cover) and GAM plots of seagrass abundance trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); b. average annual resilience score (±SE) and trends for each location (coloured lines). Colour of circles represents the number of sites assessed to calculate the average.

5.4.3.2 Seagrass abundance, community and extent

Overall, seagrass abundance changed little in the Mackay–Whitsunday region in 2021–22, with minor declines in some habitats offset by minor gains in others (Figure 62). Estuary habitats continued to improve for the third consecutive year, after declines between 2017 and 2019, and subtidal coastal habitats improved from losses in the previous reporting period. Intertidal coast and reef habitats have remained relatively unchanged. The only losses in 2021–22 were observed in the subtidal reef habitats at Tongue Bay and Lindeman Island (Figure 62).

Seagrass abundance (per cent cover) in the Mackay–Whitsunday region in 2021–22 was higher in coastal habitats (intertidal = 20.6 ±1.1 per cent, subtidal = 8.0 ±2.7 per cent) than reef (intertidal = 8.7 ±1.1 per cent, subtidal = 6.3 ±1.0 per cent) or estuarine habitats (6.4 ±1.6 per cent), respectively. Seagrass per cent cover continued to differ seasonally in estuarine meadows over 2020–21, being higher in the late dry than late monsoon (11.1 ±2.3 per cent, and 4.3 ±1.0per cent, respectively). Little or no change was detected between seasons in all other habitats within 2020–21 (Figure 62).

Seagrass abundance at estuarine and coastal 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 62). The regional long-term trend continues to indicate a declining trajectory (Table 22), with habitats on the verge of recovering from repeated losses over the last decade.

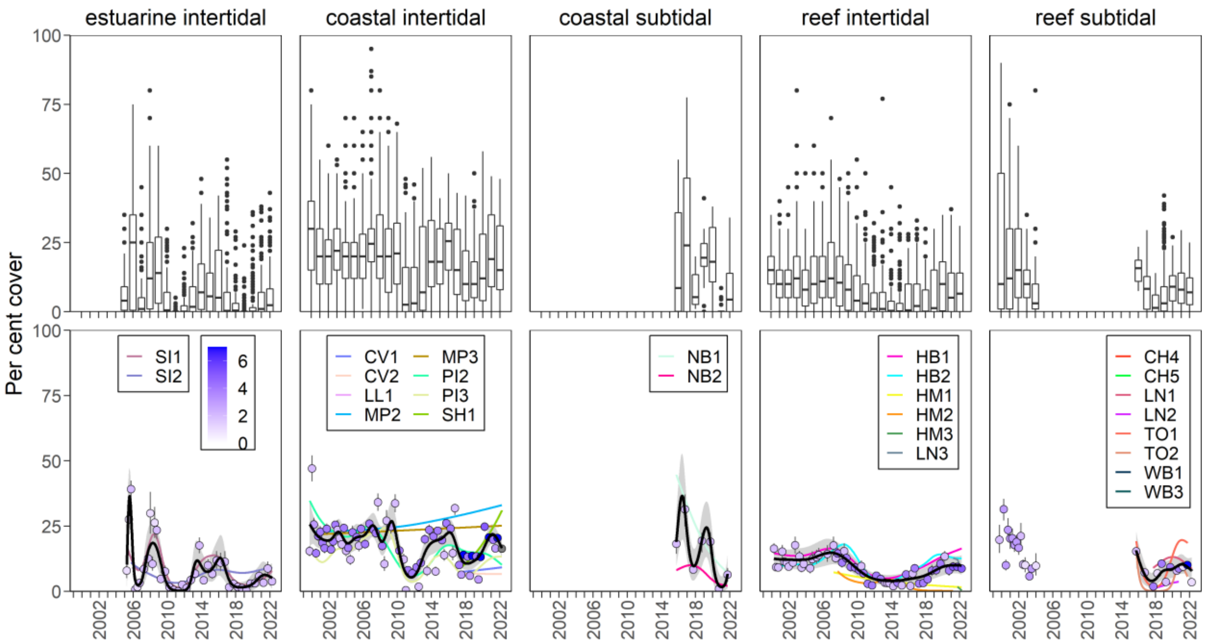


Figure 62. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the Mackay–Whitsunday NRM region from 1999 to 2022. Whisker plots (top) show thee box representing the interquartile range of values, where the boundary of the box closest to zero 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. GAM 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 *H. uninervis* and *Z. muelleri*, mixed with the colonising species *H. ovalis*. Colonising species tend to dominate intertidal meadows across the Mackay–Whitsunday region in the first few years following extreme weather events (e.g. 2011 and 2017), however, there can be differences between habitats. Estuarine habitats can fluctuate greatly between and within years, and in the last couple of years the proportion of colonisers have been above the Reef long-term average (Figure 63). Coastal subtidal habitats have only been monitored over the last five years, but they are currently dominated by colonising species. These increases suggest some level of localised disturbance in these habitats.

In contrast, over the last few years, there has been a reduction in colonising species in intertidal coastal and reef habitats. With the exception of coastal subtidal, opportunistic foundational species (*H. uninervis* and *Z. muelleri*) now dominate habitats across the region (Figure 63), suggesting meadows may have an improved ecosystem resistance to tolerate disturbances (Figure 63).

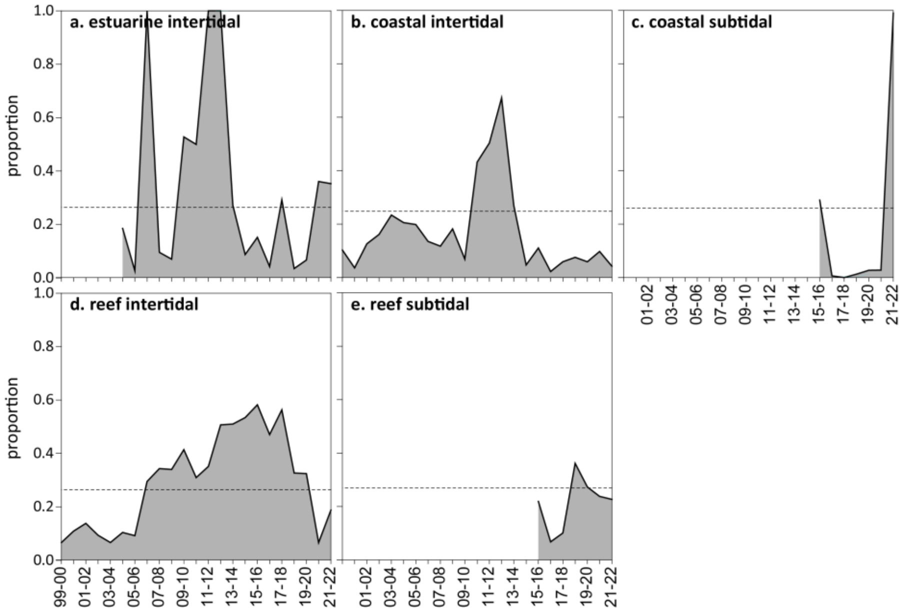


Figure 63. Proportion of seagrass abundance composed of colonising species at inshore intertidal habitats in the Mackay–Whitsunday region, 1999 to 2022. Dashed line represents Reef long-term average proportion of colonising species for each habitat type.

Seagrass meadow landscape mapping was conducted within all sentinel monitoring sites in October 2021 and the majority of sites in April 2022 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 continued to improve at across the region, although there were seasonal declines in the late wet, particularly in estuarine habitats. At coastal meadows, extent remained steady, with only slight increases relative to the previous period (Figure 64).

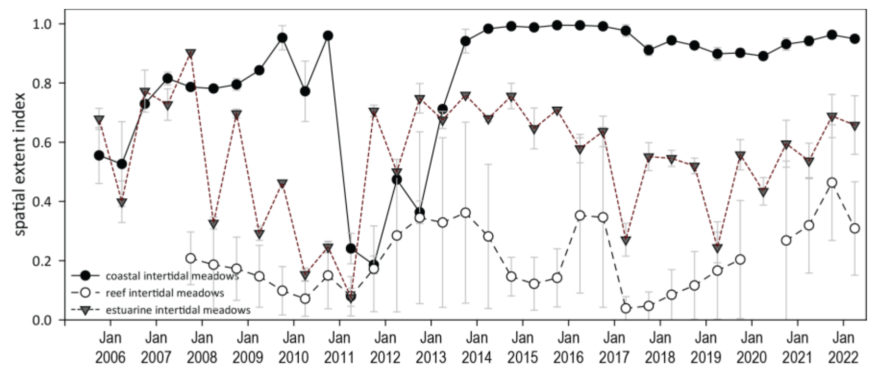


Figure 64. Change in spatial extent (± SE) of seagrass meadows within monitoring sites for each inshore intertidal habitat and monitoring period across the Mackay–Whitsunday NRM region.

5.4.3.3 Seagrass reproductive status

Reproductive effort remained highly seasonal and highly variable between years and seagrass habitats in the Mackay–Whitsunday region, changing little overall in 2020–21 relative to the previous period (Figure 65). Reproductive effort marginally increased while remaining below the long-term average and seed banks declined slightly in coastal habitats, relative to the previous period. At the estuarine meadow (Sarina Inlet), sexual reproductive structures were not observed for the second consecutive year, however seed banks have persisted with a marginal decline in 2021–22. No reproductive structures or a seed bank were reported at intertidal reef sites in 2021–22, indicating the loss of the above-average seed bank in the previous year (Figure 65).

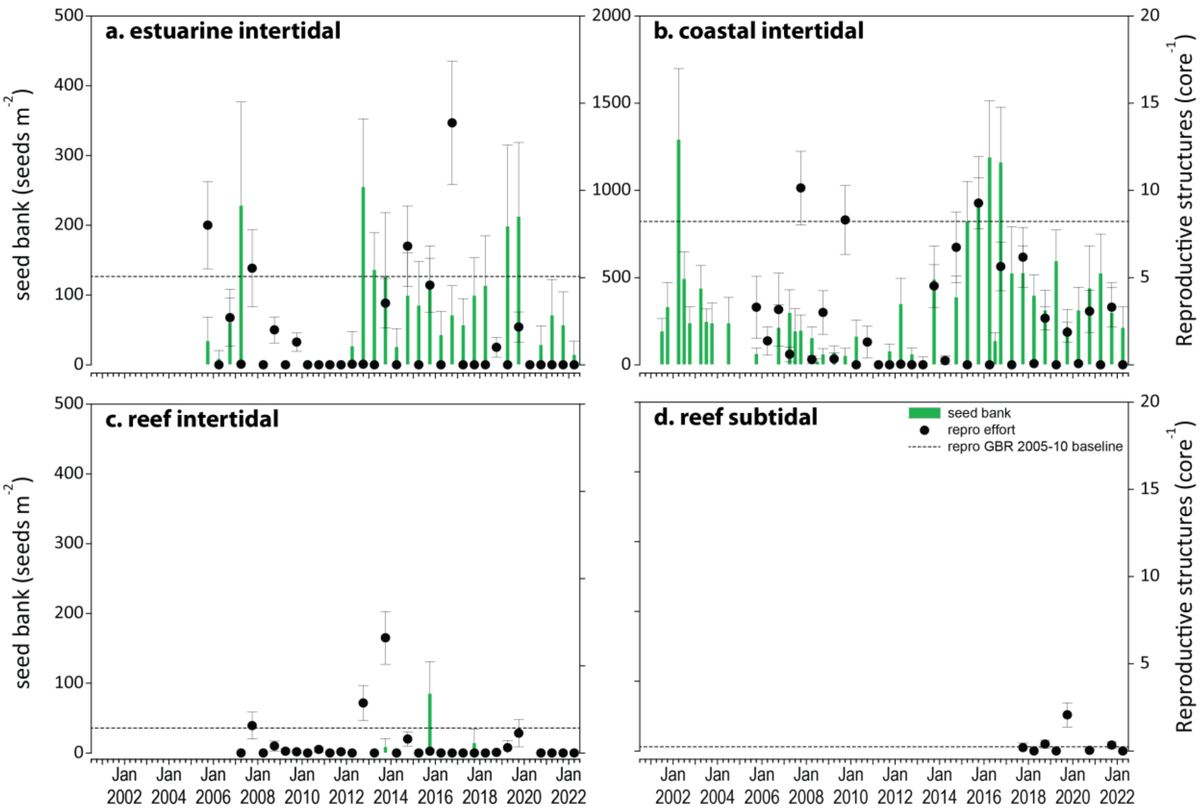


Figure 65. Seed bank and reproductive effort at inshore estuarine intertidal, coastal intertidal and reef intertidal and subtidal habitats in the Mackay–Whitsunday region, 2001–2022. Seed bank presented as the total number of seeds per m² sediment surface (green bars ±SE), and late dry season reproductive 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 Resilience

The overall resilience score for the Mackay–Whitsunday region was moderate and reached its highest level in five years but still below the good scores from 2013–14 to 2016–17 (Figure 66). In estuarine habitat at Sarina Inlet, resilience stayed low and the score was unchanged from the previous year. At SI1, the species composition continues to be dominated by colonising species *H. ovalis* placing it into the lowest resilience category. At SI2, the cover and composition is slightly better and therefore is in category two. There were no reproductive structures of foundational species this year or last year, but there were some in the year prior.

Resilience was high and slightly improved at coastal sites due to an increase in the number of reproductive structures. The largest changes were at reef sites, both intertidal and subtidal, where improvements in resilience at Lindeman Island led to large increases in the scores of both habitat types. At both the intertidal site at LN3 and subtidal site at LN1, there was a reproductive structure of foundational species. This is very rare in reef habitats in the region and was the highest count for the intertidal site leading the maximum score, but it wasn't the first time this was observed at the subtidal site so the score was not as elevated.

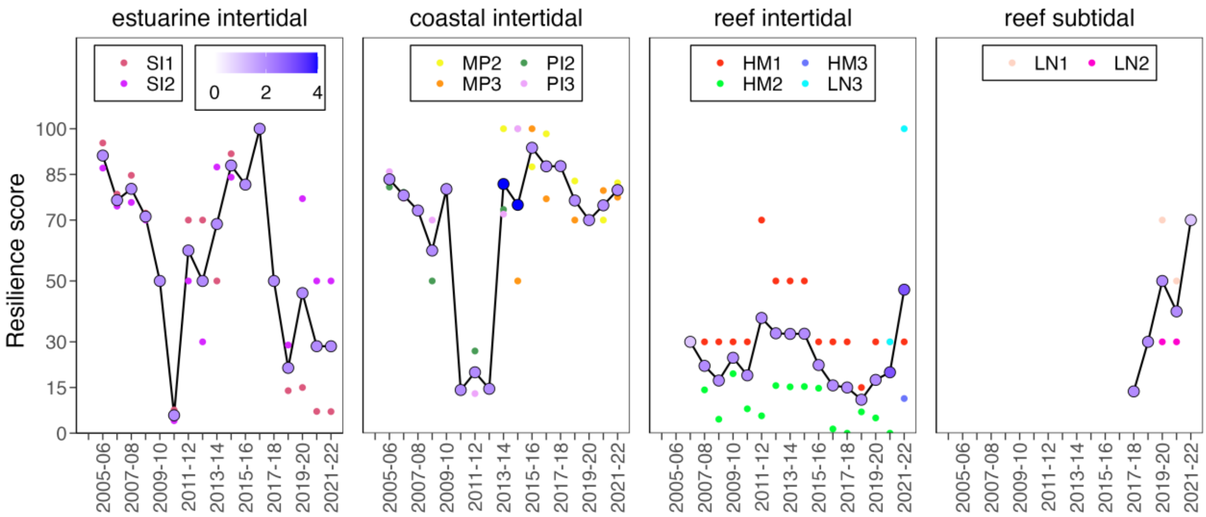


Figure 66. Resilience for each habitat type in the Mackay–Whitsunday region, 2006 to 2022. Coloured small points represent different sites. Shades of blue for the larger points indicate the number of sites that contribute to the score.

5.4.3.5 Epiphytes and macroalgae

Epiphyte cover on seagrass leaf blades in 2021–22 varied between the dry and wet seasons at all habitats, except coastal, falling above and below the overall inshore Reef long-term averages, respectively (Figure 67). At coastal habitats, epiphyte cover remained remained below the long-term average (Figure 67c).

Percentage cover of macroalgae remained unchanged, at or below the overall inshore Reef long-term average for intertidal habitats throughout 2021–22 (Figure 67). At subtidal habitats, macroalgae cover remained predominately above the Reef long-term average and increased slightly at coastal habitats (Figure 67).

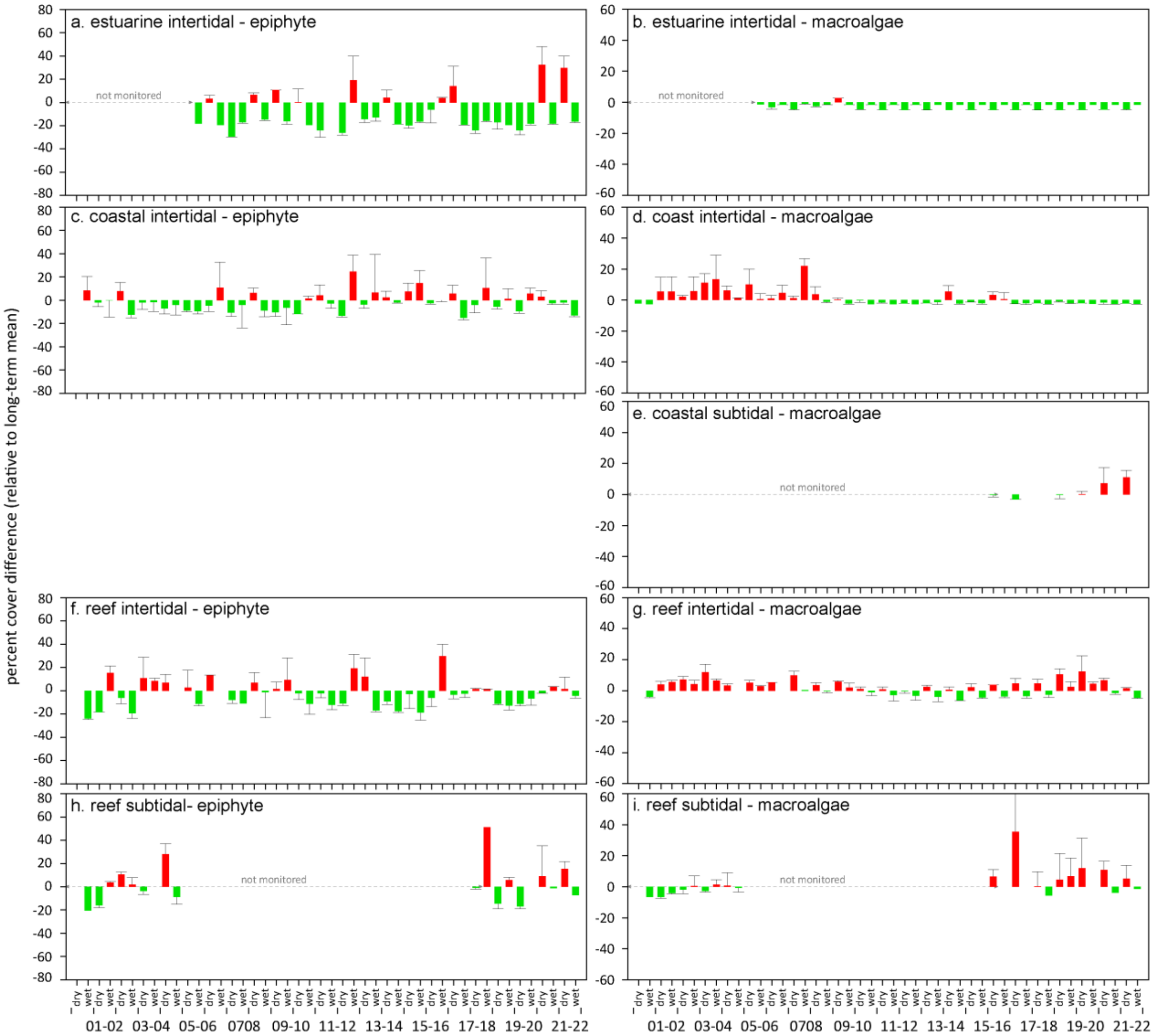


Figure 67. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term average for each inshore intertidal habitat in the Mackay–Whitsunday region, 1999–2022 (sites pooled, ±SE).

5.5 Fitzroy

5.5.1 2021–22 Summary

Environmental conditions were challenging in 2021–22. River discharge from the Fitzroy River in 2021–22 was more than 1.5 times the annual median and exposure to turbid water (water types I and II) was above the long-term average. Daily light levels were also lower than average. Average annual water temperature was higher than average and the maximum recorded temperature (42.7°C, was close to highest for the region (42.9°C) and a further 49 days between 35 and 40°C. The Fitzroy is surveyed in the late dry season before the wet season and therefore the seagrass condition Index reflects a legacy of the environmental conditions in the previous year, which were more benign.

Overall, the seagrass condition score for the Fitzroy NRM region reduced and remained **poor** in 2021–22 (Figure 68). Both indicators declined:

- abundance score was very poor
- resilience was poor.

Seagrass abundance declined at all locations and habitats on average across the Fitzroy region in 2021–22, but there were increases in abundance at two sites. The largest declines were in the coastal habitats in Shoalwater Bay. Extent of habitat declined to the lowest level on record at the estuarine sites in Gladstone Harbour and abundance declined slightly. Abundances remain very low at the reef intertidal sites, however there was an increase in the proportion of *H. univervis*, a foundational species, to the highest level on record.

Overall resilience in the Fitzroy region was poor but the trend varied among habitats and sites. Resilience declined slightly in estuarine habitat in Gladstone. At coastal habitats, resilience declined sharply at one site, but increased at the other to the highest level in 12 years due to an increase in reproductive effort. In reef intertidal habitat, resilience increased to the highest level in 13 years at one site due to an improvement in species composition, but declined at the other.

Inshore seagrass meadows across the region continue to decline for the second year in a row, after what had been gradual recovery over 2012–13 to 2019–20 from multiple years of climate related impacts which, similar to Mackay–Whitsunday, are more recent than in other regions. There are local-scale impacts and process that are driving declines in indicators at some sites, while the other within the same habitat improves. The Fitzroy region also has the fewest number of sites, and so changes in one sites, can have a greater influence on the score compared to other regions.

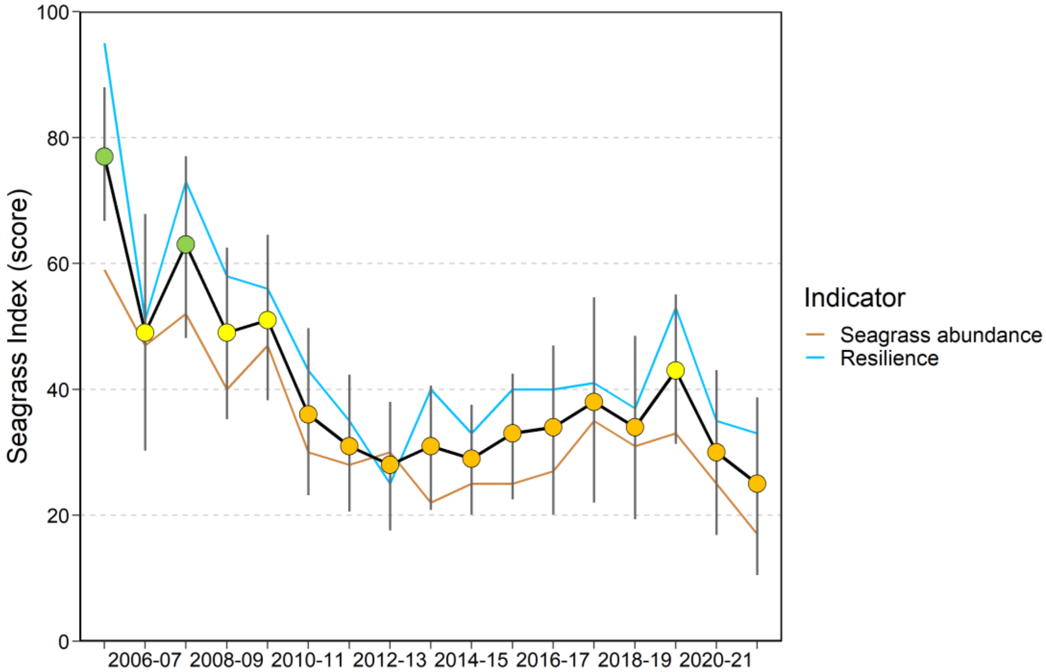


Figure 68. Report card of seagrass status index and indicators for the Fitzroy NRM region (averages across habitats and sites). Values are indexed scores scaled from 0–100 (± SE) and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

5.5.2 Climate and environmental pressures

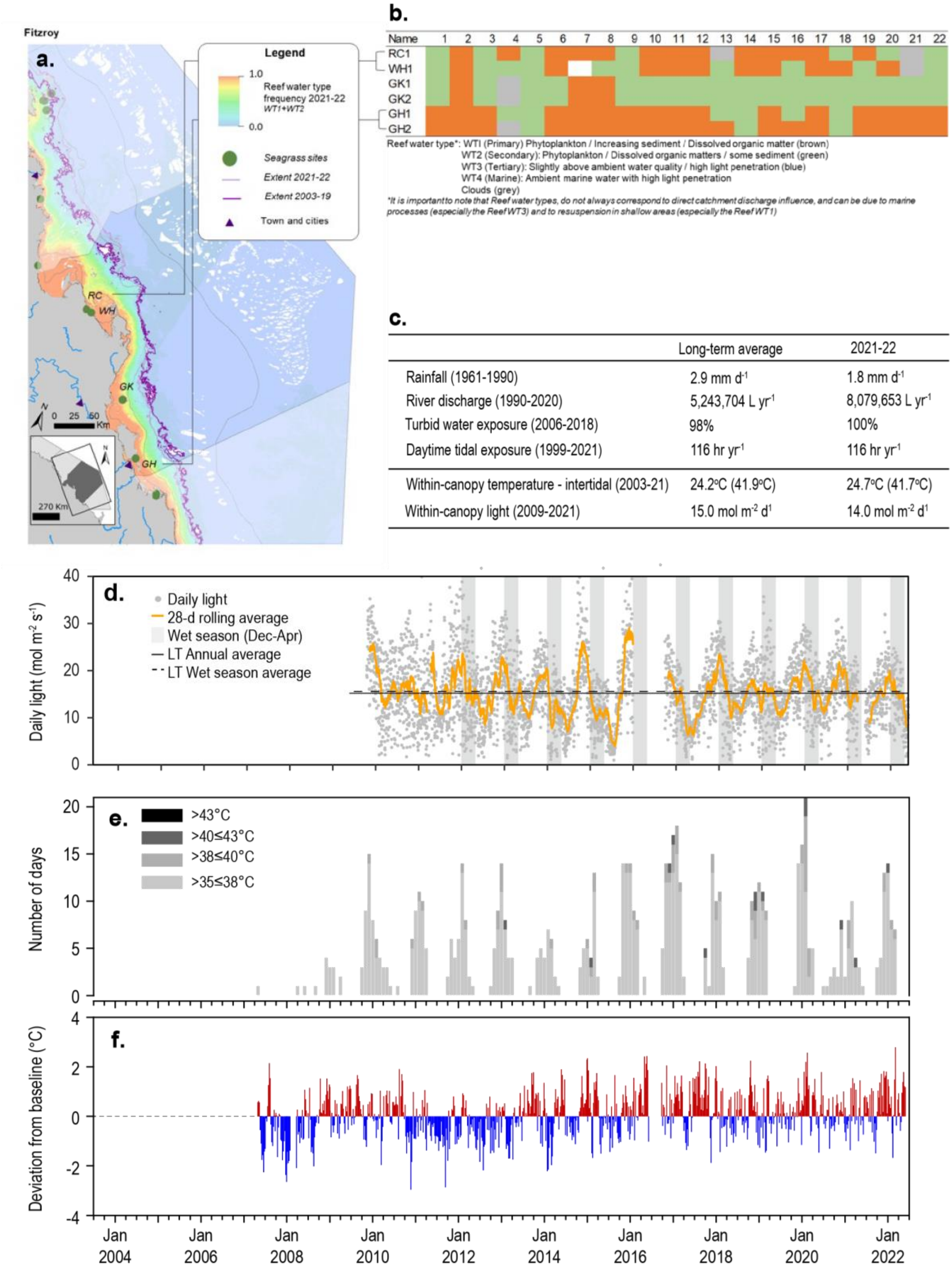
Wet season rainfall in the Fitzroy basins in 2021–22 was below the long-term average, but annual river discharge was 1.5 times the annual median for the region (Figure 69c). Inshore seagrass habitats were exposed to turbid waters of water type I or II for all weeks during the wet season which was slightly above the long-term average (Figure 69c). There was relatively more water type II waters at the reef sites at Great Keppel Island and more frequent exposure to water type I at the coastal and estuarine sites (Figure 69a, b).

Annual averaged daily light availability was also lower in 2021–22 than the long-term average for the region (Figure 8, Figure 69c, d). At Shoalwater Bay, daily light was 16.2 mol m^{-2} d^{-1} on average, which was well below the average of 18.6 mol m^{-2} d^{-1}. Daily light was also below average at the estuarine site in Gladstone Harbour, but slightly above average at the reef site at Great Keppel Island (Figure 103). Daily light reached an annual maximum in late November, and declined throughout the wet season to the lowest 28-day average in five years. Daytime tidal exposure was average for the region in 2021–22 (Figure 96).

2021–22 within-canopy temperatures were warmer on average than the previous period and above the long-term average for the 9th consecutive year (Figure 69c,f). Maximum intertidal within-canopy temperatures exceeded 35°C for a total of 50 days during 2021–22, with the second highest temperature ever recorded in the region at 41.7°C (RC1, 4pm 04Jan22) (Figure 69e). Daytime tidal exposure in 2021–22 was below the long-term average at estuarine and reef habitats, but above at coastal habitats for the seventh consecutive year (Figure 69c, Figure 95), which may have exacerbated stresses experienced at these intertidal sites.

Estuarine habitat sediments in 2021–22 were composed primarily of finer sediments, with the mud portion remaining below the overall inshore Reef long-term average (Figure 117). Coastal and reef habitat sediments were dominated by fine sand/sand, with the proportion of mud at coastal habitats remaining above the long-term average for the fifth consecutive year (Figure 118, Figure 119).

It is, however, important to note that the Fitzroy is only surveyed once per year in the late dry season, before these wet season and summer impacts. Therefore, the seagrass results reflect a legacy of the environmental conditions into the previous year which were more benign.



	Long-term average	2021-22
Rainfall (1961-1990)	2.9 mm d^{-1}	1.8 mm d^{-1}
River discharge (1990-2020)	5,243,704 L yr^{-1}	8,079,653 L yr^{-1}
Turbid water exposure (2006-2018)	98%	100%
Daytime tidal exposure (1999-2021)	116 hr yr^{-1}	116 hr yr^{-1}
Within-canopy temperature - intertidal (2003-21)	24.2°C (41.9°C)	24.7°C (41.7°C)
Within-canopy light (2009-2021)	15.0 mol m^{-2} d^{-1}	14.0 mol m^{-2} d^{-1}

Figure 69. Environmental pressures in the Fitzroy region including: a. frequency of exposure to primary and secondary water from December 2021 to April 2021 ranging from frequency of 1 (orange, always exposed) to 0 (pale blue, never exposed) (white = no data), also showing the long-term average (2003–2018) exposure boundary (purple line), and the first (blue line) and third quartile (white line) of the long-term average (from Moran *et al.* 2023); b. wet season water type at each site; c. average conditions and max temperature over the long-term and in 2020–21; 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 at intertidal sites.

5.5.3 Inshore seagrass and habitat condition

Three seagrass habitat types were assessed across the Fitzroy region in 2021–22, 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 Fitzroy NRM region. For site details see Table 5 and Table 6.

Habitat	Site		abundance	composition	distribution	reproductive effort	seed banks	meadow sediments	epiphytes	macroalgae
estuarine 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 2021–22 monitoring period, the seagrass condition index declined and remained a **poor** grading in a declining trend since 2019–20 (Figure 68). The Index was the lowest on record since 2005 for the Fitzroy NRM.

The abundance score decreased to the lowest level on record and reaching very poor for the first time in the Fitzroy region (Figure 70). Unlike in other regions, there has been no change to the sites surveyed since 2008, so the trends reflect long-term changes at these sites.

In 2021–22, the resilience score continued to decline and was the second lowest score since monitoring commenced (Figure 70). This was primarily driven by declining resilience at Shoalwater Bay.

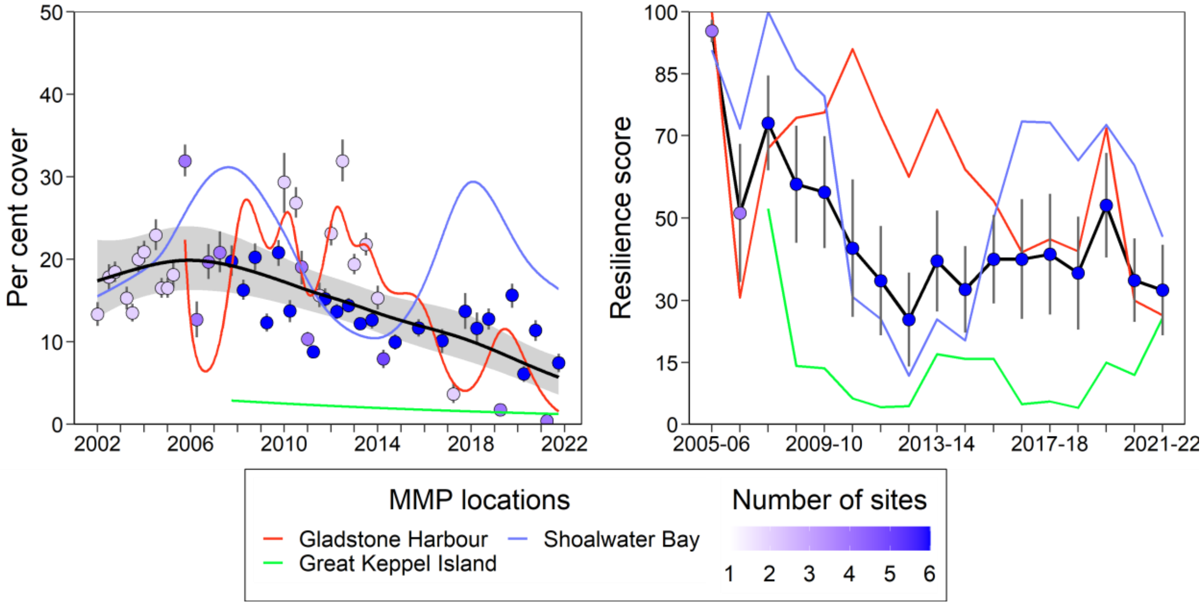


Figure 70. Temporal trends in the Fitzroy seagrass indicators used to calculate the seagrass condition index: a. average (circles, ±SE) seasonal abundance (per cent cover) and GAM plots of seagrass abundance trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); b. average

annual resilience score (±SE) and trends for each location (coloured lines). Colour of circles represents the number of sites assessed to calculate the average.

5.5.3.2 Seagrass abundance, composition and extent

In 2021–22, seagrass abundances across the Fitzroy region continued to decline from the previous reporting period (Figure 71). Seagrass abundance (per cent cover) in the Fitzroy region in 2021–22 was significantly higher in coastal (20.2 ±1.4per cent) habitats than estuarine (15.6 ±1.6per cent), and reef habitats (1.7 ±0.6 per cent) (Figure 71). Seagrass abundances at estuarine and coastal intertidal habitats have fluctuated greatly between years over the life of the monitoring program, with some sites experiencing total or near total loss followed by recovery (Figure 71). In reef and estuarine habitats, seagrass abundances remain below their long-term averages for the third and seventh consecutive years, respectively. In the coastal meadows of Shoalwater Bay, abundances declined below the long-term average in 2021–22, and were at their lowest in 6 years (Figure 71).

Examination of the long-term trend in seagrass abundance (per cent cover) across the region reveals a significant decrease (Figure 70, Table 22). These decreases have primarily occurred in the estuarine and reef habitats, although two thirds of all monitoring sites in the region (including coastal) show no significant trend (Table 22).

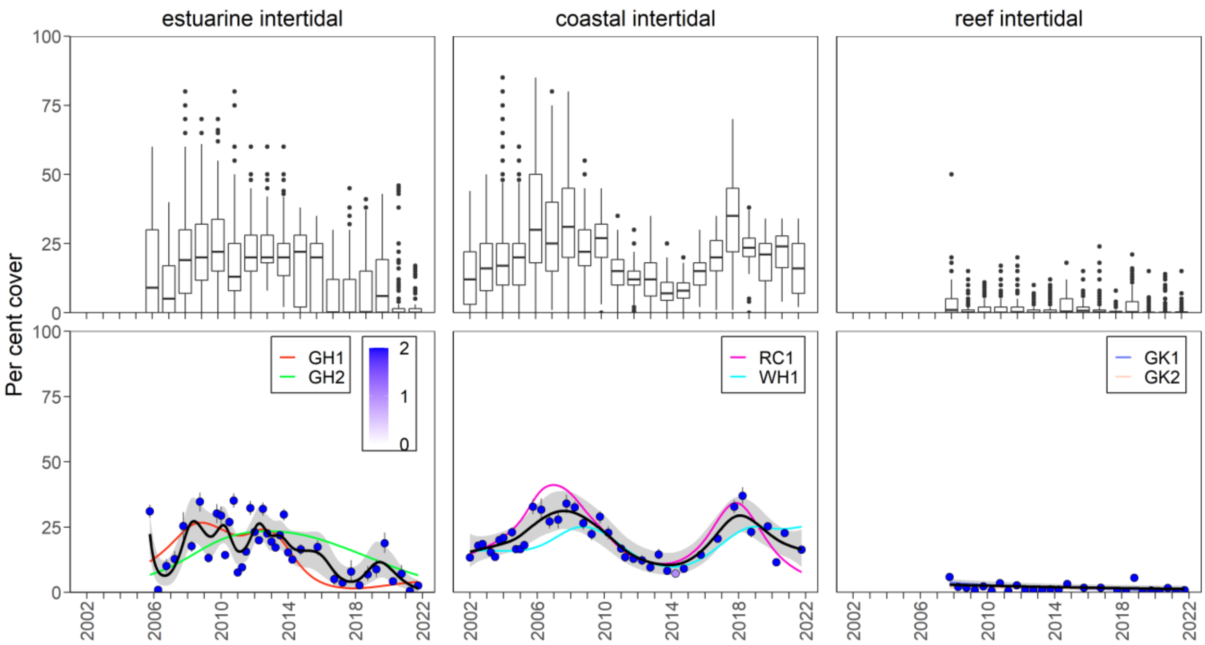


Figure 71. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the Fitzroy NRM region from 2002 to 2022. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero indicates 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. GAM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

The seagrass species in the coastal meadows in Shoalwater Bay (Ross Creek and Wheelans Hut) have returned to compositions dominated by the opportunistic species *Z. muelleri* and *H. uninervis*, with the lowest proportion of colonising species (*H. ovalis*) since 2005. The proportion of colonising species (*H. ovalis*) peaked after the extreme climatic events of 2011, and has gradually been declining since (Figure 72). In 2021–22, the proportion of these opportunistic species increased above the Reef long-term average at estuarine sites (Figure 72), although the sites continued to be dominated by *Z. muelleri*. Colonising species continued to dominate the reef habitat sites (well above the overall inshore Reef long-term average), however there has been an increased in the opportunistic *H. uninervis* over the last few years (Figure 72).

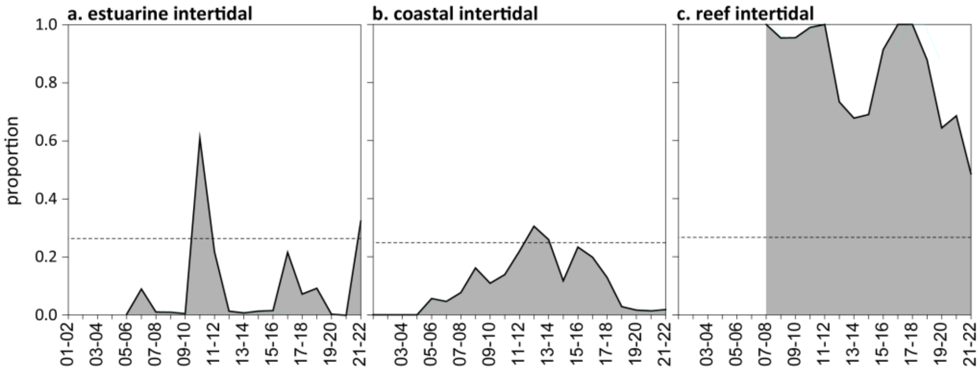


Figure 72. Proportion of seagrass abundance composed of colonising species in inshore intertidal habitats of the Fitzroy region, 2001–2021. Dashed line represents Reef long-term average proportion of colonising species for each habitat type.

The extent of the coastal meadows within monitoring sites in Shoalwater Bay has changed little since monitoring commenced in 2005. Conversely, the extent of the estuarine meadows at Pelican Banks in Gladstone Harbour has fluctuated greatly since 2015–16 when there was a large reduction in one of the sites due to extensive scarring and sediment deposition. In 2019–20, the sediment deposition abated and the meadow was showing signs of recovering with shoot extension and improved meadow cohesion. However, since 2020–21 the entire meadow seascape has deteriorated (Figure 73), with increased erosion along drainage channels and increased scarring. Meadows on the reef flat at Great Keppel Island remained highly fragmented after the 2015–16 losses and continued to show little sign of recovery in 2021–22.

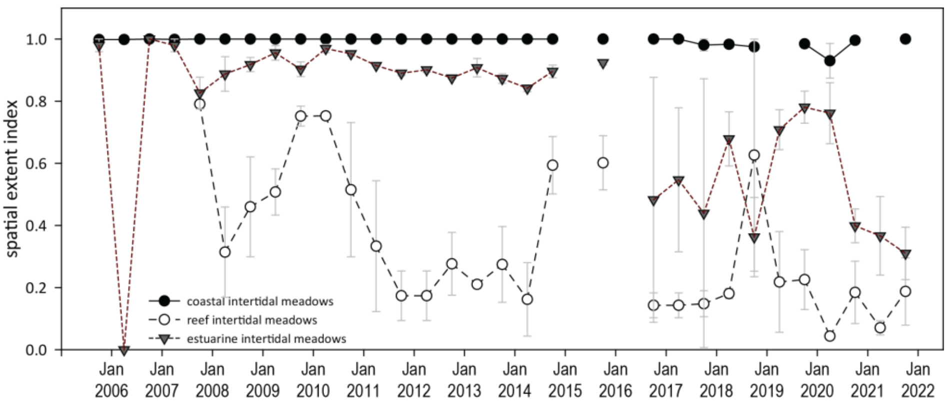


Figure 73. Change in spatial extent (± SE) of seagrass meadows within monitoring sites for each inshore intertidal habitat across the Fitzroy NRM region, 2005–22.

5.5.3.3 Seagrass reproductive status

The abundance of sexually reproductive structures (flowers and fruits) has varied seasonally and inconsistently between years and across habitats in the Fitzroy region over the life of the MMP (Figure 74). The number of repro structures tends to decline in meadows with distance from the coast, with the highest abundances on average in estuarine habitats and the lowest at reef habitats. Reproductive effort remains low at all habitats in 2021-22 for the 11th consecutive year, with a marginal increase at estuarine sites (Gladstone Harbour), an increase at coastal sites (Shoalwater Bay) and a loss at reef sites (Great Keppel Island) (Figure 74). Nevertheless, a seed bank has persisted over the last decade in estuarine and coastal intertidal habitats, although densities have been below the long-term average for six consecutive years, with some of the lowest in the last two years. No seeds have ever been observed in the reef meadows at Great Keppel Island. This limits the meadow capacity to recover making them highly vulnerable to future disturbances. The absence of seeds in the reef meadows was likely the result of the chronic and greatly depressed reproductive effort. Other possible explanations for the low seed bank include failure to set seed, or rapid loss of seeds from germination or grazing (Heck and Orth 2006).

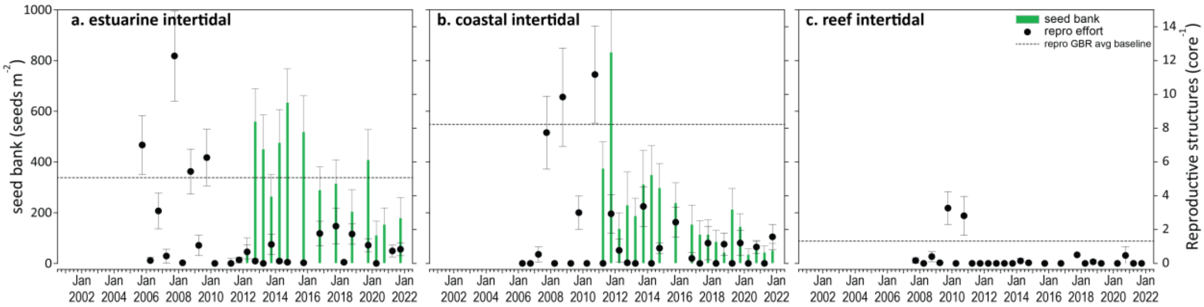


Figure 74. Seedbank and reproductive effort at inshore intertidal coastal, estuarine and reef habitats in the Fitzroy region, 2005–2022. Seed bank presented as the total number of seeds per m^2 of sediment surface (green bars ±SE). Reproductive effort for the late dry season presented as the average number of reproductive structures per core (species and sites pooled) (dots ±SE).

5.5.3.4 Resilience

Overall resilience in the Fitzroy region was poor but the trends in the resilience score varied among locations (Figure 75).

At estuarine intertidal habitats in Gladstone, meadow condition was below critical thresholds for resistance due to very low overall abundance (<20th percentile) and so were in category 1.1. The species composition was dominated by opportunistic species and reproductive structures were present. The score declined in 2021–22 because there was a reduction in the proportion of foundational species which were replaced by colonisers at GH1 indicating disturbances.

At coastal intertidal sites in Shoalwater Bay, there were large differences in resilience between sites. At WH1, resilience was the highest it has been since 2009–10. It was into the second highest category, and there was a moderate count of reproductive structures. At RC1, abundance was below the low resilience threshold, and there were no reproductive structures so it was into the lowest category.

At reef intertidal sites resilience improved the highest score since 2008–09. This was due to improvements at GK2 because there was an increase in the proportion of foundational species (*H. uninervis*). There were no reproductive structures present in 2021–22, but there had been in 2020–21. At GK1, species composition was dominated by the colonising species H. ovalis, and so there was a low score at that site.

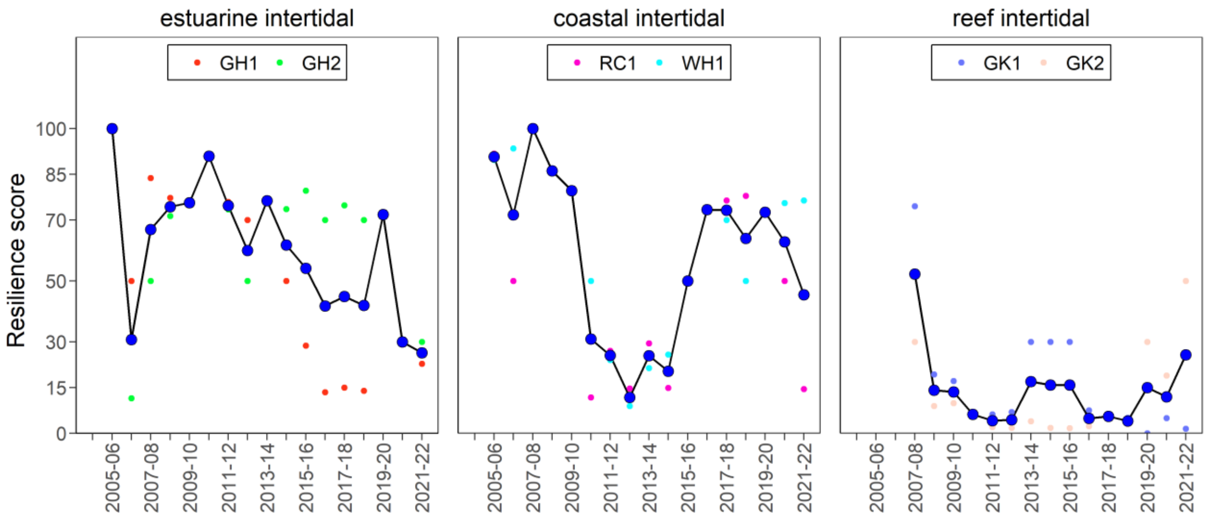


Figure 75. Resilience in each habitat in the Fitzroy region 2006 to 2022. Coloured small points represent different sites. Shades of blue for the larger points indicate the number of sites that contribute to the score.

5.5.3.5 *Epiphytes and Macroalgae*

Epiphyte cover on seagrass leaves generally decreased across the region in 2021–22, with covers at or below the overall inshore Reef long-term average for all habitats (Figure 76).

Macroalgae cover remained very low and below the overall inshore Reef long-term average at all habitats in the Fitzroy region, for the third consecutive year (Figure 76).

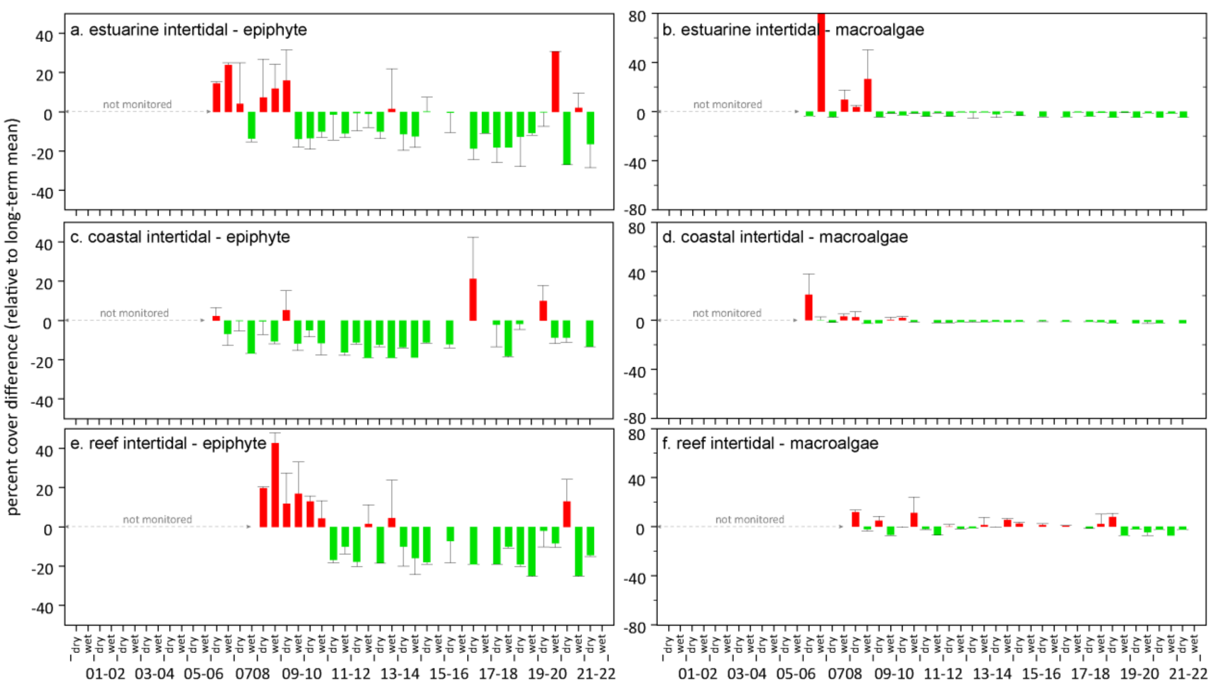


Figure 76. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term average (2005-2018) for each inshore intertidal seagrass habitat in the Fitzroy region, 2005–2022 (sites pooled, ±SE).

5.6 Burnett–Mary

5.6.1 2021–22 Summary

Extreme weather events affected the Burnett-Mary NRM region in 2021–22. Annual river discharge was nine times greater than the long-term median and was affected by late periods of elevated rainfall after the wet season (i.e. in May).

Inshore seagrass meadows across the Burnett–Mary NRM region declined in overall condition in 2021–22, with the index score declining and remaining as a **poor** grade (Figure 77). Contributing indicators to the overall score were:

- abundance score was very poor
- resilience score was poor.

The seagrass abundance score declined to poor for the first time since 2013–14. The decline is a continuing trend that has been occurring for the NRM region since 2015–16. Abundances declined in both estuarine and coastal habitats, in a trend continuing since 2015–16 in estuarine habitats but only since 2019–20 in coastal habitats. Spatial extent in estuarine habitat also declined to the lowest level since 2008.

Resilience declined to poor overall in the Burnett–Mary NRM region, and is only one of three years since 2005–06 that the score has declined below moderate. This was due to a large change in resilience in coastal habitat at Burrum Heads where abundance fell below the thresholds indicative of low resistance and there were no reproductive structures observed. By contrast, resilience improved slightly at estuarine sites where the score was buoyed by flowering in recent years, which indicates capacity to have formed a seed bank. However, seeds had been depleted at estuarine sites by late in the wet season of 2021–22.

The decrease in the seagrass condition index in 2021–22 to the second lowest on record, was based on surveys prior to elevated discharge in May when further declines were likely to have occurred in vulnerable meadows. The region has a history of variable seagrass condition but has shown a reasonable capacity for recovery following extreme events.

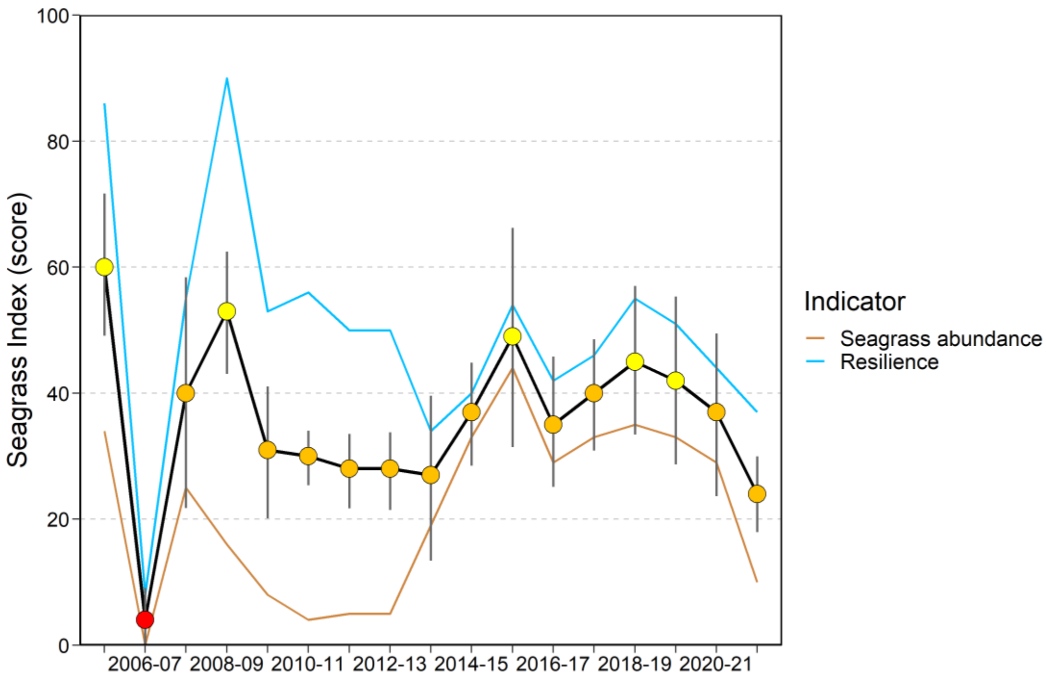


Figure 77. Report card of seagrass index and indicators for the Burnett–Mary region (averages across habitats and sites). Values are indexed scores scaled from 0–100 (± SE) and graded: ● = very good (81–100), ● = good (61–80), ● = moderate (41–60), ● = poor (21–40), ● = very poor (0–20). NB: Scores are unitless.

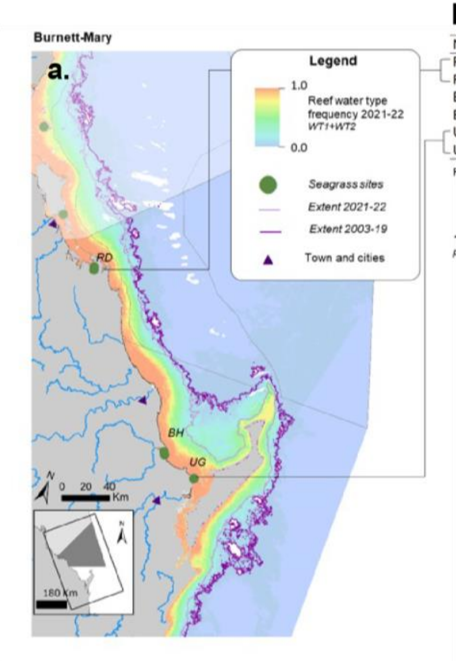
5.6.2 Climate and environmental pressures

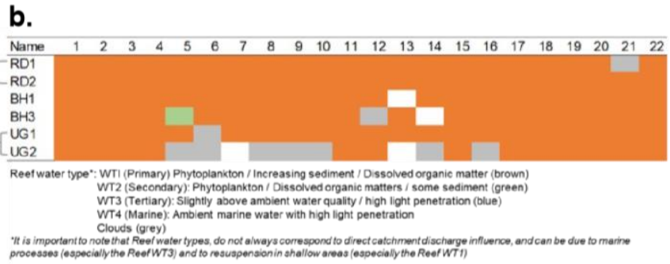
During 2021–22, there were several periods of elevated rainfall and river discharge in the Burnett–Mary region. This resulted in a total annual discharge that was more than 9 times greater than the long-term median for the basins of the NRM region (Figure 78c, Table 9). In the Burnett-Mary region there are only estuarine and coastal monitoring locations, and these are generally exposed to high frequencies of primary water and in 2021–22 it was for 97% of weeks in the wet season (Figure 78a, b). These were the high turbidity water type I waters in all but one week at one site. Light loggers failed during the wet season and so the average daily light is around the long-term, but this likely underestimates the exposure to low daily light levels in the wet season (Figure 78c, d).

Within-canopy temperatures in 2021–22 were similar to the previous year and marginally above the long-term average for the 3rd consecutive year (Figure 78c,f). Maximum intertidal within-canopy temperatures exceeded 35°C for a total of 12 days during 2021–22 (4 fold higher than the previous period) (Figure 78e), with the highest temperature recorded at 39.9°C (UG2, 4:30pm 18Jan22).

Daytime tidal exposure was above the regional long-term average in 2021–22 (Figure 78c), however, there were differences across the region. Levels of exposure differed with meadows in the north being exposed less often, while conversely, meadows in the south were exposed longer than any other reporting period in the last decade (Figure 97). The less than long-term average exposure may have reduced the risk of temperature and desiccation stress in the south, but may also have increased the risk of light limitation in the turbid water areas.

Sediments in the estuarine seagrass habitats of the Burnett–Mary region are generally dominated by mud. In 2021–22, however, the proportion of mud in the estuarine habitats decreased, after experiencing a period of above-average mud in the previous reporting period. Meadows in the north varied, with a noticeable increase in mud content at one site (RD1), while the other site remained dominated by sands (Figure 120). Coastal meadows in 2021–22 continued to be dominated by fine sand with little change from the previous year (Figure 121).





c.

	Long-term average	2021-22
Rainfall (1961-1990)	3.3 mm d^{-1}	3.8 mm d^{-1}
River discharge (1990-2020)	1,975,525 L yr^{-1}	17,465,982 L yr^{-1}
Turbid water exposure (2006-2018)	100%	97%
Daytime tidal exposure (1999-2021)	104 hr yr^{-1}	110 hr yr^{-1}
Within-canopy temperature - intertidal (2003-2021)	23.5°C (40.9°C)	23.9°C (39.9°C)
Within-canopy light (2009-2021)	12.0 mol m^{-2} d^{-1}	11.6 mol m^{-2} d^{-1}

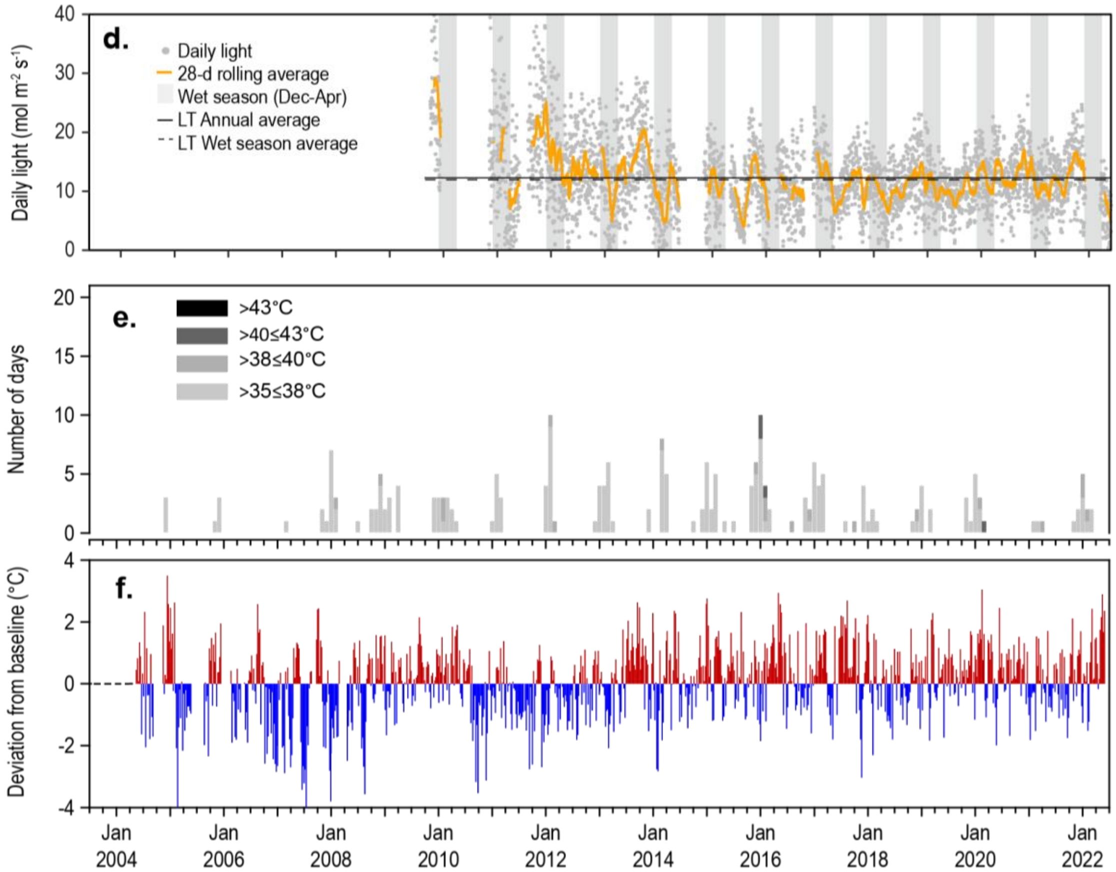


Figure 78. Environmental pressures in the Burnett–Mary region including: a. frequency of exposure to primary and secondary water from December 2021 to April 2022 ranging from frequency of 1 (orange, always exposed) to 0 (pale blue, never exposed) (white = no data), also showing the long-term average (2003–2018) exposure boundary (purple line), and the first (blue line) and third quartile (white line) of the long-term average (from Moran *et al.* 2023); b. wet season water type at each site; c. average conditions and max temperature over the long-term and in 2020–21; 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 at intertidal sites.

5.6.3 Inshore seagrass and habitat condition

Only estuarine and coastal habitats were assessed across the Burnett–Mary region in 2021–22, with data from 6 sites (Table 18).

Table 18. 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 5 and Table 6.

Habitat	Site		abundance	composition	distribution	reproductive effort	seed banks	meadow sediments	epiphytes & macroalgae
estuarine 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 2021–22 monitoring period, the Burnett–Mary region seagrass condition index declined and remained rated as a poor grade, which was the second lowest on record (Figure 77). The decline continues a trend that occurred since 2015–16 and changes in both indicators contributed to this result (Figure 79).

Over the long-term the regional average of seagrass abundance 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 then declined in 2018–19 and remained low. Recently trends have also been driven by change in abundances at the other locations, and the recent trends are strongly influenced by the abundance of seagrass in the wet season, (Figure 79).

Seagrass resilience declined in 2021–22 to reach the third lowest score on record and only the third time to reach poor or very poor in the Burnett–Mary region. This was driven by large declines in coastal habitats at Burrum Heads (Figure 79).

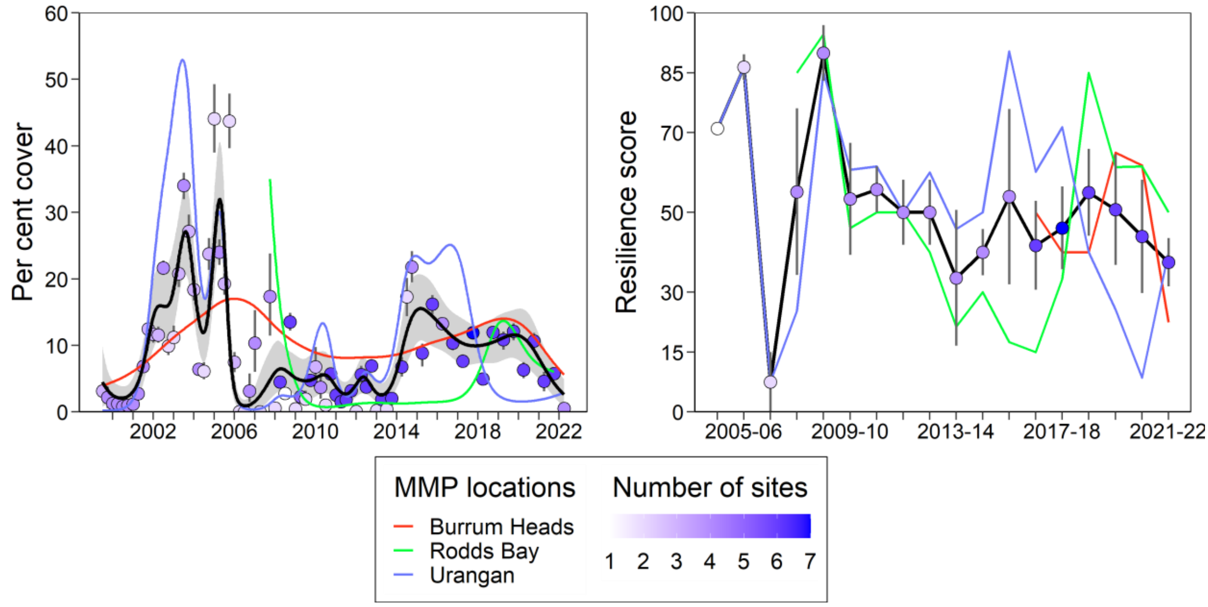


Figure 79. Temporal trends in the Burnett–Mary seagrass indicators used to calculate the seagrass condition index: a. average (circles, ±SE) seasonal abundance (per cent cover) and GAM plots of seagrass abundance trends for each location (coloured lines) and the region (black line with grey shaded area defining 95 per cent confidence intervals); b. average annual resilience score (±SE) and trends for each location (coloured lines). Colour of circles represents the number of sites assessed to calculate the average.

5.6.3.2 Seagrass abundance, composition and extent

Since monitoring was established, the estuarine meadows across the Burnett–Mary region have come and gone on an irregular basis, with no apparent long-term trend as of 2021–22 (Table 22). The coastal meadows at Burrum Heads have been slightly more steady, except one of the sites (BH3) which has significantly increased over the long-term (Table 22).

Historically, seagrass abundances (per cent cover) across the Burnett–Mary region are generally greater on average in estuarine than coastal habitats (11.3 ±1.5 per cent and 9.9 ±0.9 per cent long-term average, respectively). In 2021–22, however, seagrass abundance was greater at coastal habitats (4.03 ±0.4 per cent), as estuarine abundances (2.27 ±0.8 per cent) remained below their long-term average for the fifth consecutive year (Figure 80). Overall, seagrass abundances declined across the Burnett–Mary region during 2021–22. The largest decline was at coastal habitats where abundances were 7.58 ±0.5 per cent in the late dry season, declining to 7.58 ±0.5 to 0.49 ±0.1 per cent in the late wet. The difference was not as great at estuarine habitats as abundance had already been low, declining from 4.09 ±1.1 to 0.47 ±0.2 per cent in the late dry to the late wet season, respectively (Figure 80). This represents the most significant decline in inshore seagrass resources across the region since 2017.

The estuarine and coastal seagrass habitats have remained dominated by *Z. muelleri* with varying components of *H. ovalis*. In 2021–22, the proportion of colonising species decreased at both estuarine and coastal meadows compared to the previous monitoring year (Figure 81). A decrease in the proportion of colonising species in the meadows suggests reduced levels of physical disturbance which may assist in the ability to resist moderate disturbances in future.

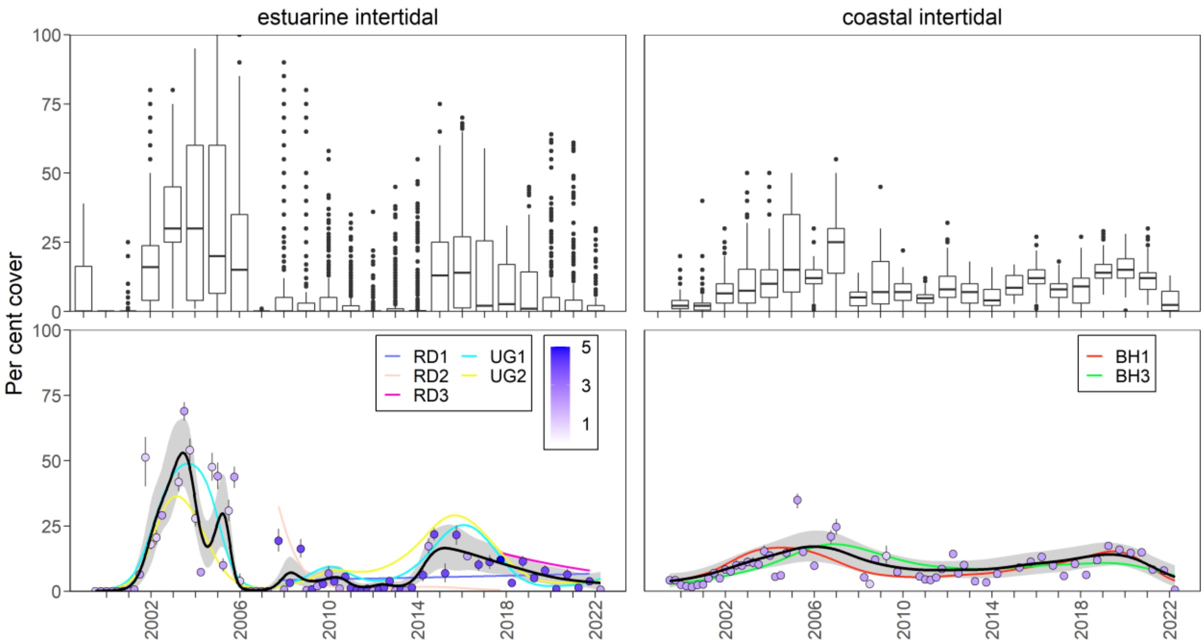


Figure 80. Seagrass per cent cover measures per quadrat (sites pooled) and long-term trends, for each habitat monitored in the Burnett–Mary NRM region from 1999 to 2022. Whisker plots (top) show the box representing the interquartile range of values, where the boundary of the box closest to zero indicates 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. GAM plots (bottom), show trends for each habitat and coloured lines represent individual site trends.

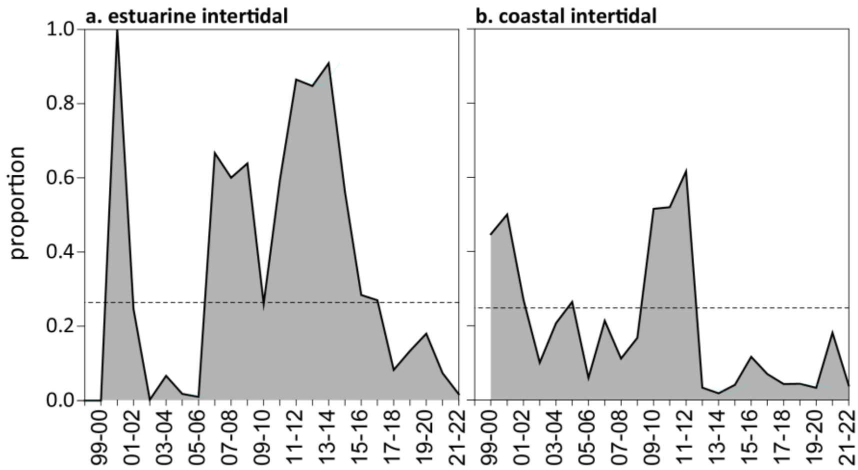


Figure 81. Proportion of seagrass abundance composed of colonising species at: a. estuarine and b. coastal habitats in the Burnett–Mary region, 1998 to 2022. Dashed line represents Reef long-term average proportion of colonising species for each habitat type.

Meadow spatial extent has remained stable at coastal meadows relative to the previous year (Figure 82). Estuarine meadows, however, continued to decline, with the greatest losses occurring in March 2022 as a consequence of the severe flooding events in the south of the region. These losses are a result of the southern located sites, which are adjacent to the Mary River, as the northerly located sites in Rodd Bay are only surveyed once per year in the late dry season.

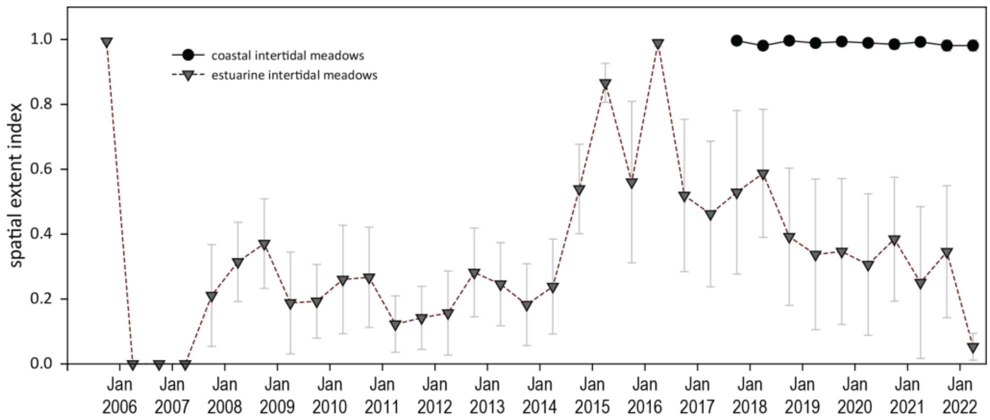


Figure 82. Change in spatial extent (± SE) of estuarine seagrass meadows within monitoring sites for each habitat and monitoring period across the Burnett–Mary NRM region.

5.6.3.3 Seagrass reproductive status

Over the last five years, reproductive effort has remained below the GBR baseline and in 2021-22 declined across the region relative to the previous period; with no reproductive structures reported from any monitoring site (Figure 83). Over the previous two years, reproductive effort in estuarine habitats has not only been below the region's long-term average, but has been successively declining. Similarly, reproductive structures have remained below the GBR baseline at coastal sites, however, abundances were above the regional long-term average in previous years.

During 2021-22, seagrass seed banks in the late dry season were slightly higher on average at both coastal and estuarine habitats than the previous monitoring period, but overall remain well below the long-term average (Figure 83). Seed banks are historically higher during the late dry season than the late wet season. During the 2021–22 wet season, seed bank densities typically declined, but at two sites where the late dry season density was low (UG1 and BH3), the seed banks were lost following periods of elevated rainfall and driver discharge in early 2022. The lower reproductive effort in the meadows across the region may hinder replenishment of the depauperate seed banks, and seed banks 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 (i.e. low resilience).

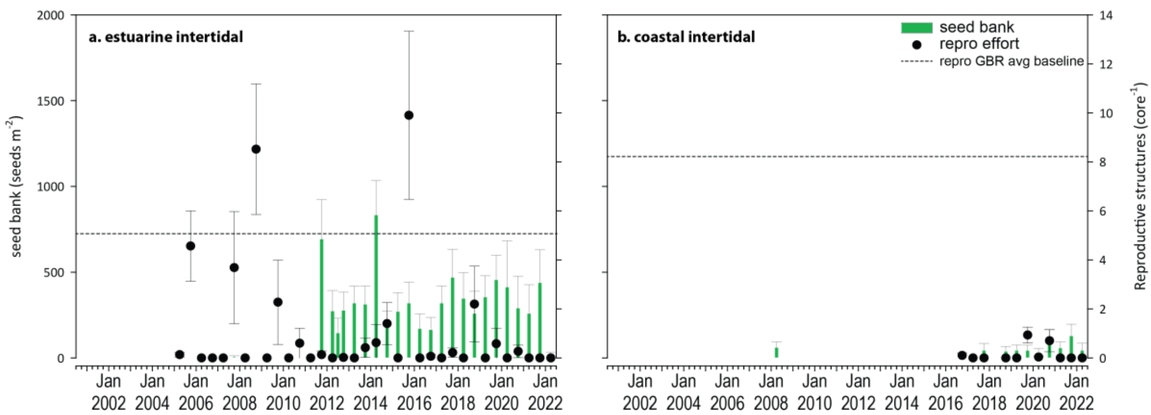


Figure 83. Seedbank and reproductive effort at inshore coastal and estuarine intertidal habitats in the Burnett–Mary region. Seed bank presented as the total number of seeds per m^2 sediment surface (green bars ±SE). Reproductive effort for late dry season presented as the average number of reproductive structures per core (species and sites pooled) (dots ±SE).

5.6.3.4 Resilience

Resilience was poor overall in the Burnett–Mary NRM region.

At estuarine intertidal sites, resilience was similar among locations and sites (Figure 84). Per cent cover was above critical thresholds at all sites. There were no reproductive structures, but there had been in the previous three years at three of the four, while there was no recent history of reproduction at UG2.

At coastal intertidal sites at Burrum Heads, there had in recent years been a large difference in resilience between the two sites, but in 2021–22, both sites had low resilience. At BH1, abundance declined below the threshold for the sites that is indicative of low resistance both sites were in a good condition indicative of high resistance capacity to disturbances and was therefore in the lowest category (1.1). Neither sites had reproductive structures in 2021–22.

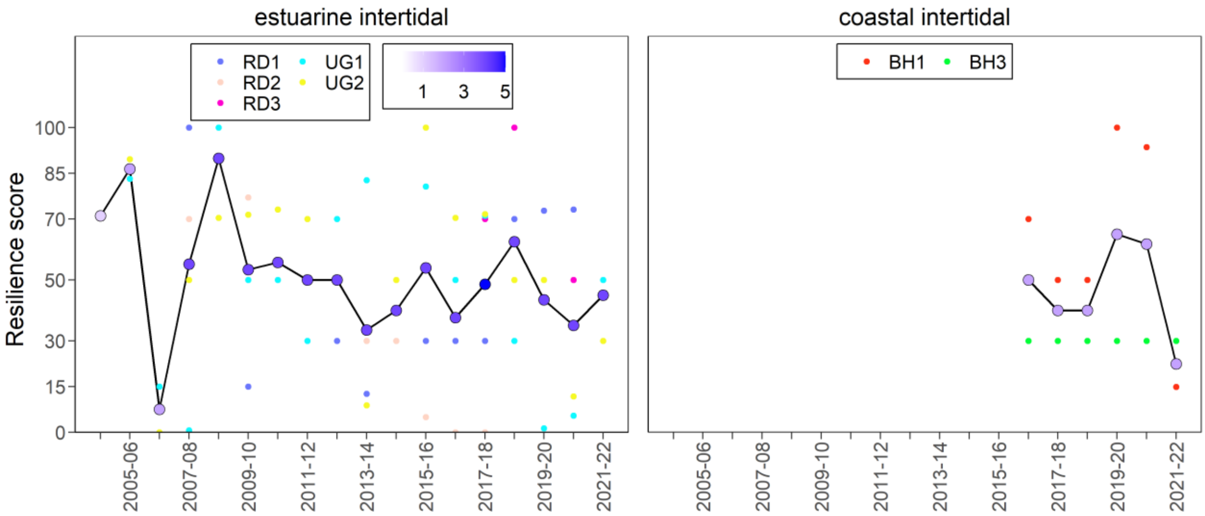


Figure 84. Resilience score in each habitat in the Burnett–Mary region from 2006 to 2022. Coloured small points represent different sites. Shades of blue for the larger points indicate the number of sites that contribute to the score.

5.6.3.5 Epiphytes and macroalgae

Epiphyte cover on seagrass leaf blades in 2021–22 generally increased, remaining higher than the long-term average for the eighth consecutive year at estuarine habitats (Figure 85). However, at coastal habitats, epiphyte abundance remained below the long-term average for the sixth consecutive year (Figure 85).

Per cent cover of macroalgae remained low and below the long-term average across the habitats monitored (Figure 85).

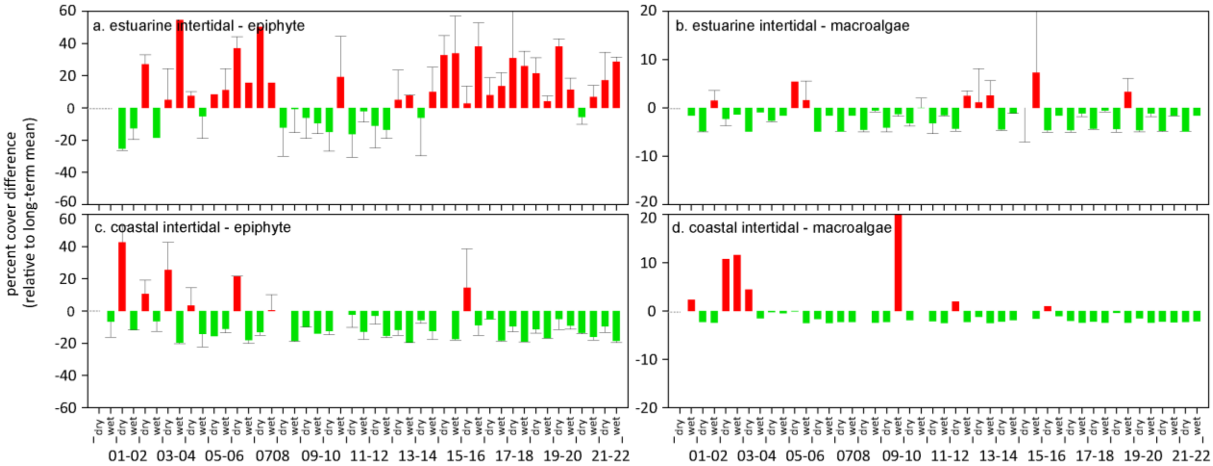


Figure 85. Long-term trend in mean epiphyte and macroalgae abundance (per cent cover) relative to the long-term average for each seagrass habitat in the Burnett–Mary NRM region (sites pooled, ±SE).

6 Discussion

Inshore seagrass condition was largely unchanged in 2021–22 with small declines in the overall seagrass abundance score and small improvements in the resilience score. However, there were regional differences, with improvements in condition in the northern and central regions, while southern NRM regions (Fitzroy and Burnett–Mary) declined.

River discharge was above average in the southern regions and nine times above the regional long-term average in the Burnett–Mary; due predominantly to floods in the Mary River. The seagrass Index declined to the second lowest on record and the lowest since 2006–07. Both resilience and abundance declined overall with both driven by loss at Rodds Bay and Burrum Heads. However, abundance had been declining at these sites since early 2018. At Urangan, abundance and resilience have been low for several years which appeared to be associated with highly dispersive sodic sediments at the sites, which are easily resuspended. In 2021–22 abundance and resilience improved slightly due to increases in the late dry season prior to the elevated discharges. These trends highlight that there is an interplay between local-scale processes, and region wide pressures influencing seagrass condition.

There were also positive signs of recovery. In the Wet Tropics the overall score was the fourth highest on average, and just a few points below the maximum. The Wet Tropics are described in terms of southern and northern Wet Tropics because of differences in the pressures and the seagrass responses to them. In the northern Wet Tropics, the abundance score increased to the highest on record and was a good rating, although resilience declined and was moderate. In the southern Wet Tropics, the Index has been on an increasing trend since 2012–13, but in 2021–22, abundance declined a little and was poor, though resilience increased to moderate and the highest score on record. There was elevated discharge in 2018–19, particularly in the far north of the region from the Daintree River, but otherwise environmental conditions were relatively benign in the Wet Tropics from 2010–11 to 2021–22. The exception is water temperature, which was elevated in 2021–22 and which continues a trend for warm within-canopy temperature anomalies to be more frequent than cool within-canopy temperature anomalies in the region. Otherwise, the relatively low pressure conditions have supported recovery across the Wet Tropics.

Rising temperatures are a Reef-wide trend in seagrass habitats. In all regions, region-wide within-canopy temperature was higher than average in 2021–22, and all sites (except at Burrum Heads where there was elevated rainfall and river discharge) had higher than average temperature (Figure 7). The largest rise above long-term average was in Cape York where it was 1.4ºC above average for the region. However, temperature extremes (>40ºC) were uncommon across the Reef in 2021–22. The impact of temperature extremes are relatively easy to assess (e.g. experiment papers) and to identify in the field (e.g. burning) (Campbell *et al.* 2006; Collier and Waycott 2014). By contrast, the impact of chronic rises in temperature are difficult to discern in seagrass habitat. Rises in temperature increase net productivity in seagrasses up to their thermal optima after which net productivity and potential for growth decline. These thresholds are only known for a few species. The influence of temperature on other biological processes critical to resilience are unknown. For example, temperature is likely to affect flowering onset, flowering density, seed development, condition of the sediment, seed viability and seed germination. These are information gaps that are becoming increasingly urgent to address as rising temperatures continue to dominate the pressures of the inshore Reef, and they may influence resilience of habitats to other pressures such as water quality.

Site-scale monitoring is sensitive to site-scale pressures in addition to the regional pressures of water quality and thermal stress. There are local-scale processes that appear to have had a substantial influence in the past decade. For example, changes in the sediment or substrate have been observed at sites in all NRM regions. For example, in Cape York, one of the sites at each of Shelburne Bay and Bathurst Bay had a drainage channel from nearby tidal inlets moving through the site, which eroded sediment and brought more organic rich deposits. In the Wet Tropics at Lugger Bay the sediment level dropped following cyclone Yasi, and became too deep for rapid colonisation in the turbid waters and at Dunk Island, removal of sand from the reef substrate following the cyclone also slowed recovery. In Gladstone Harbour at Pelican Banks, deep mud banks with high levels of bioturbation moved through one of the sites. At Urangan, sediments became highly dispersive and easily resuspended over the site as seagrass abundance declined. Low seagrass cover can make sediments more unstable and create negative feedbacks to accelerate decline (Maxwell *et al.* 2016). Quantitative indicators of local-scale processes would enable these to be integrated into routine pressures analysis affecting the inshore seagrass habitats. This would be comparable to the inclusion of Crown of Thorn Starfish pressures at inshore reefs in the coral monitoring program (Thompson *et al.* 2022), which is a site-level pressure. In some cases, there may be no suitable management action to respond to local-scale processes, however understanding their role in seagrass trends is important contextual information. In other cases, management actions could target these local-scale issues or processes to facilitate recovery. Such localised actions could include using seed-based or transplant-based restoration approaches, or ecological engineering to elucidate conditions where growth, settlement and/or colonisation of seagrass can be promoted (Tan *et al.* 2020).

Daily light is affected by concentrations of suspended sediments, nutrients and organic matter in the water and these are in turn affected by river discharge, resuspension and biological processes (Bainbridge *et al.* 2018; Lewis *et al.* 2021; Fabricius *et al.* 2016). Inshore seagrass monitoring sites are exposed to a very high frequency of turbid water even in low discharge years (Figure 25, Figure 34, Figure 35, Figure 51, Figure 60, Figure 69, Figure 78). These turbid waters constrain the depth limit of seagrasses, therefore influencing their spatial extent and also influence changes in abundance and resilience.

Daily light levels were below average at sites throughout the Reef in 2021–22 in all NRM regions, despite benign conditions in the northern and central regions. At other sites daily light was slightly above the long-term average, with the largest positive increase at Green Island, a reef site in the Wet Tropics. Light is measured only at intertidal sites starting with this reporting year i.e. not at any subtidal sites. Intertidal sites can be exposed to very high light during low tide and on either side of the low tide when water level is shallow. The long-term regional and Reef-wide daily light averages were updated so that those baselines are comparable to current sites. Even the level and frequency of exposure can influence the average daily light of a site, and so comparisons are made with the long-term conditions of each site (Figure 7).

Benthic light is a pressure of concern in intertidal seagrass habitats, as they are rarely exposed to air/shallow water especially in the wet season when they are only exposed at night due to the annual luna and tidal cycles. Therefore, in terms of daily light, intertidal habitats are much like subtidal habitats during the wet season when the risk of light stress is also the highest due to river discharge and resuspension associated with storms. In previous reports, daily light has been reported against light thresholds that indicate acute stress and an increased probability of seagrass loss (6 mol m^{-2} d^{-1}) and an estimate of a light threshold to support optimum growth over the long-term (10 mol m^{-2} d^{-1}). These values were developed for shallow subtidal habitats from *in situ* measures or experimental testing (Collier *et al.* 2012a; Collier *et al.* 2016a) or *in situ* experiments in very turbid habitats (Chartrand *et al.* 2016) as summarised in (Collier *et al.* 2016b). Frequent or prolonged exposure to high light increases average daily light levels when averaged over months or a year as they are reported here. This likely underestimates the risk of light stress in shallow intertidal turbid habitats. There is a need to develop light thresholds that accommodate the exposure regime of intertidal habitats.

The depth limit of seagrass and deeper or subtidal seagrass habitats tend to be more susceptible to changes in daily light as they grow in conditions that are near to their minimum light requirements (for example, the subtidal habitats of the Burdekin region undergo large changes in abundance when there is elevated discharge (Petus *et al.* 2014)). There is an information gap between daily light in intertidal habitats (currently measured with *in situ* loggers) and mid-shelf and offshore daily light that is modelled from remote sensing or with eReefs. These models are less accurate in shallow inshore optically complex waters despite the importance of light as pressure in those habitats (Robson *et al.* 2019; Lambert *et al.* 2020).

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).

Securing a future for seagrasses on the Great Barrier Reef

Resilience-based management places a strong emphasis on the use of forecasting tools to inform planning and actions, together with monitoring and diagnostic tools to adjust actions. These actions need to be designed to maximise recovery and limit disturbances or impacts.

Resilience-based management also recognises that ecological health is influenced by processes at a range of spatial and temporal scales. This program focusses on site-level monitoring, representative of habitats and gradients of pressure across the entire inshore Reef in the late dry season and the late wet season in some locations. Integrating this level of information with spatial data on pressures provides a mean to examine how management initiatives, such as reversing wider-scale catchment degradation and poor water quality (i.e. Paddock to Reef Program) influence habitat condition. This is achieved through examination of exposure to turbid water types I and II. This information is also used to assess the extent to which seagrass habitat is affected by turbidity across the region (Moran *et al.* 2023).

Within canopy temperature is influenced by tides, changes in sea level and weather, so the risk of thermal stress will vary across habitats that have gradients of exposure to these. Existing spatial products (e.g. eReefs, ReefTemp) do not model these tidal changes or provide thorough coverage of the inshore Reef. Therefore, there is a need to develop a fit for purpose spatial model of inshore thermal risk, which is currently under development.

Improving the accuracy of indicators, and refining thresholds and indices of pressures, including cumulative stress, will improve our understanding of the processes of resilience to guide management actions and adaptation responses. For example, as temperatures continue to rise, there is also a need to examine how long-term averages compare to setting a fixed average (*sensu.* climatology) so that pressures indicators continue to be sensitive and informative.

Practicable conservation opportunities exist, which can make substantial and quantifiable improvements to seagrass condition. In addition to managing pressures, there are direct actions that can be taken to facilitate recovery. Some of these include:

1. Developing accurate models of seagrass recovery to identify when recovery is on track or when intervention actions may be required.
2. Improving our understanding of poor and variable reproductive effort through focussed research, as reproduction underpins the capacity for meadows to recover naturally, and seeding offers a potential restoration strategy
3. 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). This may include active environmental engineering in localised areas to improve habitat suitability, by mitigating limiting factors (e.g. wave energy, erosion) or creating new habitat.

Continuous revision and examination of opportunities for improvement of the monitoring program will also ensure that the information is current, relevant, and makes the most for emerging technologies.

Some of the most pressing updates include:

1. Developing a spatial inshore thermal stress risk model (under way).
2. Updating the light indicators and thresholds to be more suitable for *in situ* light monitoring of intertidal habitats and explore ways to apply existing information (e.g. eReefs) to complement the current pressures reporting for inshore subtidal habitats.
3. Development of a fragmentation index based on the current and historical seagrass extent data, and development of protocols for using drones to complement spatial extent/fragmentation monitoring.
4. Scaling monitoring undertaken in this program to broader-levels (e.g. RIMReP) to fully capture the extent of habitat decline and recovery so that the potential ecological consequences can be more accurately inferred. For example, continuous improvements in earth observing (airborne and spaceborne) image capture of the Reef using Unoccupied Aerial Vehicles (UAV) and Autonomous Underwater Vehicles (AUV), 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.

7 Conclusion

In 2021–22 inshore seagrass meadows across the Reef marginally improved in overall condition, with the seagrass Index remaining **moderate**. The slight improvement was due to the decrease in seagrass abundance being offset by a greater increase in the resilience indicator. The abundance indicator decreased in 2021–22 after improving from poor to moderate in 2020–21, and the resilience score continued to improve, but remained moderate.

Environmental conditions were generally just above long-term averages across the Reef, with the exception of water temperatures which have increased across the regions and are now near record levels.

In 2021–22, the inshore seagrass of the Reef was in a moderate condition in all northern NRM regions, but poor and declining in the two southern most regions. The score increased in the northern regions compared to the previous monitoring period, but declined in southern regions. Improvements overall were driven mostly by increases in the resilience indicator.

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 these changes (i.e. declines and subsequent recovery) are complex.

Inshore seagrass meadows of the Reef were in an overall Good state in late 2008. In particular, locations in the northern Wet Tropics and Burdekin regions were in a good 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 and Moderate state, respectively, with low abundance, reduced reproductive effort and small or absent seed banks (Figure 86).

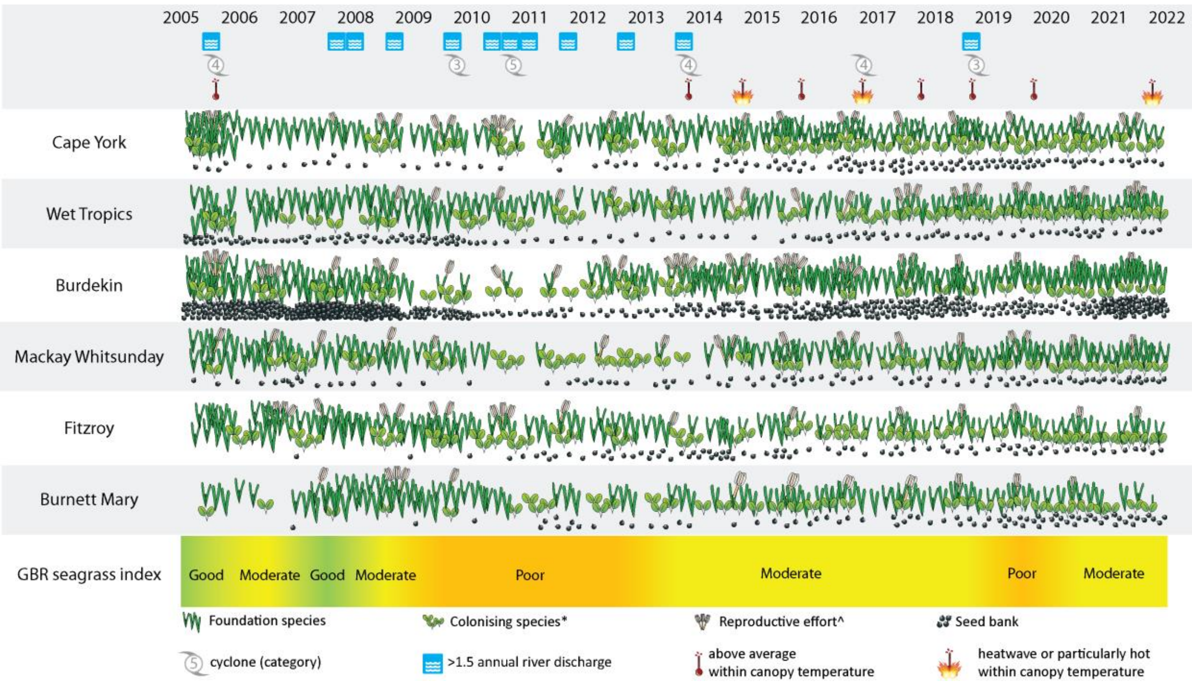


Figure 86. Summary of inshore seagrass state illustrating pressures, abundance of foundation / colonising species, seed bank and reproductive effort in each NRM from 2005 to 2022. * colonising species are represented by the genus *Halophila*, however, *Zostera* and *Halodule* can be both colonising and 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 began the gradually decline. Cumulative pressures, including severe climatic events, continued to undermine the resilience of inshore seagrass meadows of the Reef. Frequent and repeated disturbances seemed 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. By 2019–20, the inshore Reef seagrass had fallen back to a poor state. Since then, recovery has been buoyed across northern regions by a couple of years of low to negligible climatic pressures.

For the Reef's inshore seagrass meadows to continue improving will require extended periods of conducive conditions for seagrass growth and reduced environmental pressures. While climatic conditions cannot be controlled, the scale of effect they have on seagrasses can be lessened through initiatives which reduce terrestrial runoff to the Reef 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.

To secure the future of the Reef's seagrass ecosystems, improved ecosystem science on resilience and recovery would be valuable. In conjunction with over-arching research, it is critical to maintain adaptive resilience-based management by placing a strong emphasis on the use of forecasting tools to inform planning and actions, together with monitoring and diagnostic tools to adjust and implement actions to enhance resilience, maximise recovery and limit disturbances or impacts.

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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 87).

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 plateaued, 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 an 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 19).

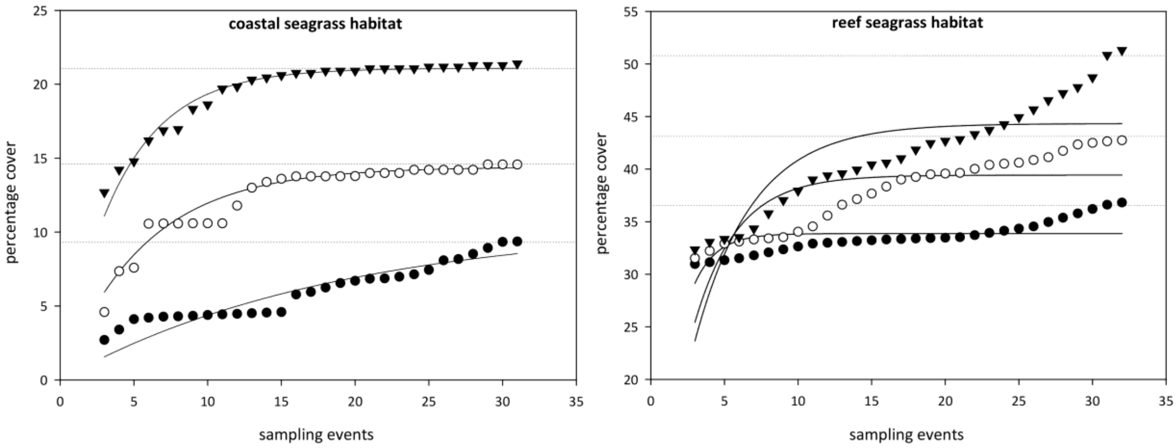

Figure 87. Relationship between sample size and the error in estimation of percentile values for seagrass abundance (per cent cover) in coastal and reef seagrass habitats in the Wet Tropics NRM. ▼ = 75th percentile, ○ = 50th percentile, ● = 20th percentile. Horizontal lines are asymptotic averages for 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 88), it indicates that the meadows were in a poor condition in mid-2000, mid-2001 and mid-2006 (based on abundance).

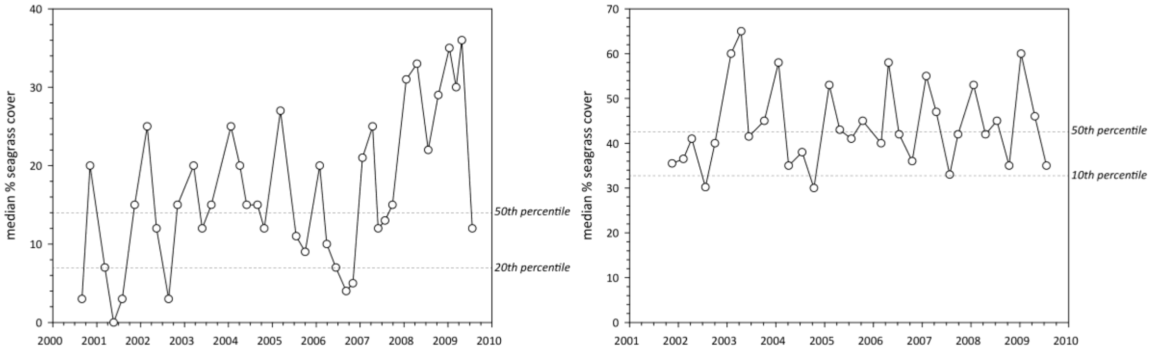

Figure 88. Median seagrass abundance (per cent cover) at Yule Point (left) and Green Island (right) plotted against the 50th and 20th percentiles for coastal and intertidal reef seagrass habitat in the Wet Tropics.

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 19). 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 19. 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		26	33	39.2
	NRM	***reef subtidal****	***22***	***26***	***33***	***39.2***
	BY*	coastal intertidal		6.6	12.9	14.8
	SR*	coastal intertidal		6.6	12.9	14.8
	NRM	***coastal intertidal****	***5***	***6.6***	***12.9***	***14.8***
	BY*	coastal subtidal		6.6	12.9	14.8
	LR*	coastal subtidal		6.6	12.9	14.8
	MA*	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

NRM region	site/ location	Habitat	percentile guideline 10th	20th	50th	75th
	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		26	33	39.2
	GI3^	reef subtidal	22	26	33	39.2
	LI2	reef subtidal		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		13.2	19.1	22.2
	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
	LN3	reef intertidal		9.2	12.2	13.8
	NRM	***reef intertidal***		***9.2***	***12.2***	***13.8***
	CH	reef subtidal		22.5	32.7	36.7
	LN	reef subtidal		22.5	32.7	36.7
	TO	reef subtidal		22.5	32.7	36.7
	WB	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 resilience

The status of seagrass resilience was determined using a multi-faceted resilience metric informed by existing metrics, historical data, and a conceptual understanding of resilience. Resilience can be considered as having two main elements (e.g. Timpane-Padgham *et al.* 2017; Connolly *et al.* 2018): an ability to resist disturbance, and an ability to recover from disturbances. We used a decision tree approach, which includes thresholds defining the splits, and methods for calculating scores (Figure 89). The main splits in the tree are based around:

- a 'resistance' component that assesses the seagrass meadow capacity to cope with disturbance based on their seagrass abundance and species composition. A low resistance site is one that has very low abundance based on the history of that site and/or has a high proportion of colonising species. These meadows are considered to be highly vulnerable to disturbances and, therefore, to have very low resilience.
- a 'reproduction' component that is based around likelihood of producing seed banks given the presence and count of reproductive structures. These are scored based on the levels of expected reproductive effort given the life history strategy of the species present. For example, some 'persistent' species such as *Thalassia* are not expected to have a high number of reproductive structures, and nor does it depend on them quite as much for long-term survival compared to 'colonising' species.

Those two components work both individually and in collaboration, thus giving the best estimate of resilience using the existing data and indicators. The metric is scored linearly from 0 to 100. The 0–100 scale was split into thirds (rounded to the nearest ten score). This resulted in the following:

- Low resistance sites = 0–30
- Non-reproductive high resistance site = 30–70
- Reproductive high resistance site = 70–100

The methods used to arrive at each step are outlined in detail in Collier *et al*. (2021a).

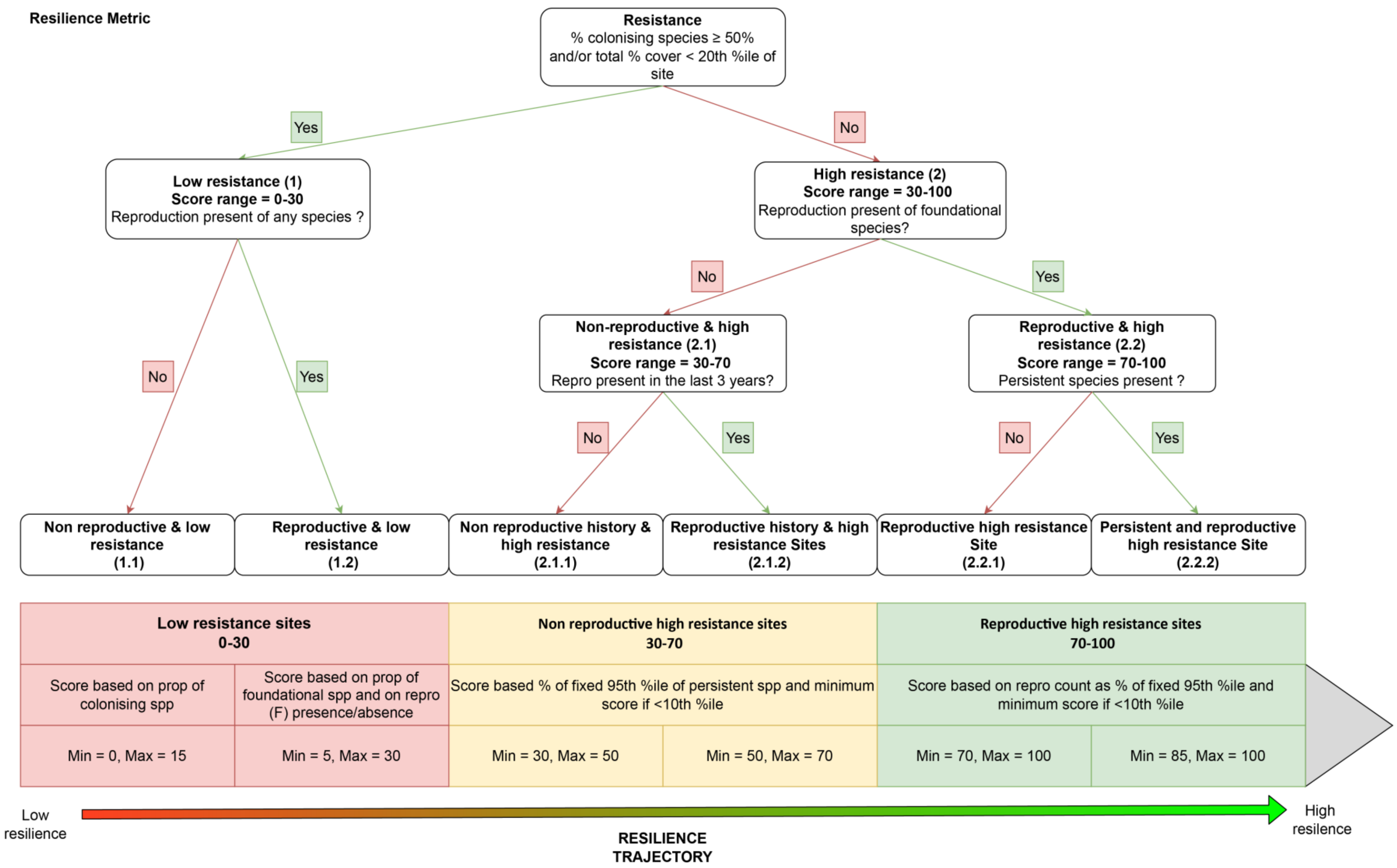

Figure 89. Overall structure of the proposed MMP resilience metric. The score ranges from 0 to 100. Splits in the tree are used to place a site in a grouping (red, yellow, or green), with grading within each grouping based on species composition and reproductive effort. Reproduction refers to sexual reproduction. From Collier *et al.* (2021a).

Appendix 2 Detailed data

Table 20. Samples collected at each inshore monitoring site per parameter for each season. Activities include: SG = seagrass cover & composition, SB=seed bank monitoring, EM=edge mapping, RH=reproductive effort, TL=temperature loggers, LL=light loggers. ^=subtidal.

Reef region	NRM region	Basin	Monitoring location		late dry Season (2021)						late wet Season (2022)					
					SG	SB	EM	RH	TL	LL	SG	SB	EM	RH	TL	LL
Far Northern	Cape York	Jacky Jacky / Olive Pascoe	Shelburne Bay	**SR1**	33	30	✓	15	✓							
				SR2	33	30	✓	15	✓	✓						
			Margaret Bay	**MA1**	10											
				MA2	10											
			Piper Reef	**FR1**	33	30	✓	15	✓							
				FR2	33	30	✓	15	✓	✓						
		Lockhart	Weymouth Bay	**YY1**												
			Lloyd Bay	**LR1^**	10											
				LR2^	10											
		Normanby / Jeanie	Flinders Group	**ST1**	33	30	✓	15	✓	✓						
				ST2	33	30	✓	15	✓							
				FG1^	10											
				FG2^	10											
			Bathurst Bay	**BY1**	33	30	✓	15	✓							
				BY2	33	30	✓	15	✓	✓						
				BY3^	10											
				BY4^	10											
		Endeavour	Archer Point	**AP1**												
				AP2												
Northern	Wet Tropics	Daintree	Low Isles	**LI1**	33	30	✓	15	✓	✓	33	30	✓	15	✓	✓
				LI2^	33			15			33		✓	15		
		Mossman / Barron / Mulgrave - Russell / Johnstone	Yule Point	**YP1**	33	30	✓	15	✓		33	30	✓	15	✓	
				YP2	33	30	✓	15	✓	✓	33	30	✓	15		
			Green Island	**GI1**	33	30	✓	15	✓	✓	33	30	✓	15	✓	✓
				GI2	33	30	✓	15	✓		33	30	✓	15	✓	
				GI3^	33		✓	15			33		✓	15		
		Tully / Murray / Herbert	Mission Beach	**LB1**	33	30	✓	15			33	30	✓	15		
				LB2	33	30	✓	15			33	30	✓	15		
			Dunk Island	**DI1**	33	30	✓	15	✓		33	30	✓	15	✓	
				DI2	33	30	✓	15	✓	✓	33	30	✓	15	✓	✓
				DI3^	33		✓	15			33		✓	15		
			Rockingham Bay	**GO1**												
			Missionary Bay	**MS1^**	10											
				MS2^	12											
Central	Burdekin	Ross / Burdekin	Magnetic Island	**MI1**	33	30	✓	15	✓		33	30	✓	15	✓	
				MI2	33	30	✓	15	✓	✓	33	30	✓	15	✓	✓
				MI3^	43		✓	15			33		✓	15		
			Townsville	**SB1**	33	30	✓	15	✓	✓	33	30	✓	15	✓	✓
				SB2	33	30			✓		33	30	✓	15	✓	
				BB1	33	30	✓	15	✓	✓	33	30	✓	15	✓	✓
			Bowling Green Bay	**JR1**	33	30	✓	15	✓	✓	33	30	✓	15	✓	✓
				JR2	33	30	✓	15	✓		33	30	✓	15	✓	
		Don	Bowen	**BW1**	33	30					33	30				

Reef region	NRM region	Basin	Monitoring location		late dry Season (2021)						late wet Season (2022)					
					SG	**SB**	**EM**	**RH**	**TL**	**LL**	**SG**	**SB**	**EM**	**RH**	**TL**	**LL**
				BW3	33	30					33	30				
	Mackay–Whitsunday	Don	Shoal Bay	**HB1**	33	30			✓		33	30			✓	
				HB2	33	30			✓		33	30			✓	
		Proserpine	Pioneer Bay	**PI2**	33	30			✓		33	30			✓	
				PI3	33	30			✓		33	30			✓	
		Proserpine / O'Connell	Repulse Bay	**MP2**	33	30	✓	15	✓	✓	33	30	✓	15	✓	✓
				MP3	33	30	✓	15	✓		33	30	✓	15	✓	
			Hamilton Is.	**HM1**	33	30	✓	15	✓		33	30	✓	15	✓	
				HM2	30	30	✓	15	✓	✓	30	30	✓	15	✓	✓
			Whitsunday Island	**TO1^**	10											
				TO2^	10											
		O'Connell	Lindeman Island	**LN1^**	37		✓	15			33	30	✓	15	✓	✓
				LN3	33	30	✓	15	✓	✓	33	30	✓	15	✓	✓
			St Helens Bay	**SH1**	33						33					
			Newry Islands	**NB1^**	10											
				NB2^	10											
		Plane	Sarina Inlet	**SI1**	33	30	✓	15	✓	✓	33	30	✓	15	✓	✓
				SI2	33	30	✓	15	✓		33	30	✓	15	✓	
			Clairview	**CV1**	33						33					
				CV2	33						33					
Southern	Fitzroy	Fitzroy	Shoalwater Bay	**RC1**	33	30	✓	15	✓							
				WH1	33	30	✓	15	✓	✓						
			Great Keppel Island	**GK1**	33	30	✓	15	✓	✓						
				GK2	33	30	✓	15	✓							
		Boyne	Gladstone Harbour	**GH1**	33	30	✓	15	✓	✓						
				GH2	33	30	✓	15	✓							
	Burnett–Mary	Burnett	Rodds Bay	**RD1**	33	30	✓	15	✓	✓						
				RD3	33	30	✓	15	✓							
		Burrum	Burrum Heads	**BH1**	33	30	✓	15	✓		33	30	✓	15	✓	
				BH3	33	30	✓	15	✓		33	30	✓	15	✓	
		Mary	Hervey Bay	**UG1**	33	30	✓	15	✓		33	30	✓	15	✓	
				UG2	33	30	✓	15	✓	✓	33	30	✓	15	✓	✓

A2.1 Environmental pressures

A2.1.1 Tidal exposure

Table 21. 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, 2022. * are predicted. 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 2020–22 (hrs)	Per cent of annual daylight hours meadow exposed (2020–22)
Cape York	AP1	0.46	1.02	0.46	54	1.30	44.83	1.02
	AP2	0.46	1.02	0.46	54	1.30	44.83	1.02
Wet Tropics	LI1	0.65	0.90	0.65	166.09	3.76	109.33	2.50
	YP1	0.64	0.94	0.64	158.92	3.60	103.67	2.37
	YP2	0.52	1.06	0.52	90.42	2.03	56.67	1.29
	GI1	0.51	1.03	0.61	115	2.59	87.67	2.00
	GI2	0.57	0.97	0.67	152.5	3.42	122.33	2.79
	DI1	0.65	1.14	0.54	74.17	1.65	51.33	1.17
	DI2	0.55	1.24	0.44	41.33	0.93	28.17	0.64
	LB1	0.42	1.37	0.31	17.17	0.40	10.33	0.24
	LB2	0.46	1.33	0.35	18.67	0.45	15.5	0.35
Burdekin	BB1	0.58	1.30	0.58	80.5	1.72	52.33	1.19
	SB1	0.57	1.31	0.57	64.5	1.43	49.33	1.13
	MI1	0.65	1.19	0.67	161.5	3.48	77.33	1.77
	MI2	0.54	1.30	0.56	149.17	2.98	46.33	1.06
	JR1	0.47	1.32	0.47	55.67	1.27	43.83	1.00
	JR2	0.47	1.32	0.47	55.67	1.27	43.83	1.00
Mackay–Whitsunday	PI2*	0.28	1.47	0.44	80.42	1.84	86.67	1.98
	PI3*	0.17	1.58	0.33	40.75	0.93	38.67	0.88
	HM1*	0.68	1.52	0.38	55.92	1.26	57.83	1.32
	HM2*	0.68	1.52	0.38	55.92	1.26	57.83	1.32
	SI1	0.60	2.80	0.54	25.83	0.61	26.83	0.61
	SI2	0.60	2.80	0.54	25.83	0.61	26.83	0.61
Fitzroy	RC1	2.03	1.30	1.06	168.17	4.14	218.83	5.00
	WH1	2.16	1.17	1.19	250	5.86	297	6.78
	GK1	0.52	1.93	0.43	33.33	0.79	6.67	0.15
	GK2	0.58	1.87	0.49	49.17	1.15	15.83	0.36
	GH1	0.80	1.57	0.69	96.17	2.25	79	1.80
	GH2	0.80	1.57	0.69	91.33	2.14	79	1.80
Burnett–Mary	RD1	0.56	1.48	0.56	67	1.61	46.33	1.06
	RD2	0.63	1.41	0.63	94.5	2.29	83.17	1.90
	UG1	0.70	1.41	0.70	141.5	3.13	182.5	4.17
	UG2	0.64	1.47	0.64	101.17	2.18	126.67	2.89

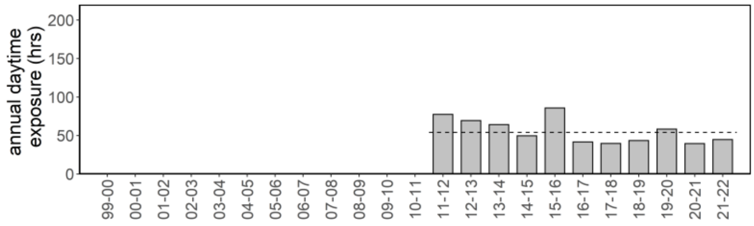

Figure 90. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of reef intertidal seagrass meadows at Archer Point, Cape York NRM region; 2011–2022. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 21. Observed tidal heights courtesy Maritime Safety Queensland, 2022. NB: Meadow heights have not yet been determined in the far northern Cape York sites.

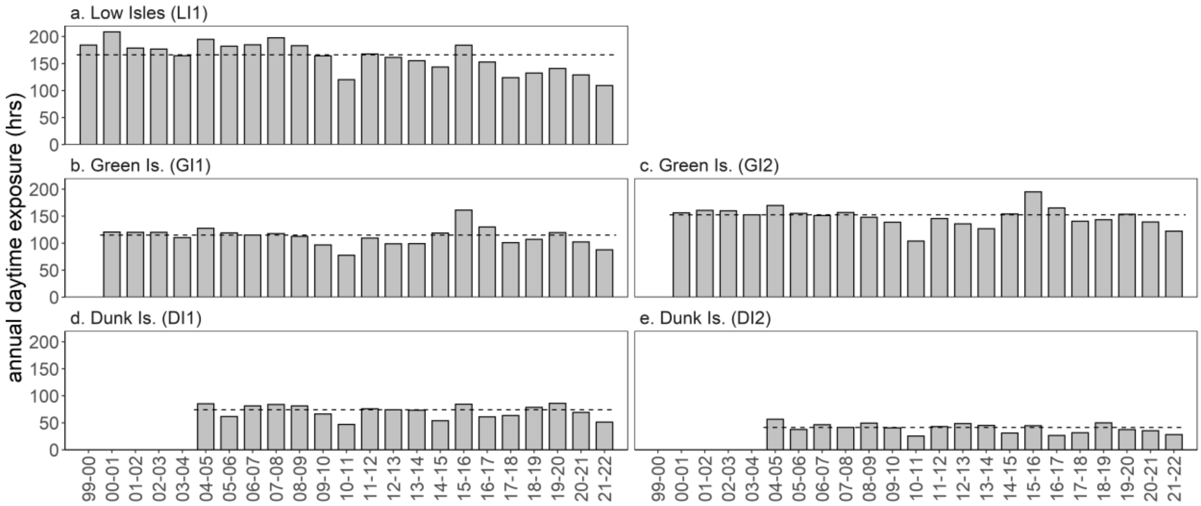

Figure 91. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of reef intertidal seagrass meadows in the Wet Tropics NRM region; 1999–2022. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 21. Observed tidal heights courtesy Maritime Safety Queensland, 2022.

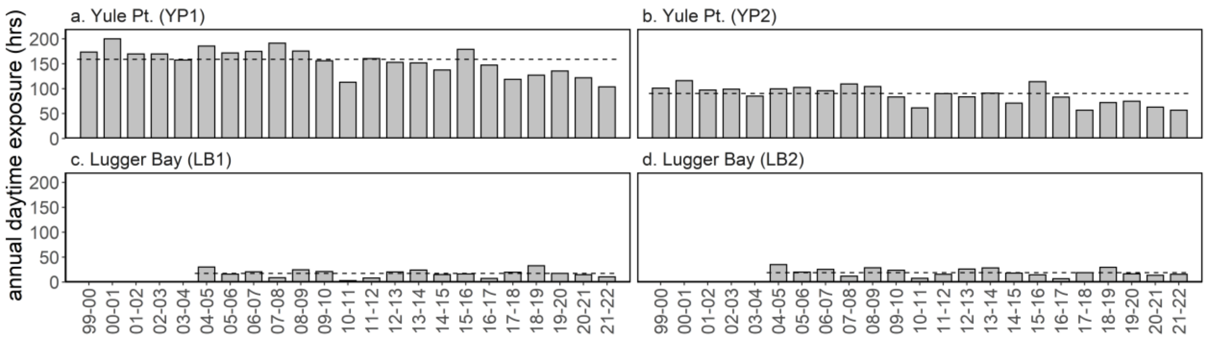

Figure 92. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of coastal intertidal seagrass meadows in Wet Tropics NRM region; 1999–2022. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 21. Observed tidal heights courtesy Maritime Safety Queensland, 2022.

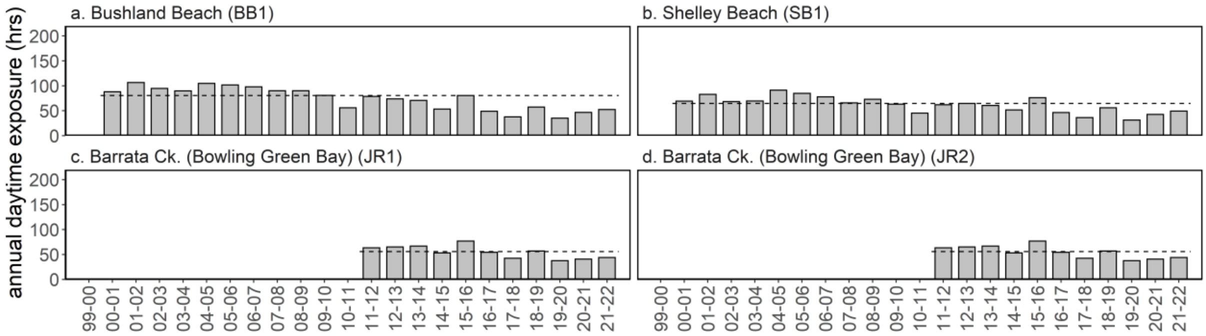

Figure 93. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of coastal intertidal seagrass meadows in Burdekin NRM region; 2000–2022. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 21. Observed tidal heights courtesy Maritime Safety Queensland, 2022.

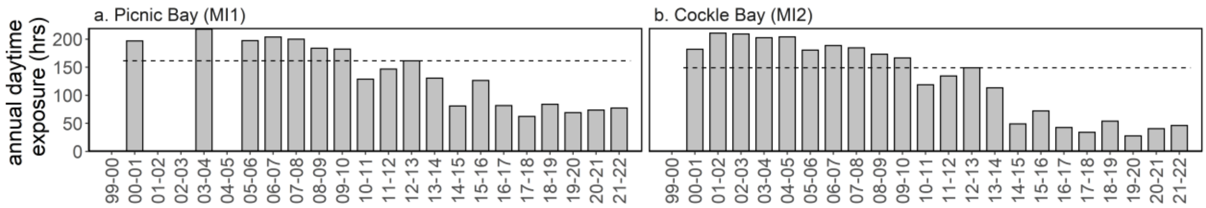

Figure 94. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of reef intertidal seagrass meadows in Burdekin NRM region; 2000–2022. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 21. Observed tidal heights courtesy Maritime Safety Queensland, 2022.

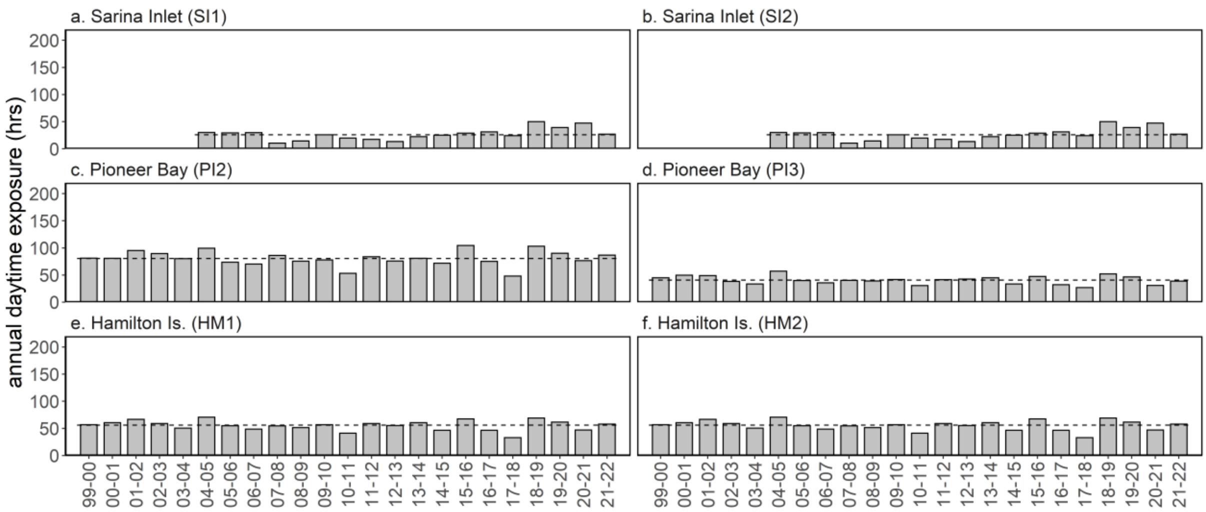

Figure 95. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of estuarine intertidal (a, b) coastal intertidal (c, d) and reef intertidal (e, f) seagrass meadows in Mackay–Whitsunday NRM region; 1999–2022. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 21. Observed tidal heights courtesy Maritime Safety Queensland, 2022.

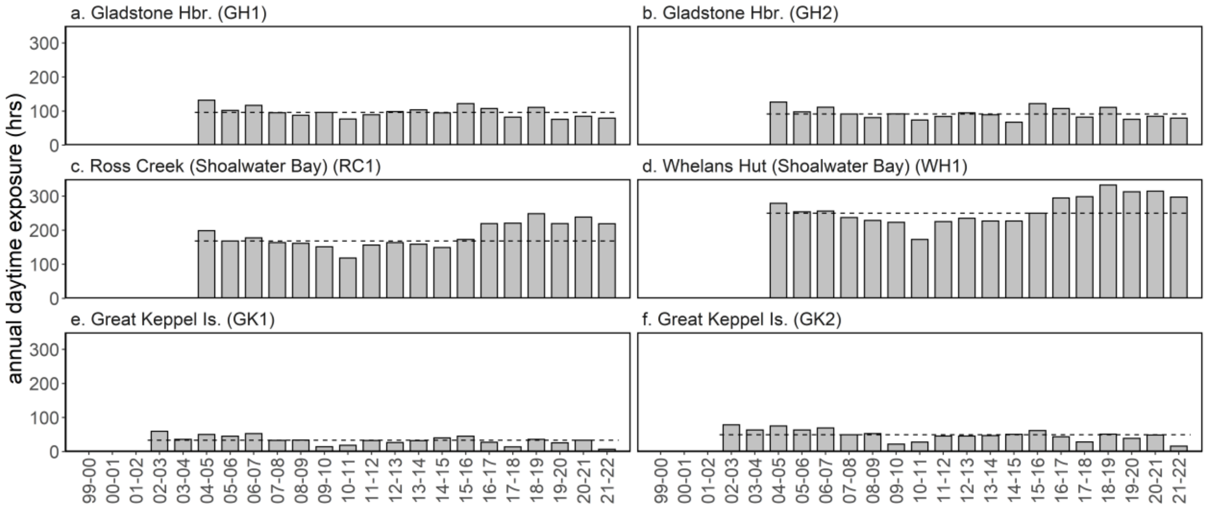

Figure 96. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of estuarine intertidal (a, b) coastal intertidal (c, d) and reef intertidal (e, f) seagrass meadows in the Fitzroy NRM region; 1999–2022. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 21. Observed tidal heights courtesy Maritime Safety Queensland, 2022.

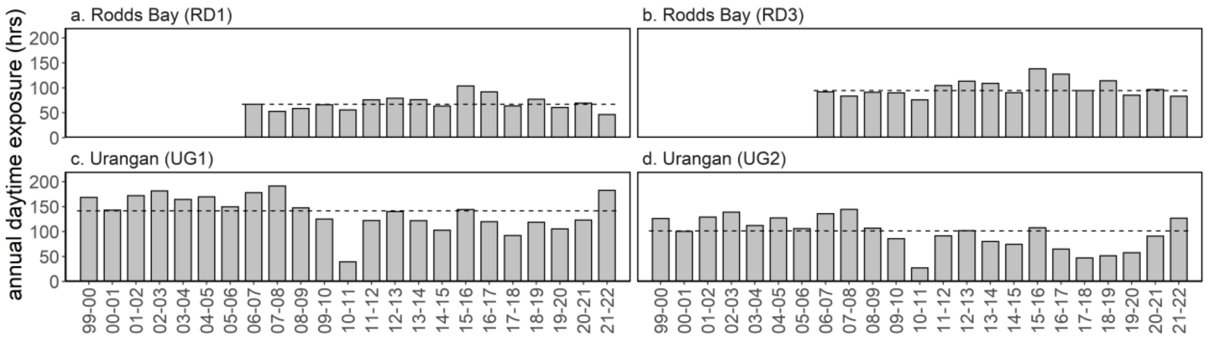

Figure 97. Annual daytime tidal exposure (total hours) and long-term median (dashed line) of estuarine intertidal seagrass meadows in the Burnett–Mary NRM region; 1999–2022. Year is June–May. For tidal exposure (when intertidal banks become exposed at a low tide) height at each site, see Table 21. Observed tidal heights courtesy Maritime Safety Queensland, 2022.

A2.1.2 Light at seagrass canopy

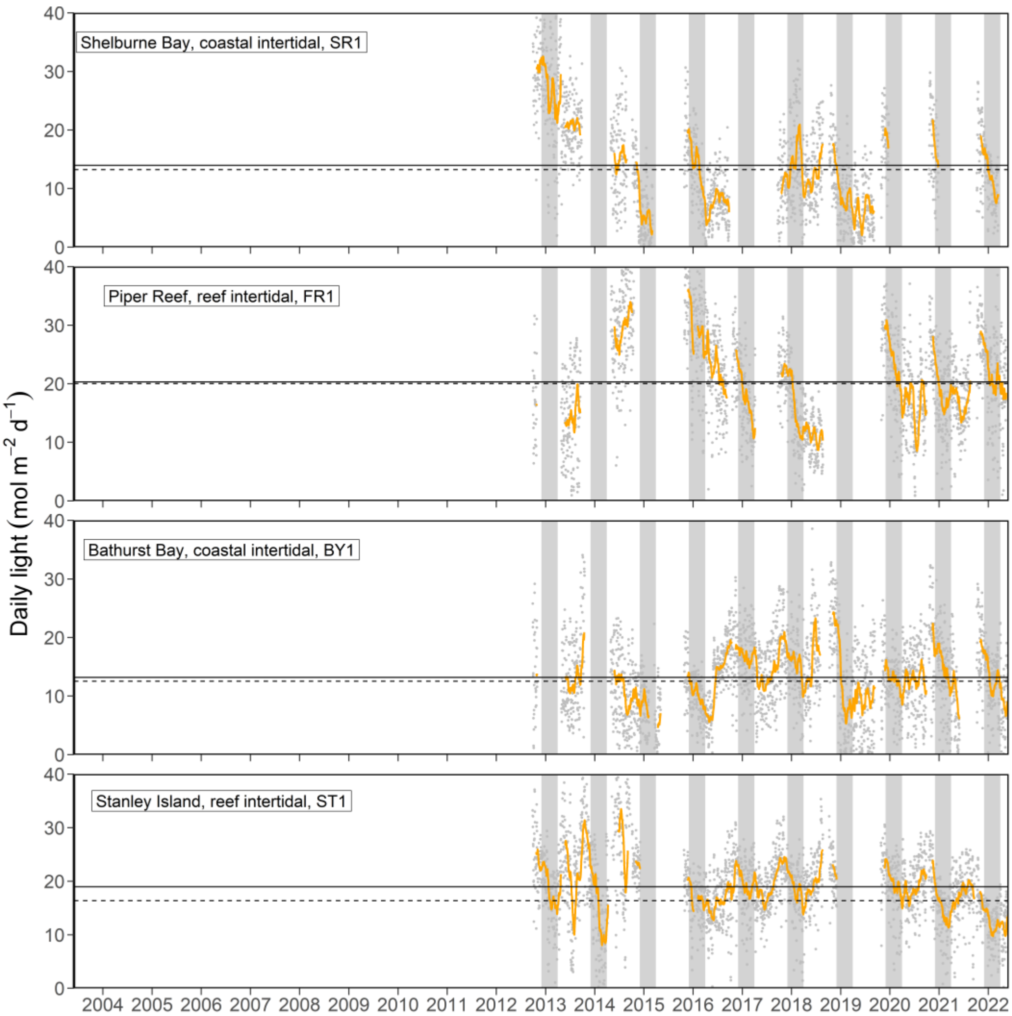

Figure 98. Daily light (yellow points) and 28-day rolling average (orange, bold line) at monitoring locations in the Cape York NRM region.

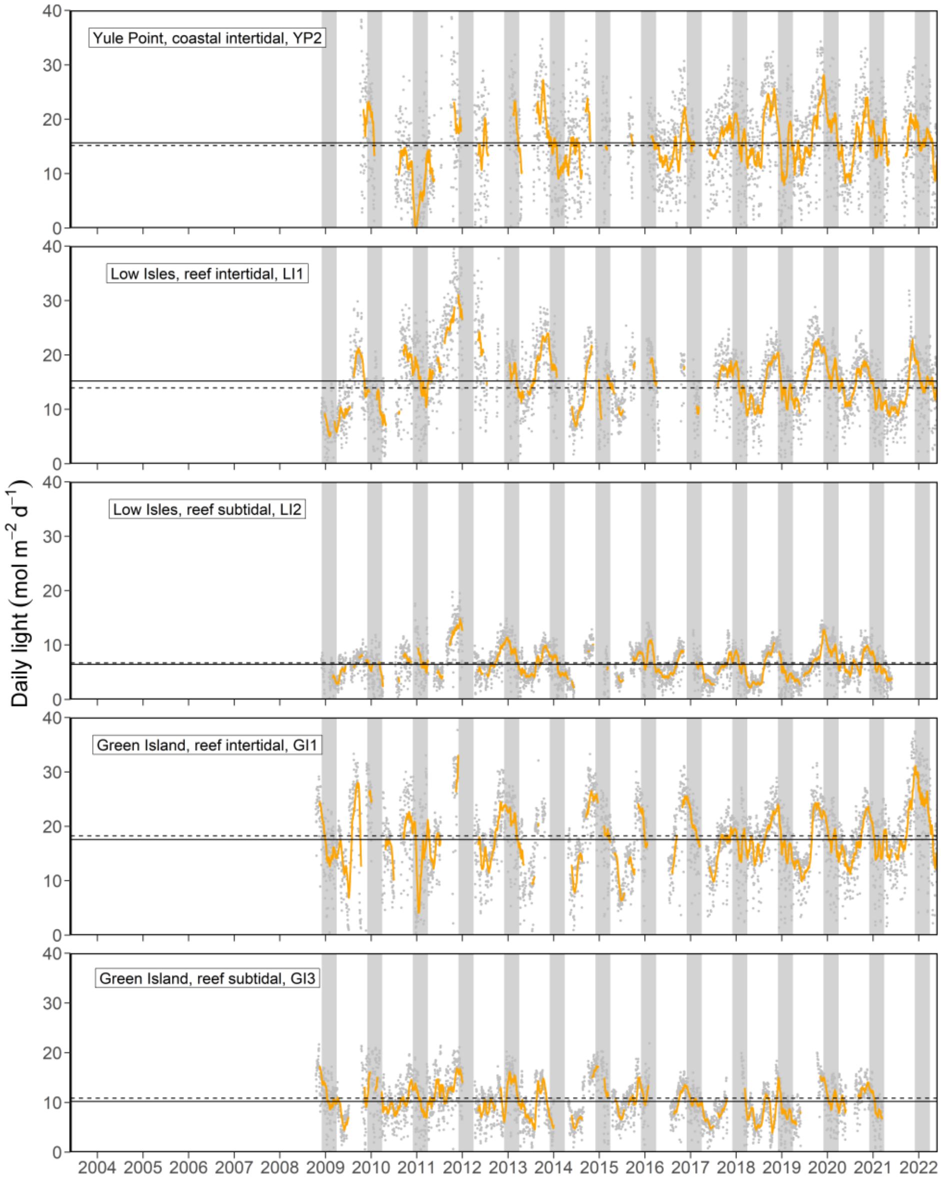

Figure 99. Daily light (yellow line) and 28-day rolling average (orange, bold line) at monitoring locations in the northern Wet Tropics.

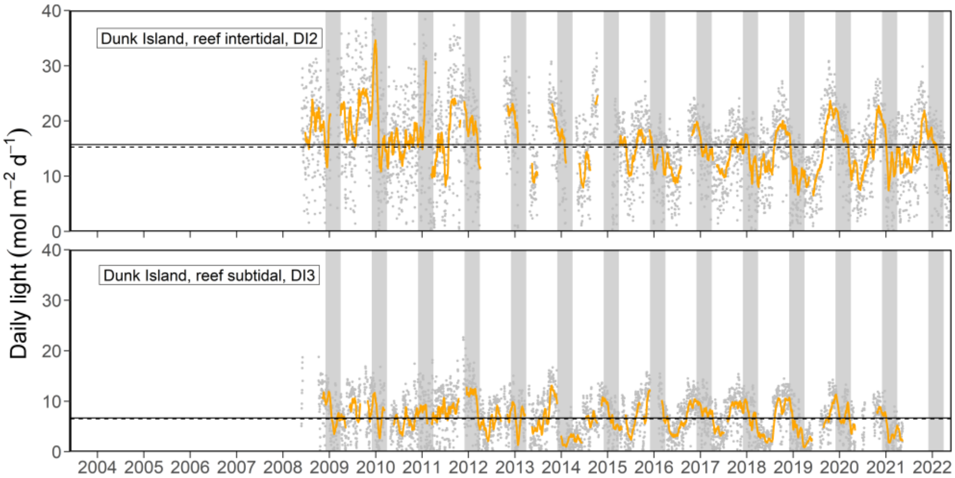

Figure 100. Daily light (yellow line) and 28-day rolling average (orange, bold line) at monitoring locations in the southern Wet Tropics.

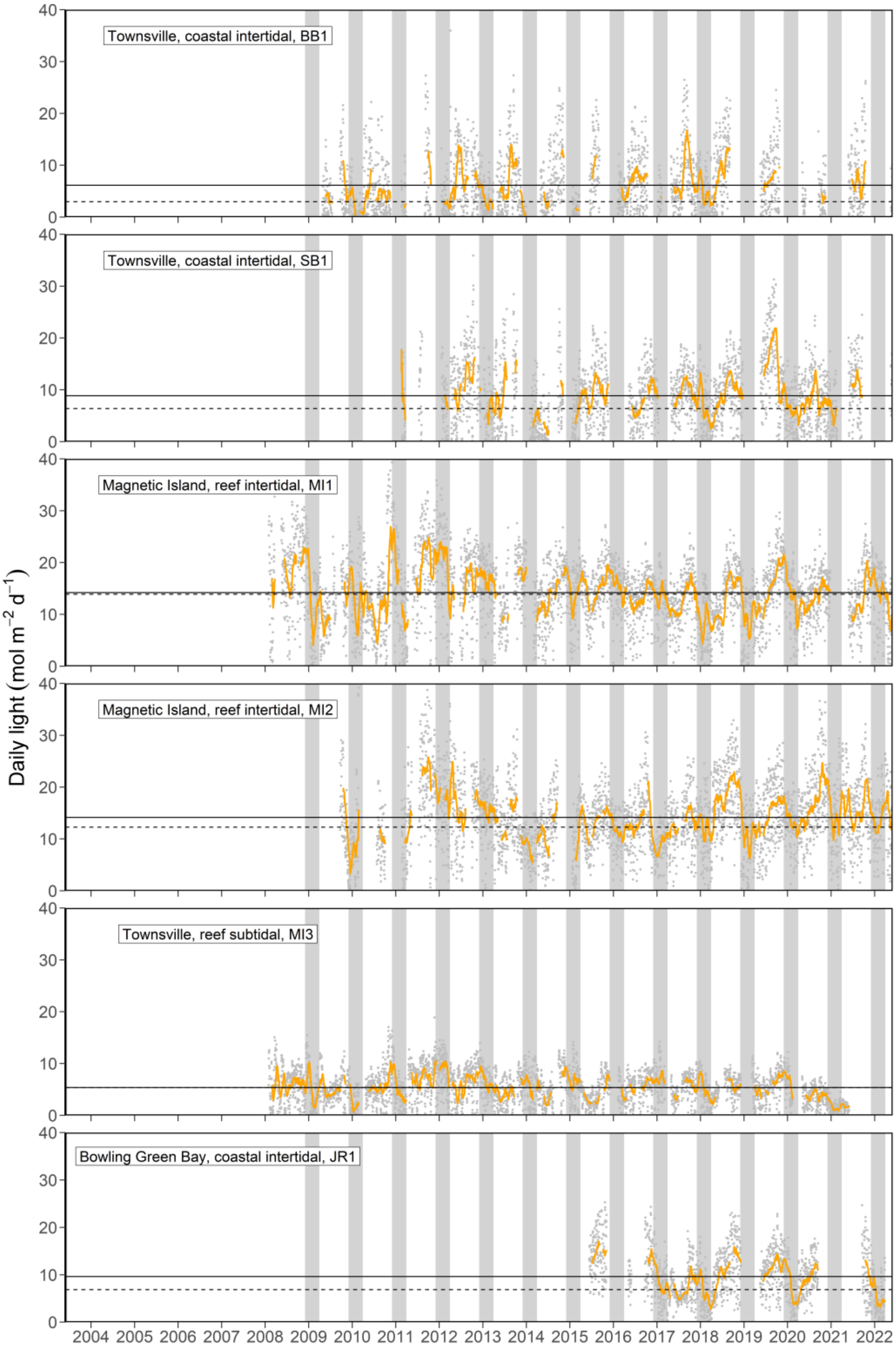

Figure 101. Daily light (yellow line) and 28-day rolling average (orange, bold line) at monitoring locations in the Burdekin region.

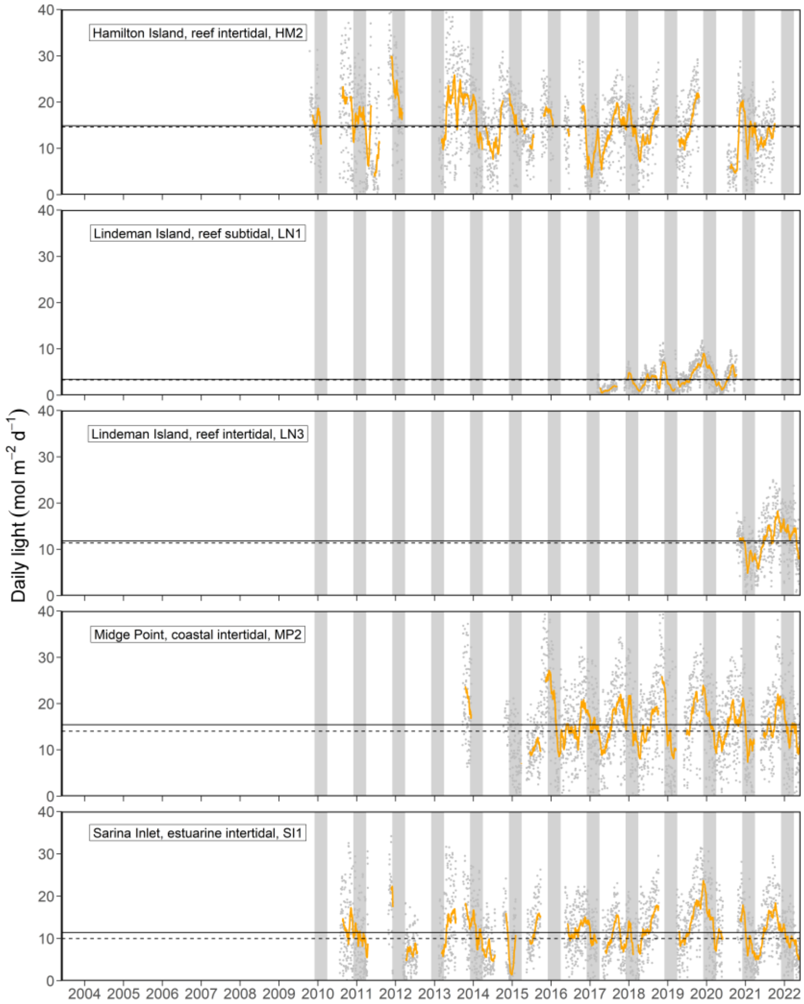

Figure 102. Daily light (yellow line) and 28-day rolling average (orange, bold line) at monitoring locations in the Mackay–Whitsunday NRM region.

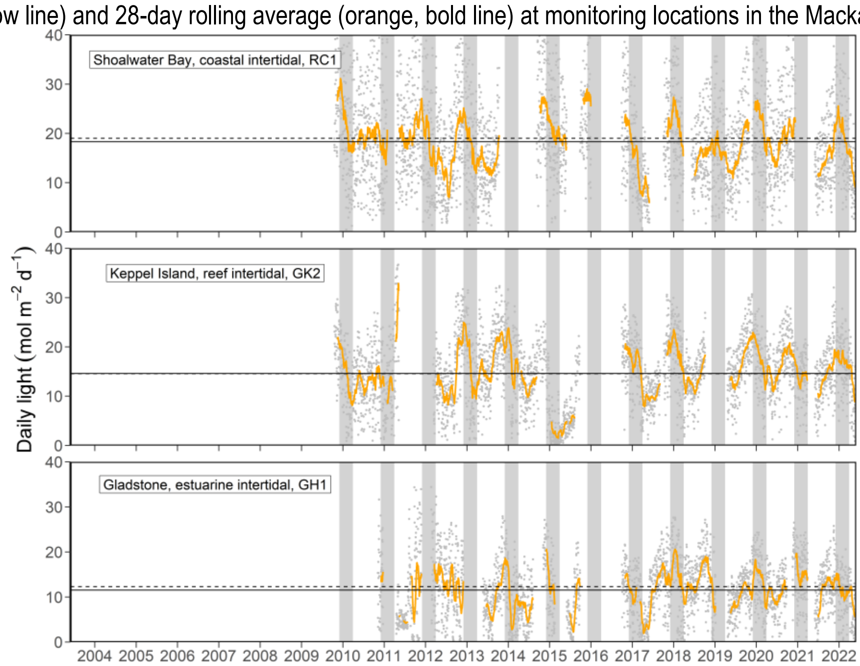

Figure 103. Daily light (yellow line) and 28-day rolling average (orange, bold line) at monitoring locations in the Fitzroy NRM region.

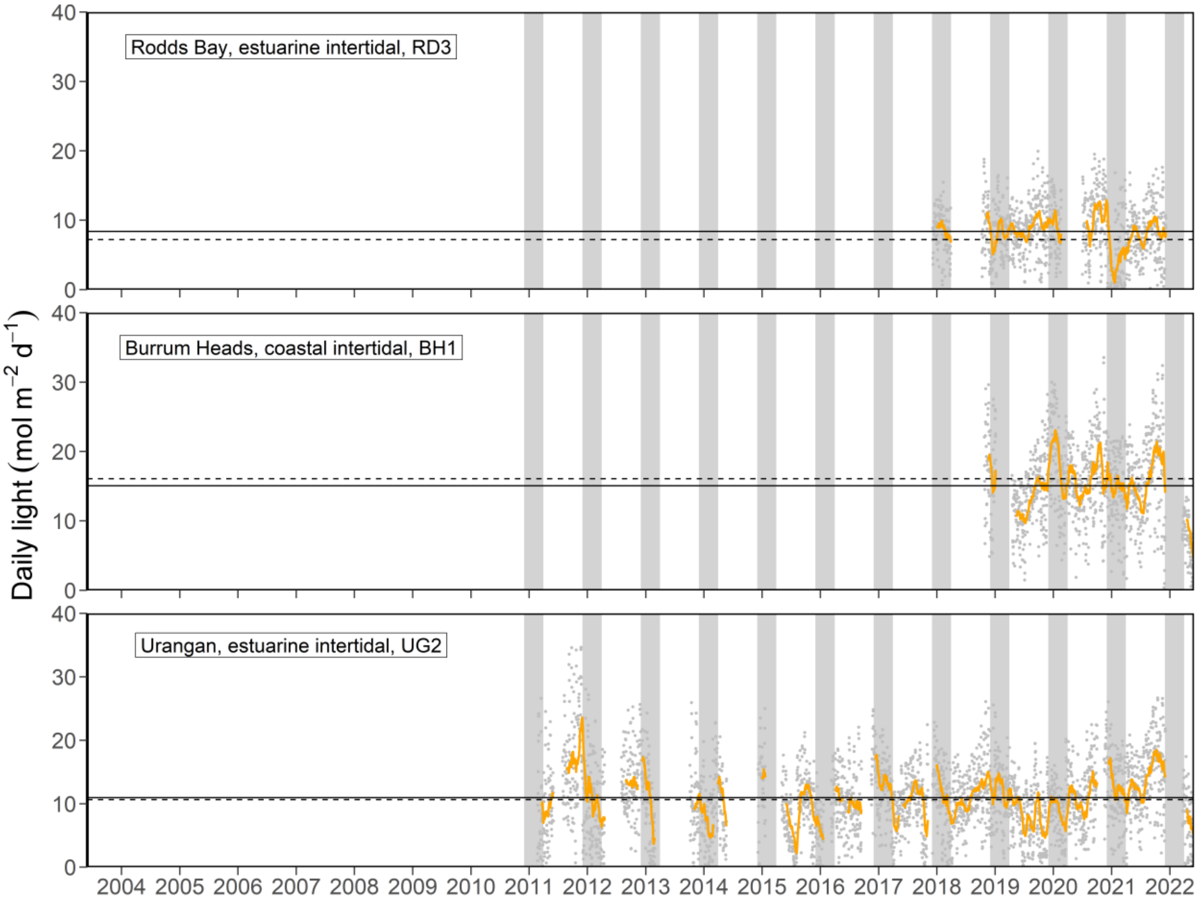

Figure 104. Daily light (yellow line) and 28-day rolling average (orange, bold line) at monitoring locations in the Burnett–Mary NRM region.

A2.2 Seagrass habitat condition: Sediments composition

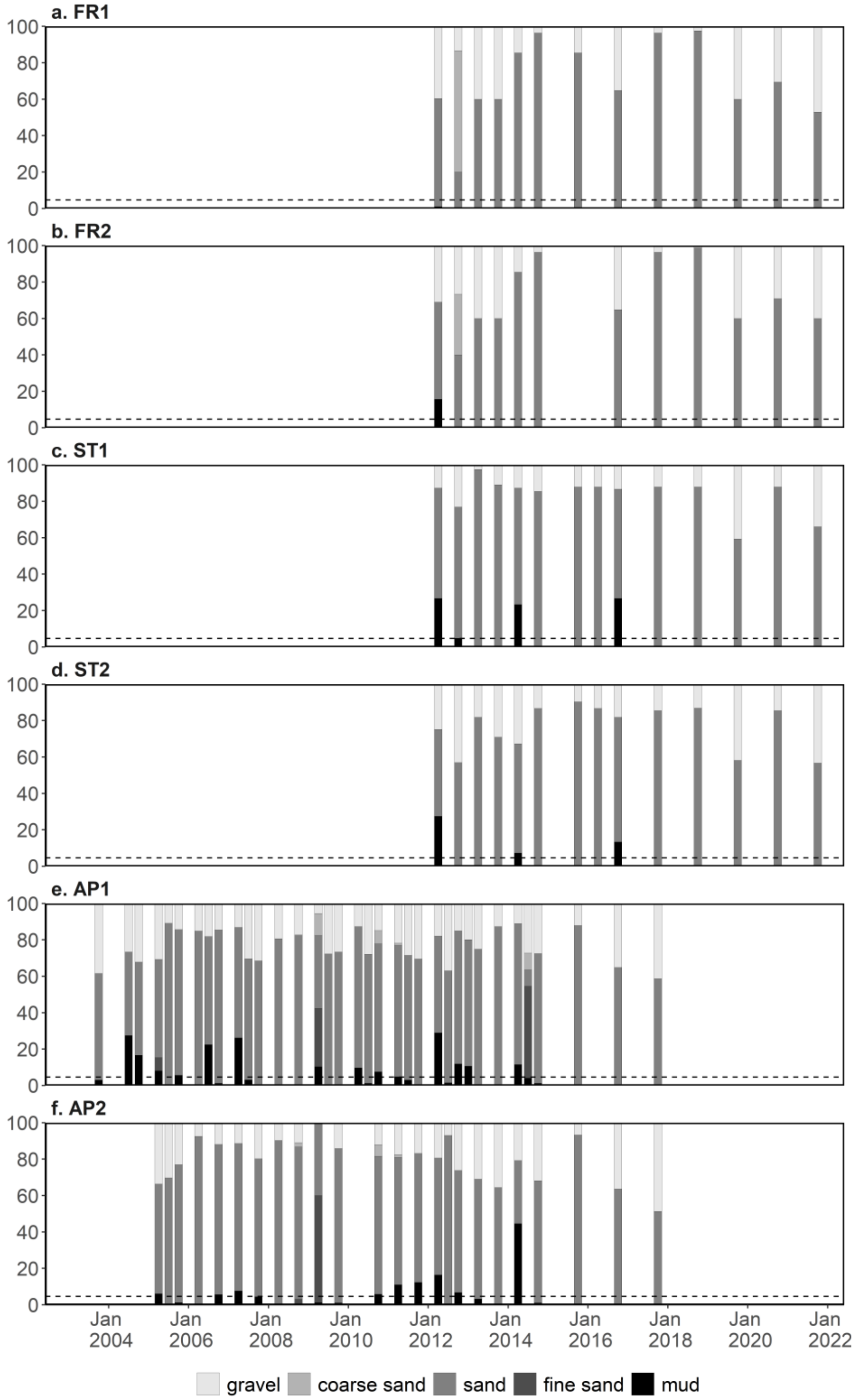

Figure 105. Sediment grain size composition at reef habitat monitoring sites in the Cape York region, 2003–2022. Dashed line is the Reef long-term average proportion of mud.

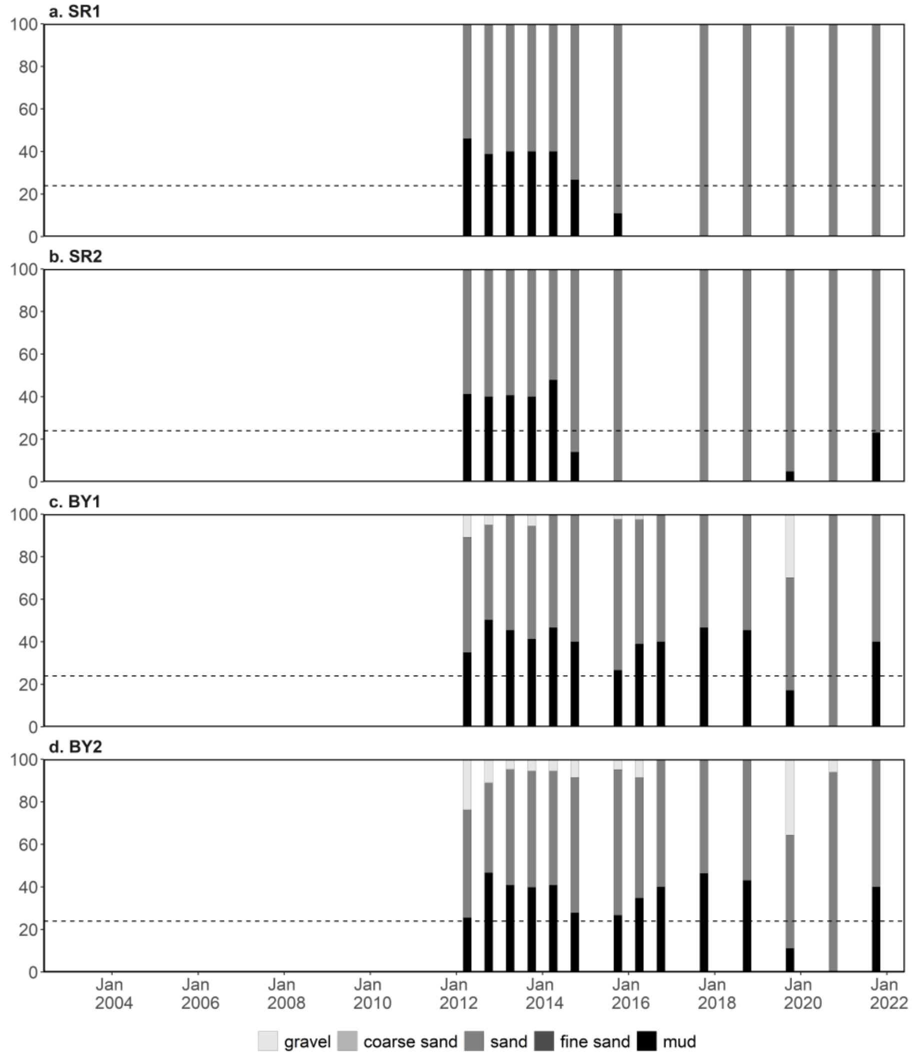

Figure 106. Sediment grain size composition at coastal habitat monitoring sites in the Cape York region, 2012–-2022. Dashed line is the Reef long-term average proportion of mud.

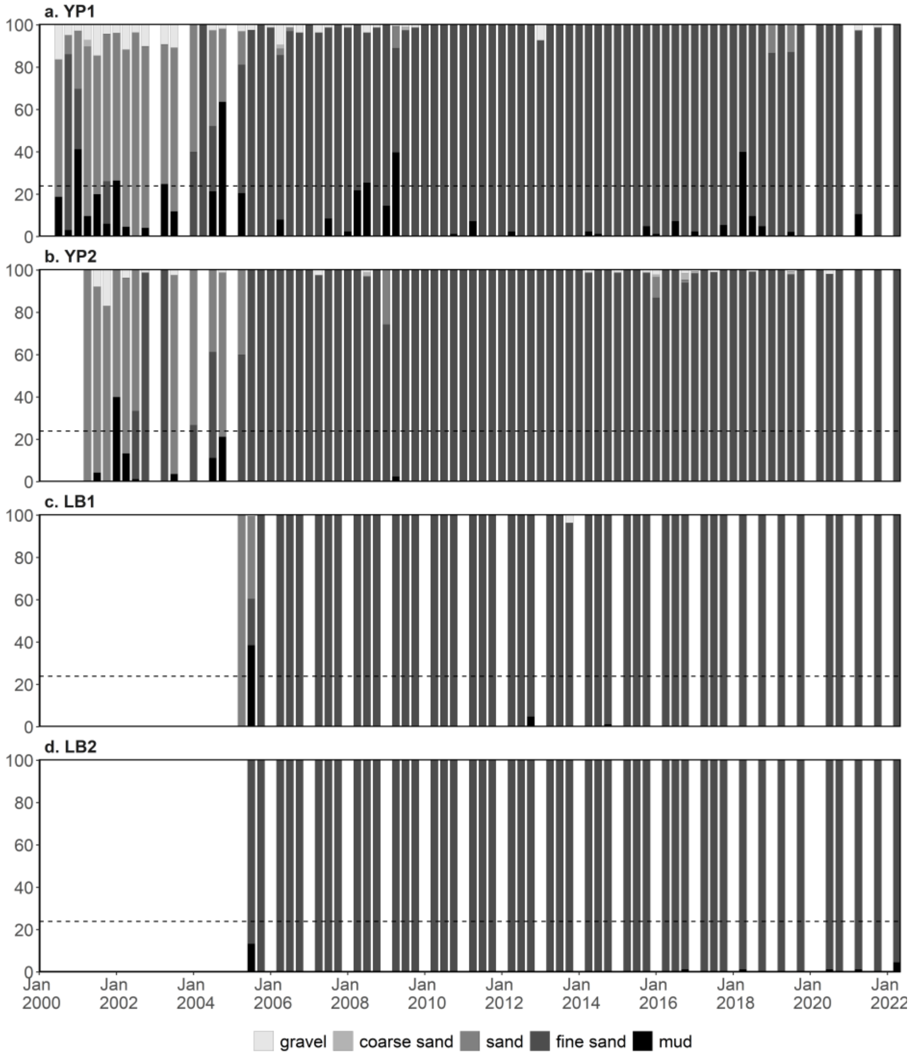

Figure 107. Sediment grain size composition at coastal intertidal habitat monitoring sites in the Wet Tropics region, 2001–2022. Dashed line is the Reef long-term average proportion of mud.

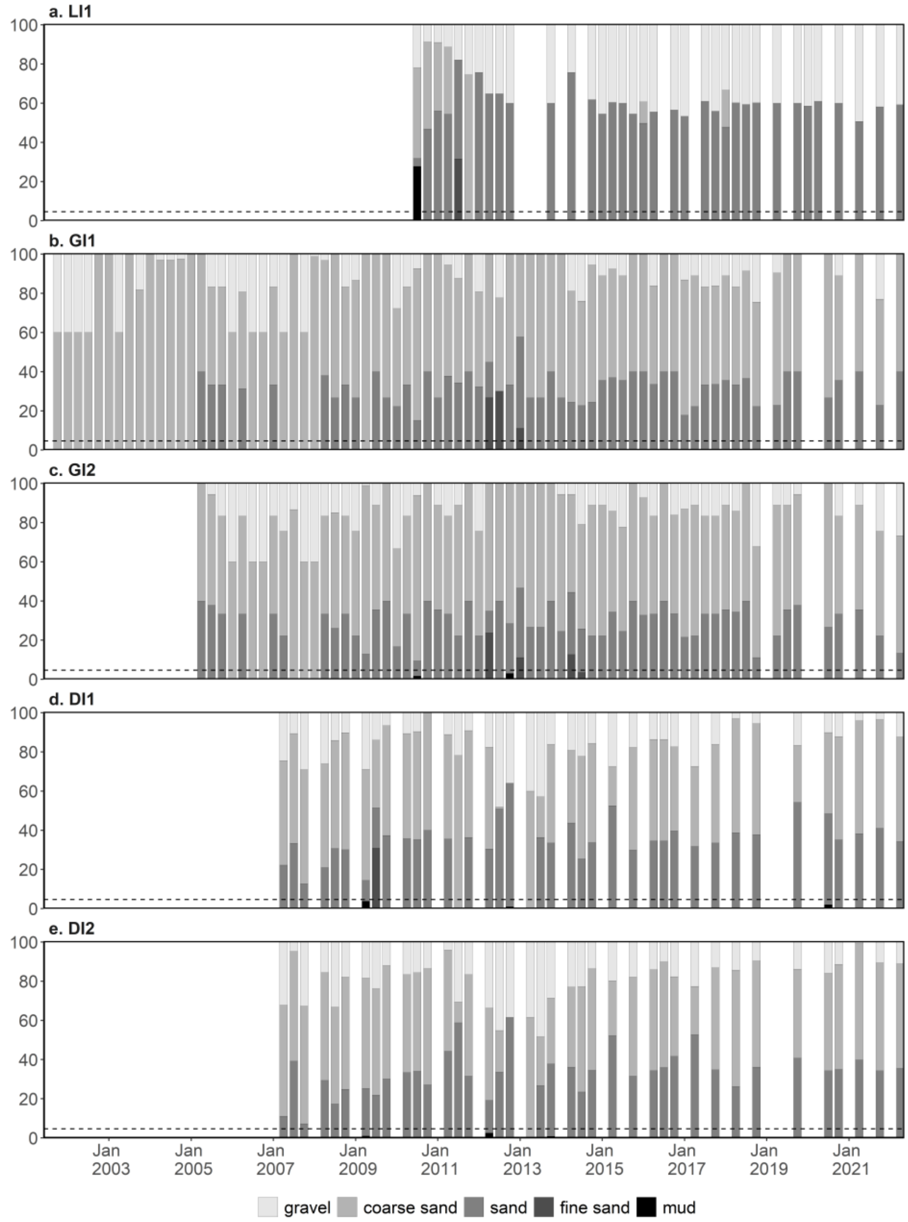

Figure 108. Sediment grain size composition at intertidal reef habitat monitoring sites in the Wet Tropics region, 2001–2022. Dashed line is the Reef long-term average proportion of mud.

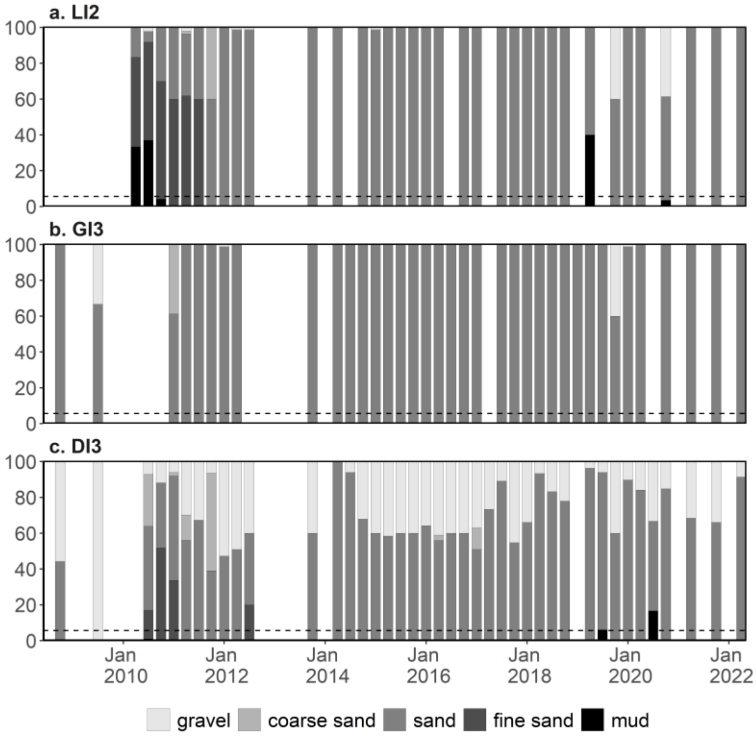

Figure 109. Sediment grain size composition at subtidal reef habitat monitoring sites in the Wet Tropics region, 2008–2022. Dashed line is the Reef long-term average proportion of mud.

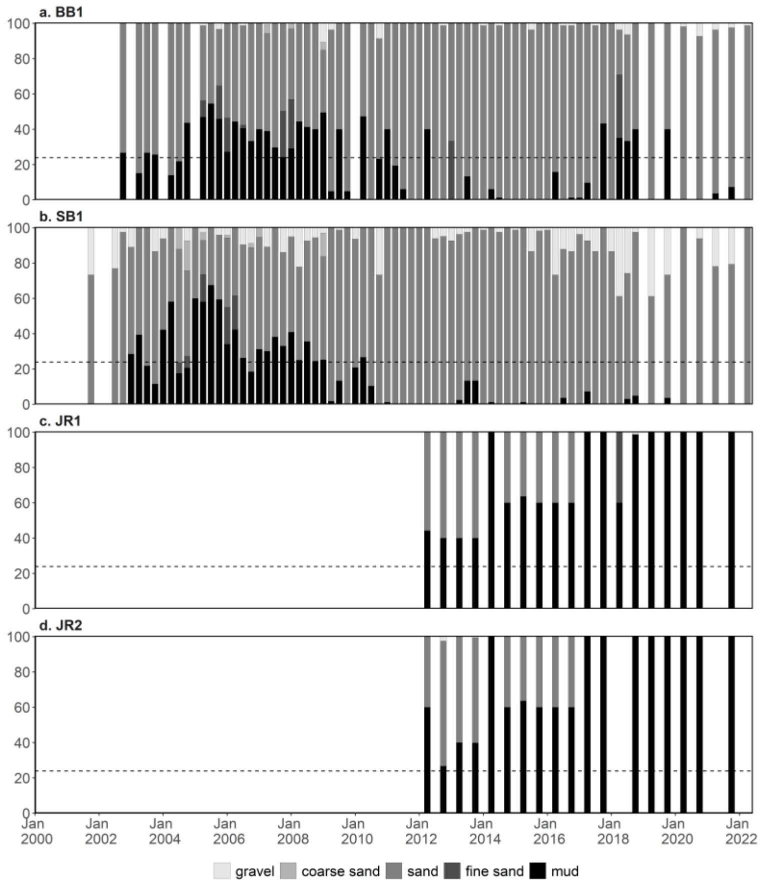

Figure 110. Sediment grain size composition at coastal intertidal habitat monitoring sites in the Burdekin region, 2001–2022. Dashed line is the Reef long-term average proportion of mud.

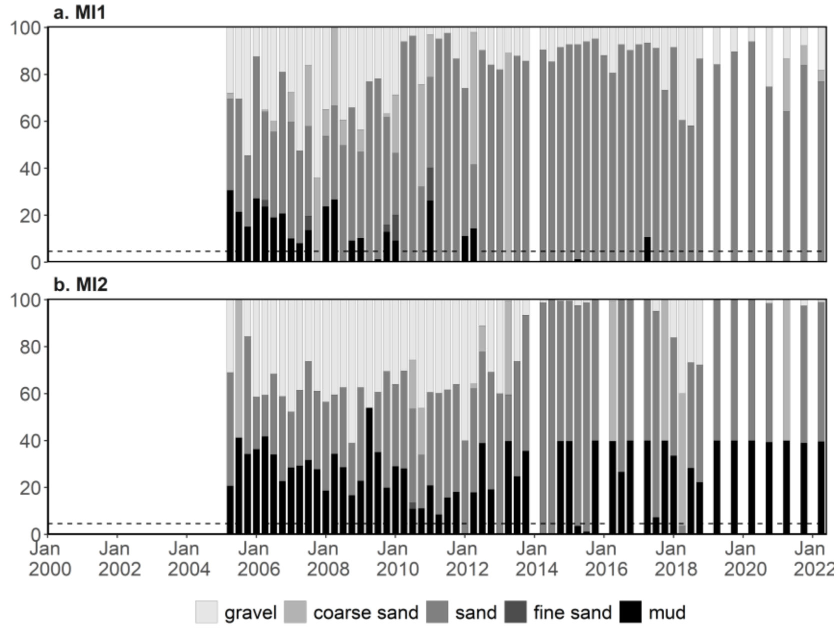

Figure 111. Sediment grain size composition at intertidal reef habitat monitoring sites in the Burdekin region, 2004–2022. Dashed line is the Reef long-term average proportion of mud.

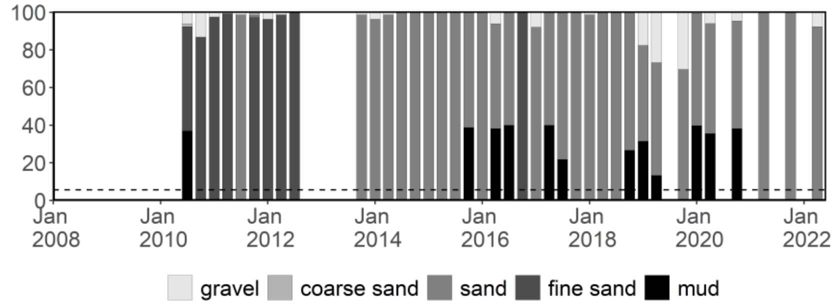

Figure 112. Sediment grain size composition at subtidal reef habitat monitoring sites in the Burdekin region, 2010–2022. Dashed line is the Reef long-term average proportion of mud.

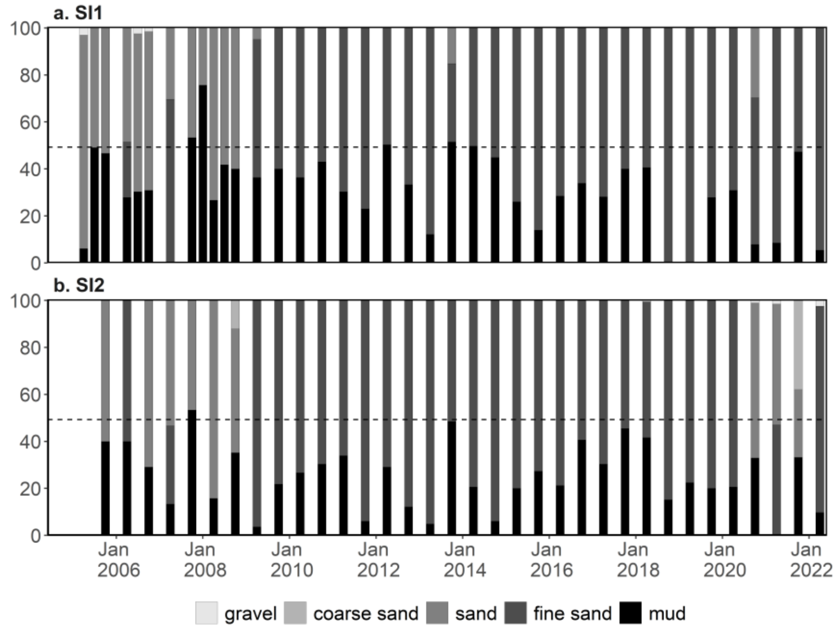

Figure 113. Sediment grain size composition at intertidal estuarine habitat monitoring sites in the Mackay–Whitsunday region, 2005–2022. Dashed line is the Reef long-term average proportion of mud.

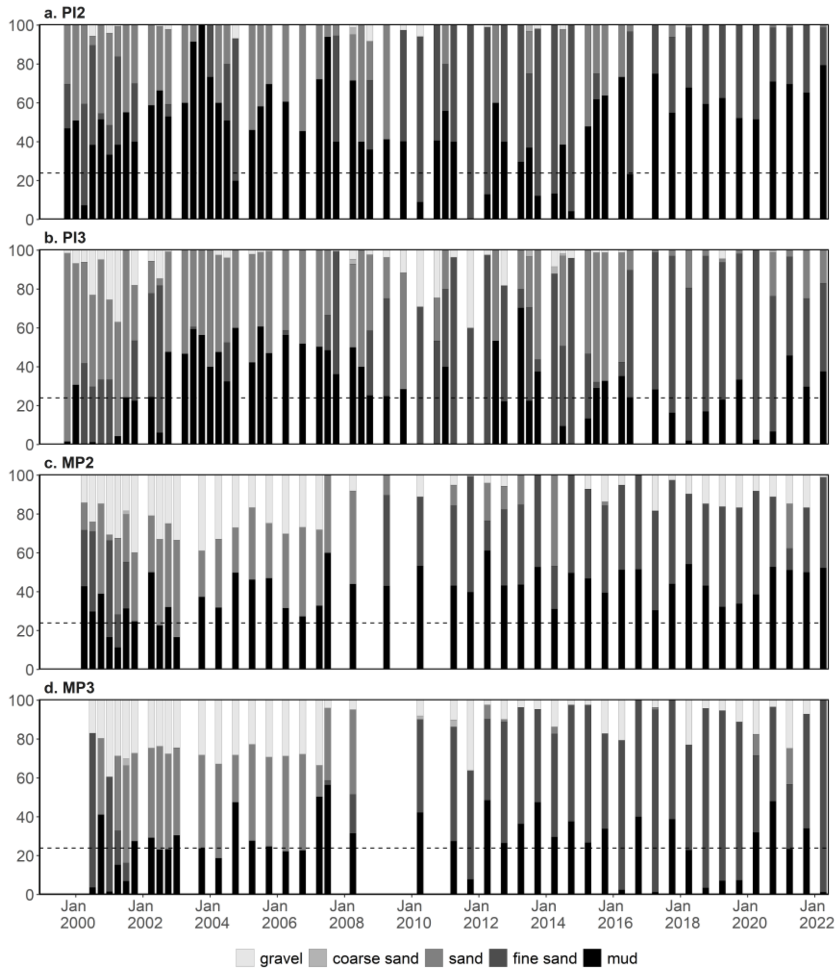

Figure 114. Sediment grain size composition at coastal intertidal habitat monitoring sites in the Mackay–Whitsunday region, 1999–2022. Dashed line is the Reef long-term average proportion of mud.

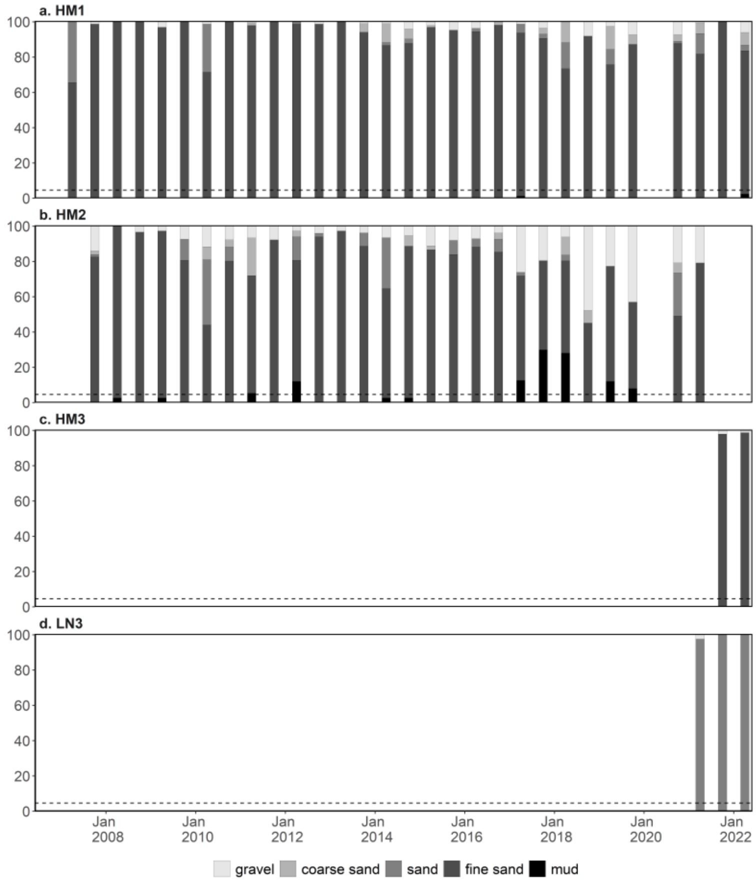

Figure 115. Sediment grain size composition at reef intertidal habitat monitoring sites in the Mackay–Whitsunday region, 2007–2022. Dashed line is the Reef long-term average proportion of mud.

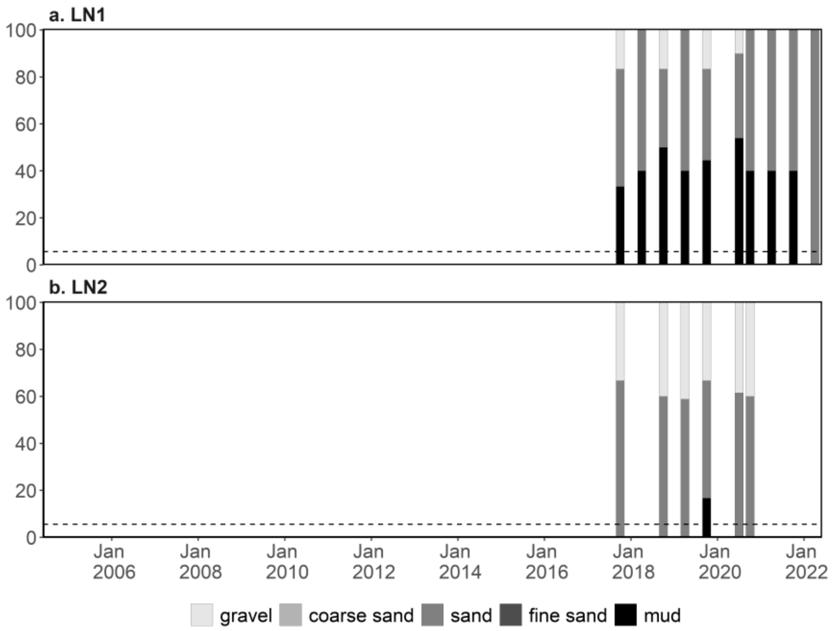

Figure 116. Sediment grain size composition at reef subtidal habitat monitoring sites in the Mackay–Whitsunday region, 2017–2022. Dashed line is the Reef long-term average proportion of mud.

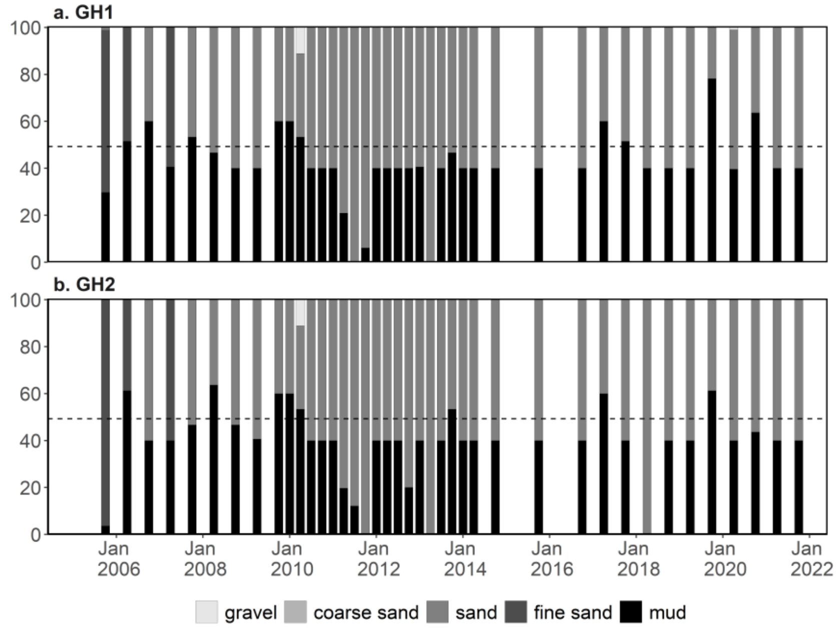

Figure 117. Sediment grain size composition at estuarine intertidal habitat monitoring sites in the Fitzroy region, 2005–2022. Dashed line is the Reef long-term average proportion of mud.

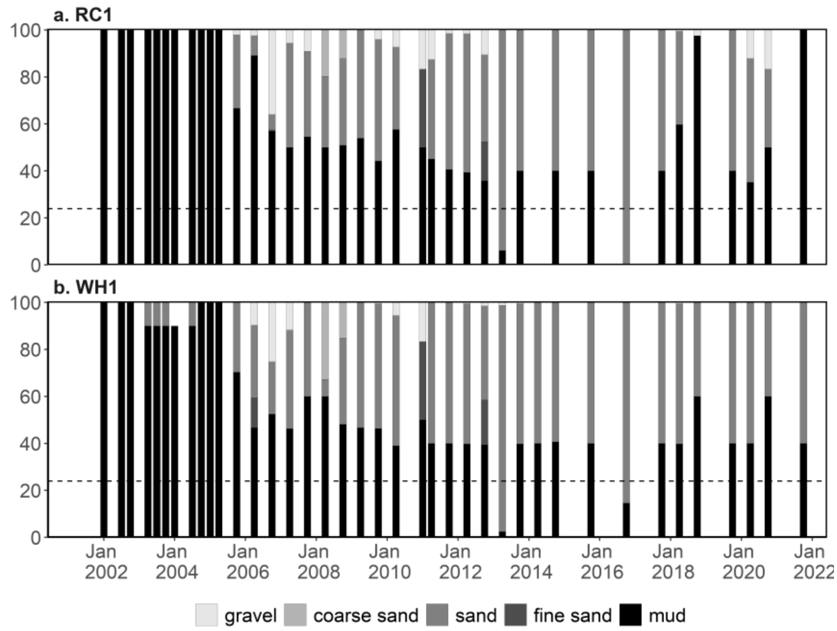

Figure 118. Sediment grain size composition at coastal intertidal habitat monitoring sites in the Fitzroy region, 2005–2022. Dashed line is the Reef long-term average proportion of mud.

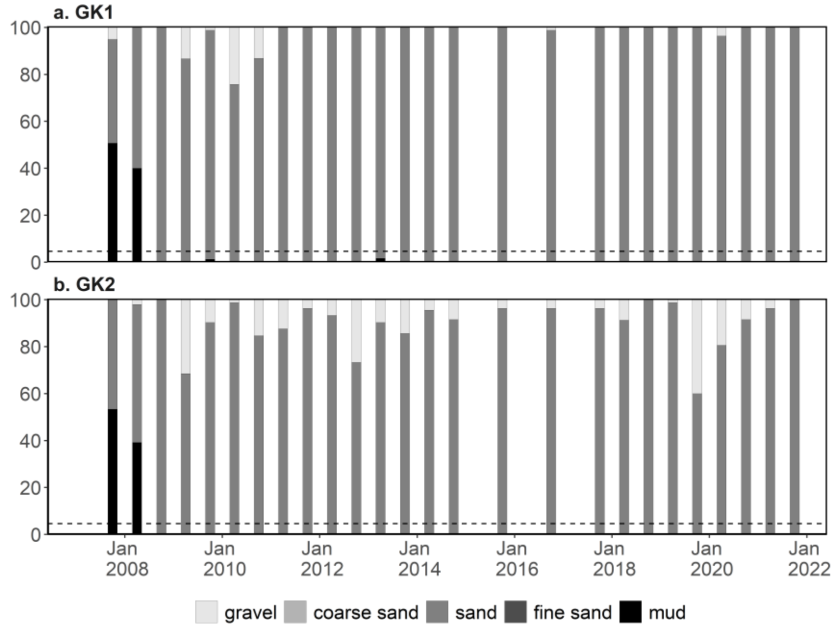

Figure 119. Sediment grain size composition at reef intertidal habitat monitoring sites in the Fitzroy region, 2007–2022. Dashed line is the Reef long-term average proportion of mud.

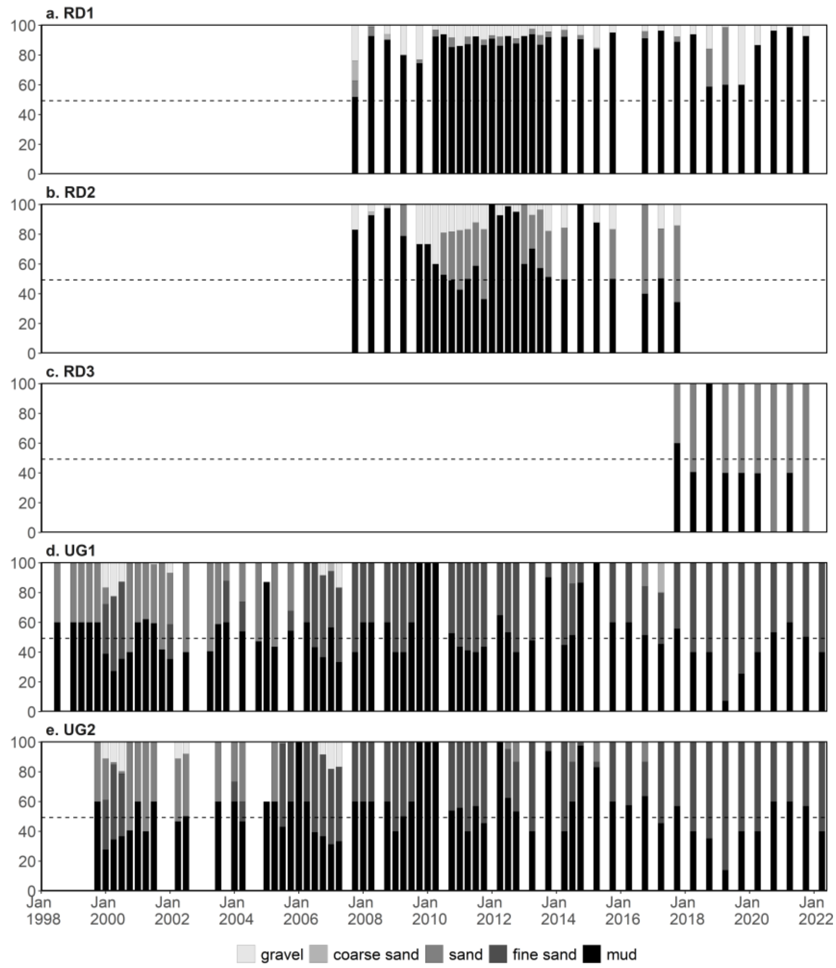

Figure 120. Sediment grain size composition at estuarine intertidal habitat monitoring sites in the Burnett–Mary region, 1999–2022. Dashed line is the Reef long-term average proportion of mud.

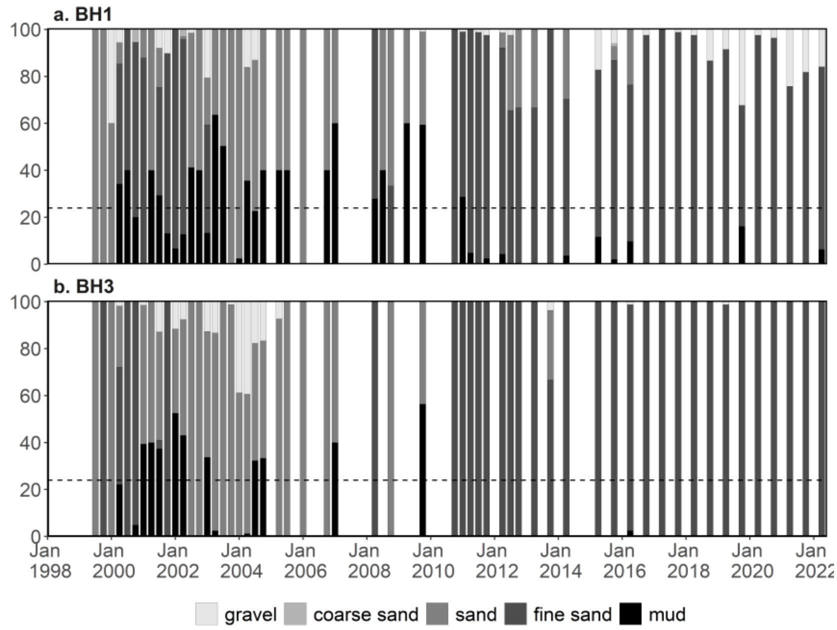

Figure 121. Sediment grain size composition at coastal intertidal habitat monitoring sites in the Burnett–Mary region, 1999–2022. Dashed line is the Reef long-term average proportion of mud.

Appendix 3 Results of statistical analysis

Table 22. 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	2021	14	0.0549	0.8266	0.206	no trend
		BY2	2012	2021	14	-0.0110	1	-0.067	no trend
		SR1	**2012**	**2021**	**12**	**-0.485**	**0.034**	**-0.543** (-0.892 to -0.144)	**decrease**
		SR2	2012	2021	12	-0.198	0.409	-0.152	no trend
	coastal subtidal	BY3	2019	2021	3	1.000	0.296	5.658	no trend
		BY4	2017	2021	4	0.000	1.000	0.762	no trend
		LR1	2015	2021	6	-0.067	1.000	-0.229	no trend
		LR2	2015	2021	6	-0.200	0.707	-2.794	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	2021	13	-0.245	0.271	-0.246	no trend
		FR2	**2012**	**2021**	**12**	**-0.515**	**0.024**	**-1.291** (-2.045 to -0.591)	**decrease**
		ST1	**2012**	**2021**	**14**	**0.626**	**0.002**	**0.674** (0.406 to 1.082)	**Increase**
		ST2	**2012**	**2021**	**14**	**0.751**	**<0.001**	**0.731** (0.527 to 0.962)	**increase**
		YY1	2012	2014	3	0.333	1.0000	1.045	no trend
	reef subtidal	FG1	2016	2021	6	-0.067	1.000	-1.300	no trend
		FG2	2016	2021	6	-0.067	1.000	-1.700	no trend
	pooled		2003	2021	40	**-0.387**	**<0.001**	**-0.256** (-0.386 to -0.097)	**decrease**
Wet Tropics	coastal intertidal	**LB1**	**2005**	**2022**	**48**	**-0.377**	**<0.001**	**-0.022** (-0.076 to 0)	**decrease**
		LB2	**2005**	**2022**	**47**	**-0.213**	**0.044**	**-0.015** (-0.061 to 0)	**decrease**
		YP1	**2000**	**2022**	**81**	**0.177**	**0.019**	**0.116** (0.020 to 0.214)	**increase**
		YP2	2001	2022	77	0.151	0.052	0.068	no trend
	coastal subtidal	MS1	2017	2021	5	-0.200	0.806	-0.718	no trend
		MS2	2015	2021	6	0.333	0.452	1.988	no trend
	reef intertidal	DI1	2007	2022	39	0.026	0.828	0.016	no trend

NRM region	Habitat	Site	First Year	Last Year	*n*	*Kendall-τ*	*p* (2-sided)	Sen's slope (confidence interval)	trend
		DI2	2007	2022	39	0.073	0.521	0.042	no trend
		GI1	2001	2022	77	-0.080	0.303	-0.042	no trend
		GI2	2005	2022	63	-0.010	0.910	-0.012	no trend
		GO1	2008	2016	7	-0.429	0.2296	-1.682	no trend
		LI1	**2008**	**2022**	**45**	**-0.257**	**0.013**	**-0.093** (-0.176 to -0.028)	**decrease**
	reef subtidal	DI3	2008	2022	51	-0.006	0.955	0.000	no trend
		GI3	**2008**	**2022**	**48**	**-0.266**	**0.008**	**-0.364** (-0.599 to -0.105)	**decrease**
		LI2	**2008**	**2022**	**45**	**0.201**	**0.053**	**0.108** (0 to 0.226)	**increase**
	pooled		2000	2022	90	-0.123	0.088	-0.054	no trend
Burdekin	coastal intertidal	BB1	2002	2022	68	0.010	0.911	0.004	no trend
		SB1	2001	2022	74	-0.036	0.651	-0.023	no trend
		SB2	2001	2022	73	-0.137	0.088	-0.114	no trend
		JR1	2012	2021	19	0.181	0.294	0.727	no trend
		JR2	**2012**	**2021**	**18**	**0.359**	**0.041**	**1.485** (0.019 to 3.071)	**increase**
		BW1	2019	2022	6	-0.067	1.000	-0.253	no trend
		BW2	2021	2022	3	-0.333	1.000	-1.712	no trend
	reef intertidal	MI1	2005	2022	61	-0.087	0.322	-0.101	no trend
		MI2	**2005**	**2022**	**59**	**-0.248**	**0.006**	**-0.430** (-0.701 to -0.128)	**decrease**
	reef subtidal	MI3	2008	2022	52	-0.036	0.711	-0.063	no trend
	pooled		2001	2022	81	-0.067	0.376	-0.050	no trend
Mackay Whitsunday	estuarine intertidal	**SI1**	**2005**	**2022**	**39**	**-0.282**	**0.012**	**-0.233** (-0.554 to -0.045)	**decrease**
		SI2	2005	2022	34	0.077	0.534	0.040	no trend
	coastal intertidal	**MP2**	**2000**	**2022**	**46**	**0.325**	**0.002**	**0.238** (0.102 to 0.361)	**increase**
		MP3	2000	2022	44	0.173	0.099	0.113	no trend
		PI2	**1999**	**2022**	**62**	**-0.326**	**<0.001**	**-0.280** (-0.418 to -0.152)	**decrease**
		PI3	1999	2022	62	-0.151	0.083	-0.093	no trend
		CV1	2017	2022	10	0.200	0.474	0.236	no trend

NRM region	Habitat	Site	First Year	Last Year	*n*	*Kendall-τ*	*p* (2-sided)	Sen's slope (confidence interval)	trend
		CV2	2017	2022	10	-0.067	0.858	-0.042	no trend
		SH1	2017	2022	11	0.527	0.029	2.608	no trend
	coastal subtidal	NB1	2015	2021	7	-0.524	0.133	-5.858	no trend
		NB2	2015	2021	7	0.238	0.548	1.424	no trend
	reef intertidal	HB1	2000	2022	48	-0.140	0.163	-0.084	decrease
		HB2	2000	2022	47	0.023	0.826	0.012	no trend
		HM1	**2007**	**2022**	**30**	**-0.430**	**0.001**	**-0.181** (-0.312 to -0.065)	**decrease**
		HM2	**2007**	**2021**	**27**	**-0.448**	**0.001**	**-0.141** (-0.282 to-0.054)	**decrease**
		LN3	2021	2022	3	-1.000	0.296	-2.344	no trend
	Reef subtidal	TO1	2015	2021	7	0.048	1.000	0.750	no trend
		TO2	2015	2021	7	0.143	0.764	0.180	no trend
		CH4	**2000**	**2021**	**14**	**-0.582**	**0.004**	**-3.009** (-4.444 to -1.083)	**decrease**
		CH5	**2000**	**2021**	**14**	**-0.648**	**0.001**	**-2.250** (-3.639 to -0.654)	**decrease**
		WB3	2000	2021	15	-0.077	0.729	-0.070	no trend
		LN1	2017	2022	10	0.022	1.000	0.285	no trend
		LN2	2017	2020	6	0.333	0.452	0.313	no trend
	pooled		1999	2022	76	**-0.307**	**<0.001**	**-0.126** (-0.183 to -0.065)	**decrease**
Fitzroy	estuarine intertidal	**GH1**	**2005**	**2021**	**40**	**-0.449**	**0.000**	**-0.685** (-0.985 to 0.377)	**decrease**
		GH2	2005	2021	40	-0.137	0.217	-0.244	no trend
	coastal intertidal	RC1	2002	2021	39	-0.111	0.327	-0.176	no trend
		WH1	2002	2021	40	0.110	0.322	0.091	no trend
	reef intertidal	**GK1**	**2007**	**2021**	**26**	**-0.493**	**<0.001**	**-0.099** (-0.160 to -0.049)	**decrease**
		GK2	2007	2021	26	-0.068	0.643	-0.016	no trend
	pooled		2002	2021	52	**-0.387**	**<0.001**	**-0.225** (-0.326 to -0.130)	**decrease**
Burnett Mary	estuarine intertidal	RD1	2007	2021	35	0.110	0.363	0.007	no trend
		RD2	2007	2017	28	**-0.409**	**0.003**	**-0.009** (-0.096 to -0.001)	**decrease**
		RD3	2017	2021	9	-0.278	0.348	-0.511	no trend

NRM region	Habitat	Site	First Year	Last Year	*n*	*Kendall-τ*	*p* (2-sided)	Sen's slope (confidence interval)	trend
		UG1	1998	2022	67	0.073	0.388	0.002	no trend
		UG2	1999	2022	63	0.162	0.062	0.020	no trend
	coastal intertidal	BH1	1999	2022	58	0.082	0.369	0.042	no trend
		BH3	**1999**	**2022**	**56**	**0.332**	**<0.001**	**0.150** (0.076 to 0.209)	**increase**
	pooled		1998	2022	80	-0.005	0.947	-0.002	no trend

Table 23. Resilience score and resilience score category for each site in 2021–22.

Region	Site	Habitat	Score	Score category
Cape York	BY1	coastal intertidal	85	2.2.2
	BY2	coastal intertidal	34	2.1.1
	FR1	reef intertidal	15	1.1
	FR2	reef intertidal	15	1.1
	SR1	coastal intertidal	6	1.1
	SR2	coastal intertidal	60	2.1.2
	ST1	reef intertidal	85	2.2.2
	ST2	reef intertidal	50	2.1.1
Wet Tropics	GI1	reef intertidal	47	2.1.1
	GI2	reef intertidal	44	2.1.1
	GI3	reef subtidal	85	2.2.2
	LI1	reef intertidal	7	1.2
	LI2	reef subtidal	5	1.2
	YP1	coastal intertidal	50	2.1.2
	YP2	coastal intertidal	75	2.2.1
	DI1	reef intertidal	85	2.2.2
	DI2	reef intertidal	85	2.2.2
	DI3	reef subtidal	30	2.1.1
	LB1	coastal intertidal	30	2.1.1
	LB2	coastal intertidal	30	2.1.1
Burdekin	BB1	coastal intertidal	71	2.2.1
	JR1	coastal intertidal	70	2.2.1
	JR2	coastal intertidal	70	2.2.1
	MI1	reef intertidal	50	2.1.2
	MI2	reef intertidal	6	1.2
	MI3	reef subtidal	50	2.1.2
	SB1	coastal intertidal	78	2.2.1
Mackay–Whitsunday	HM1	reef intertidal	30	2.1.1
	HM2	reef intertidal	11	1.1
	LN1	reef subtidal	70	2.2.1
	LN3	reef intertidal	100	2.2.1
	MP2	coastal intertidal	82	2.2.1
	MP3	coastal intertidal	78	2.2.1
	SI1	estuarine intertidal	7	1.1
	SI2	estuarine intertidal	50	2.1.2
Fitzroy	GH1	estuarine intertidal	23	1.2
	GH2	estuarine intertidal	30	1.2
	GK1	reef intertidal	2	1.1
	GK2	reef intertidal	50	2.1.2
	RC1	coastal intertidal	15	1.1
	WH1	coastal intertidal	76	2.2.1
Burnett–Mary	BH1	coastal intertidal	15	1.1
	BH3	coastal intertidal	30	2.1.1
	RD1	estuarine intertidal	50	2.1.2
	RD3	estuarine intertidal	50	2.1.2
	UG1	estuarine intertidal	50	2.1.2
	UG2	estuarine intertidal	30	2.1.1

Table 24 Results of Generalised additive models (GAMs) fitted to Reef-level abundance with habitat and NRM region as a fixed effect.

MODELS - REEF	N	EDF	CHI-SQ	*P*-VALUE	R-SQ (ADJ)	DEVIANCE EXPLAINED
% cover = s(date)	90	21.35	5206	<2e-16	0.562	0.729
% cover = s(date) + Habitat	325				0.505	0.806
Estuarine intertidal		21.602	1410.593	<2e-16		
Coastal intertidal		19.403	962.5	<2e-16		
Coastal subtidal		1.834	9.765	0.006		
Reef intertidal		14.165	974.21	<2e-16		
Reef subtidal		15.778	471.852	<2e-16		
% cover = s(date) + NRM	403				0.596	0.792
Cape York		5.278	58.3	<2e-16		
Wet Tropics		16.189	711.8	<2e-16		
Burdekin		18.424	1198	<2e-16		
Mackay Whitsunday		18.577	531.8	<2e-16		
Fitzroy		5.571	213.7	<2e-16		
Burnett Mary		21.558	1177.3	<2e-16		

Table 25 Results of Generalised additive models (GAMs) fitted to NRM region-level abundance with habitat, location or site as a fixed effect.

MODELS PER NRM REGIONS	N	EDF	CHI-SQ	*P*-VALUE	R-SQ (ADJ)	DEVIANCE EXPLAINED
Cape York						
% cover = s(date)	40	8.491	210.7	<2e-16	0.431	0.503
% cover = s(date) + Habitat	66				0.537	0.696
Coastal intertidal		1.567	15.452	0.0009		
Coastal subtidal		2.014	2.725	0.145		
Reef intertidal		6.255	139.901	<2e-16		
Reef subtidal		1.987	12.236	0.008		
% cover = s(date) + Location	108				0.615	0.752
Coastal intertidal [BY]		2.748	8.754	0.0211		
Coastal intertidal [SR]		1	1.906	0.167		
Coastal subtidal [BY]		1.923	2.158	0.35		
Coastal subtidal [LR]		2.035	3.451	0.097		
Reef intertidal [AP]		6.421	94.943	<2e-16		
Reef intertidal [FR]		1	11.813	0.0005		
Reef intertidal [ST]		1.568	15.837	0.0002		
Reef intertidal [YY]		1.605	0.369	0.754		
Reef subtidal [FG]		1.981	9.777	0.015		
% cover = s(date) + Site						
AP1	35	5.154	46.941	<2e-16	0.603	0.687
AP2	24	2.646	8.547	0.042	0.269	0.340
BY1	14	1.903	1.617	0.665	0.057	0.180
BY2	14	2.451	5.897	0.125	0.309	0.442
BY3	NA	NA	NA	NA	NA	NA
BY4	4	1.000	0.057	0.812	-0.461	0.029
FG1	6	3.431	51.007	<2e-16	0.857	0.974
FG2	6	2.763	9.174	0.043	0.533	0.832
FR1	13	4.112	17.509	0.004	0.576	0.766
FR2	12	1.000	22.202	0.000	0.673	0.714
LR1	6	1.000	0.060	0.807	-0.281	0.018
LR2	6	2.753	8.877	0.036	-0.066	0.865
SR1	NA	NA	NA	NA	NA	NA
SR2	NA	NA	NA	NA	NA	NA
ST1	12	1.374	5.827	0.061	0.328	0.365
ST2	12	1.948	2.889	0.336	0.140	0.298
YY1	14	1.644	24.249	0.000	0.621	0.696
Northern Wet Tropics						
% cover = s(date)	85	15.79	376.2	<2e-16	0.351	0.516
% cover = s(date) + Habitat	209				0.71	0.764
Coastal intertidal		12.94	215.29	<2e-16		
Reef intertidal		11.01	233.89	<2e-16		
Reef subtidal		7.87	42.22	3.22e-6		
% cover = s(date) + Location	296				0.824	0.911
Coastal intertidal [YP]		12.221	183.73	<2e-16		
Reef intertidal [GI]		5.718	47.36	<2e-16		
Reef intertidal [LI1]		3.043	26.58	4.62e-5		
Reef subtidal [GI3]		4.901	58.44	<2e-16		
Reef subtidal [LI2]		7.334	137.85	<2e-16		
% cover = s(date) + Site						
GI1	77	3.158	11.979	0.020	0.125	0.164
GI2	63	4.406	21.349	0.001	0.261	0.315
GI3	48	4.459	49.124	<2e-16	0.505	0.573
LI1	45	4.004	39.432	0.000	0.468	0.497
LI2	45	5.156	60.547	<2e-16	0.354	0.646
YP1	81	10.201	96.783	<2e-16	0.547	0.701
YP2	77	8.173	43.254	0.000	0.320	0.466
Southern Wet Tropics						
% cover = s(date)	62	14.43	1221	<2e-16	0.717	0.911
% cover = s(date) + Habitat	144				0.911	0.985

MODELS PER NRM REGIONS	N	EDF	CHI-SQ	*P*-VALUE	R-SQ (ADJ)	DEVIANCE EXPLAINED
Coastal intertidal		12.558	1035.552	<2e-16		
Coastal subtidal		1.002	1.354	0.243		
Reef intertidal		11.531	652.988	<2e-16		
Reef subtidal		11.189	260.701	<2e-16		
% cover = s(date) + Location	151				0.917	0.987
Coastal intertidal [LB]		12.577	1058.263	<2e-16		
Coastal subtidal [MS]		1.001	1.411	0.234		
Reef intertidal [DI]		11.964	507.686	<2e-16		
Reef intertidal [GO]		5.411	170.106	<2e-16		
Reef subtidal [DI3]		11.245	266.616	<2e-16		
% cover = s(date) + Site						
DI1	39	9.762	258.900	<2e-16	0.913	0.965
DI2	39	9.297	237.478	<2e-16	0.835	0.962
DI3	51	10.413	212.369	<2e-16	0.686	0.950
GO1	7	2.941	42.018	<2e-16	0.923	0.905
LB1	48	9.670	489.034	<2e-16	0.903	0.982
LB2	47	8.400	255.101	<2e-16	0.765	0.952
MS1	5	1.000	0.124	0.725	-0.287	0.035
MS2	6	1.000	1.595	0.207	-0.008	0.257
Burdekin						
% cover = s(date)	79	18.68	1706	<2e-16	0.779	0.911
% cover = s(date) + Habitat	190				0.78	0.911
Coastal intertidal		18.16	745.3	<2e-16		
Reef intertidal		13.13	435.9	<2e-16		
Reef subtidal		11.15	439.8	<2e-16		
% cover = s(date) + Location	215				0.743	0.894
Coastal intertidal [BW]		1.11	0.313	0.52		
Coastal intertidal [JR]		7.354	167.872	<2e-16		
Coastal intertidal [TSV]		17.447	498.479	<2e-16		
Reef intertidal [MI]		12.422	339.219	<2e-16		
Reef subtidal [MI3]		10.609	352.690	<2e-16		
% cover = s(date) + Site						
BB1	68	13.082	213.531	<2e-16	0.719	0.939
BW1	NA	NA	NA	NA	NA	NA
BW2	6	1.987	80.330	<2e-16	0.942	0.964
BW3	NA	NA	NA	NA	NA	NA
JR1	19	2.441	6.633	0.087	0.239	0.380
JR2	18	2.899	14.596	0.004	0.421	0.615
MI1	61	10.048	186.383	<2e-16	0.768	0.861
MI2	59	10.505	150.876	<2e-16	0.732	0.844
MI3	52	9.644	259.477	<2e-16	0.851	0.929
SB1	74	15.460	201.050	<2e-16	0.713	0.908
SB2	72	12.494	118.679	<2e-16	0.603	0.808
Mackay Whitsunday						
% cover = s(date)	73	19.04	830.3	<2e-16	0.458	0.684
% cover = s(date) + Habitat	179				0.671	0.881
Estuarine intertidal		15.670	321.21	<2e-16		
Coastal intertidal		17.979	294.75	<2e-16		
Coastal subtidal		5.636	53.42	<2e-16		
Reef intertidal		7.619	166.98	<2e-16		
Reef subtidal		4.48	19.27	0.0013		
% cover = s(date) + Location	276				0.642	0.837
Estuarine intertidal [SI]		6.864	111.097	<2e-16		
Coastal intertidal [CV]		1	0.130	0.718		
Coastal intertidal [MP]		1.583	9.010	0.008		
Coastal intertidal [PI]		8.475	146.443	<2e-16		
Coastal intertidal [SH1]		1.001	15.443	8.16e-5		
Coastal subtidal [NB]		1.821	19.597	5.0e-5		
Reef intertidal [HB]		6.204	44.219	<2e-16		
Reef intertidal [HM]		1	22.558	1.94e-6		

MODELS PER NRM REGIONS	N	EDF	CHI-SQ	*P*-VALUE	R-SQ (ADJ)	DEVIANCE EXPLAINED
Reef intertidal [LN3]		1	0.411	0.521		
Reef subtidal [CH]		7.1e-17	0	1		
Reef subtidal [LN]		1.551	0.528	0.648		
Reef subtidal [TO]		2.957	12.476	0.003		
Reef subtidal [WB]		7.8e-17	0	1		
% cover = s(date) + Site						
CH4	NA	NA	NA	NA	NA	NA
CH5	NA	NA	NA	NA	NA	NA
CV1	10	1.000	0.588	0.443	-0.051	0.067
CV2	10	1.000	0.000	0.991	-0.125	0.001
HB1	48	6.400	53.973	<2e-16	0.513	0.665
HB2	47	9.125	90.997	<2e-16	0.682	0.774
HM1	30	1.005	15.391	0.000	0.333	0.346
HM2	27	4.514	56.540	<2e-16	0.413	0.838
HM3	NA	NA	NA	NA	NA	NA
LN1	10	1.679	1.352	0.514	-0.051	0.225
LN2	6	1.282	2.395	0.283	-0.051	0.421
LN3	NA	NA	NA	NA	NA	NA
MP2	46	1.683	12.266	0.003	0.223	0.228
MP3	44	1.000	1.612	0.204	0.021	0.037
NB1	7	1.000	8.598	0.003	0.487	0.695
NB2	7	2.004	3.258	0.304	-1.312	0.394
PI2	62	7.374	46.344	0.000	0.361	0.588
PI3	62	11.303	69.461	<2e-16	0.486	0.700
SH1	11	1.000	7.940	0.005	0.455	0.462
SI1	39	8.947	52.920	0.000	0.412	0.764
SI2	34	3.964	7.432	0.214	0.041	0.322
TO1	7	3.079	9.795	0.031	-0.088	0.848
TO2	7	4.112	67.651	<2e-16	0.975	0.989
WB1	NA	NA	NA	NA	NA	NA
WB3	NA	NA	NA	NA	NA	NA
Fitzroy						
% cover = s(date)	51	4.086	148.7	<2e-16	0.348	0.491
% cover = s(date) + Habitat	105				0.776	0.906
Estuarine intertidal		13.484	180.627	<2e-16		
Coastal intertidal		8.394	102.146	<2e-16		
Reef intertidal		1.001	5.724	0.017		
% cover = s(date) + Location	105				0.775	0.906
Estuarine intertidal [GH]		13.47	180.135	<2e-16		
Coastal intertidal [SWB]		8.392	102.089	<2e-16		
Reef intertidal [GK]		10.001	5.846	0.0156		
% cover = s(date) + Site						
GH1	40	5.873	73.869	<2e-16	0.549	0.835
GH2	40	3.194	20.339	0.000	0.174	0.456
GK1	26	1.000	17.900	0.000	0.170	0.478
GK2	26	1.000	0.226	0.635	-0.022	0.009
RC1	38	7.974	82.538	<2e-16	0.704	0.773
WH1	39	8.002	94.426	<2e-16	0.718	0.789
Burnett Mary						
% cover = s(date)	75	20.67	624	<2e-16	0.493	0.739
% cover = s(date) + Habitat	129				0.51	0.875
Estuarine intertidal		19.558	690	<2e-16		
Coastal intertidal		7.034	46.37	<2e-16		
% cover = s(date) + Location	161				0.578	0.89
Estuarine intertidal [RD]		7.697	202.19	<2e-16		
Estuarine intertidal [UG]		19.090	637.40	<2e-16		
Coastal intertidal [BH]		6.898	44.77	<2e-16		
% cover = s(date) + Site						
BH1	58	7.522	47.360	0.000	0.440	0.564
BH3	56	5.669	39.136	0.000	0.389	0.513

MODELS PER NRM REGIONS	N	EDF	CHI-SQ	*P*-VALUE	R-SQ (ADJ)	DEVIANCE EXPLAINED
RD1	35	1.000	0.611	0.434	-0.027	0.017
RD2	28	3.794	52.498	<2e-16	0.550	0.755
RD3	9	1.000	1.678	0.195	0.052	0.184
UG1	63	11.517	156.487	<2e-16	0.537	0.879
UG2	61	10.315	123.234	<2e-16	0.538	0.842

Table 26. Results of Generalised additive models (GAMs) fitted to habitat-level abundance with NRM region as a fixed effect

MODELS PER HABITAT	N	EDF	CHI-SQ	*P*-VALUE	R-SQ (ADJ)	DEVIANCE EXPLAINED
Estuarine Intertidal						
% cover = s(date) + NRM	150				0.431	0.795
Mackay Whitsunday		6.634	55.51	<2e-16		
Fitzroy		3.264	43.14	<2e-16		
Burnett Mary		8.733	408.04	<2e-16		
Coastal Intertidal						
% cover = s(date) + NRM	337				0.549	0.744
Cape York		2.409	6.204	0.162		
Wet Tropics		8.510	253.334	<2e-16		
Burdekin		8.385	478.394	<2e-16		
Mackay Whitsunday		8.570	132.12	<2e-16		
Fitzroy		6.551	71.260	<2e-16		
Burnett Mary		6.879	79.132	<2e-16		
Coastal Subtidal						
% cover = s(date) + NRM	19				0.183	0.573
Cape York		2.382	10.949	0.016		
Wet Tropics		1	0.343	0.558		
Mackay Whitsunday		2.004	23.762	2.25e-5		
Reef Intertidal						
% cover = s(date) + NRM	259				0.755	0.846
Cape York		4.479	58.52	<2e-16		
Wet Tropics		6.989	536.691	<2e-16		
Burdekin		7.475	467.399	<2e-16		
Mackay Whitsunday		6.291	132.893	<2e-16		
Fitzroy		1	5.969	0.0146		
Reef Subtidal						
% cover = s(date) + NRM	122				0.79	0.803
Cape York		3.126	19.94	0.0002		
Wet Tropics		7.591	61.39	<2e-16		
Burdekin		8.395	343.02	<2e-16		
Mackay Whitsunday		3.209	6.36	0.08		