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Monitoring seagrass within the Reef 2050 Integrated Monitoring and Reporting Program:

Final Report of the Seagrass Expert Group

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Executive Summary

Seagrass is widely distributed throughout the Great Barrier Reef (the Reef), with a documented 35,000 square kilometres and a potential habitat area of 228,300 square kilometres. Seagrass meadows occur in many different environmental conditions, both within and beyond the impact of flood plumes, and are common in areas of high anthropogenic activity, such as ports and areas adjacent to urban centres.

Many processes and services that maintain the exceptional values of the Reef occur in seagrass meadows. To provide the services that support these values seagrass habitats include a range of species, growth forms and benthic landscapes, that respond to pressures in different ways. In many cases seagrasses also modify their environments to improve environmental conditions on the Reef.

Seagrasses vary spatially and temporally in their distribution and abundance across the Reef, occurring in different water quality types (estuaries, coastal, reefal and offshore) and at different water depths (intertidal, shallow subtidal, deep water). The diversity of potential seagrass habitats is one reason they support so many of the environmental services and values of the Great Barrier Reef World Heritage Area (World Heritage Area), including:

- habitat for crabs, prawns and fish — supporting recreational and commercial fishing;
- primary food resource for species of conservation significance (dugong, green turtles, migratory shore birds);
- shoreline stabilisation by binding sediment to slow erosion;
- water clarity improvement, by promoting the settlement of fine particulate matter; and
- providing a natural carbon sink.

To deliver the seagrass components of the knowledge system required to deliver *Reef 2050 Long-Term Sustainability Plan* (Reef 2050 Plan) reporting and other management activities, there will need to be modifications and enhancements made to the current seagrass monitoring programs.

The Drivers, Pressures, State, Impact, Response (DPSIR) framework was used to facilitate the identification of linkages between the *pressures* on seagrass, *state* of the seagrass, the *impact* a decline in seagrass would have on community values, and the *responses* management agencies can take to mitigate loss of values. We have also defined twelve seagrass habitat types that occur on the Reef, identified by a matrix of water body type and water depth. The seagrasses occurring in each habitat are exposed to different *pressures* and require different management actions (*responses*) to protect and enhance the values of the community and Reef ecosystems.

The proposed monitoring program has three spatial and temporal scales, with each scale providing different information (knowledge) to support resilience-based management of the Reef.

Habitat assessment*:* will occur across the Reef at all sites where seagrass has a potential of occurring. It will determine seagrass abundance, species composition and spatial extent of each habitat type within the World Heritage Area. This scale will be focused on supporting future outlook reports, but will also provide information for operational and strategic management and contribute towards other reports.

Health assessment*:* will take place at representative regional sites, for each habitat type. These sites will provide managers with annual and seasonal trends in seagrass condition and resilience at a regional scale for each habitat. This scale will provide higher temporal detail (i.e. at least annually) of seagrass condition and resilience, supporting tactical, operational and strategic management applications. This scale will provide the majority of information for regional/catchment report cards and the assessment of management effectiveness at a catchment wide scale. It will also contribute important trends in condition and resilience to Outlook reports and other communication products with more frequent reporting.

Process monitoring: will take place at the fewest number of sites, nested within *habitat* and *health assessment* sites. Due to the time-consuming and complex nature of these measurements the sampling sites will be chosen to focus on priority knowledge gaps. This scale will provide managers with information on cause-and-effect relationships and linkages between different aspects of the Reef's processes and ecosystems. This scale will include measures of seagrass resilience (for example, feedback loops, recovery time after disturbance, history of disturbance and thresholds for exposure to pressures). The attributes measured at these sites will also provide confidence to managers regarding the impact a change in seagrass condition is likely to have on other values of the Reef (for example, fish, megafauna, coral, Indigenous heritage, and human dimensions).

To ensure that future seagrass monitoring delivers the information required to report on the Reef 2050 Plan and meets the other knowledge requirements of managers, a spatially balanced random sampling design needs to be implemented on the Reef. Existing monitoring programs can and should be integrated into this design. However, current seagrass monitoring programs do not provide a balanced assessment of seagrass condition across the entire Reef, hence are not suitable to meet the Reef 2050 Plan reporting requirements and many other management information needs.

Existing sites within current monitoring are focused on habitat types that are intertidal and shallow sub-tidal and lie close to the coast. These habitats have been previously selected because they face high levels of cumulative anthropogenic risk and therefore have higher levels of management demand for information. The current sites are likely to decline more rapidly, in response to catchment run-off and other anthropogenic pressures, than the average for seagrass meadows across the entire Reef. They also have a greater potential to show improvements from Reef catchment management actions that reduce pollution associated with run-off.

This report sets out the framework for a recommended new seagrass monitoring program, highlighting the substantial improvements in knowledge and confidence this new program will deliver, and provides a scope for the statistical design work required to support implementation of this program.

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1.0 Background and design considerations

Seagrasses are true flowering plants that live submerged in marine environments. There are 12 species found within the waters of the Great Barrier Reef World Heritage Area (the World Heritage Area), occurring in lagoons, bays, intertidal and deep water environments. They are a vital component of the Great Barrier Reef (the Reef), estimated to inhabit an area of at least 35,000 square kilometres, with a potential habitat area of 228,300 square kilometres (estimated in work undertaken as part of the current project). Seagrasses are a critical food source for species of conservation significance (for example, dugongs, turtles, shorebirds) as well as habitat for many recreational and commercially important fisheries species (fish, crabs, prawns). Seagrasses are often used as indicators for ecosystem health, as they require good water quality and relatively stable benthic habitats in order to thrive. Ensuring the success of seagrasses in the Reef, by appropriately targeted management actions, will support the general health of the ecosystem and the fauna that depend on it. Effective monitoring of seagrasses will allow the improvements from management actions to be identified and valued by the community.

The seagrass monitoring program proposed in this document considers the "*drivers"* and "*pressures"* that are likely to cause a change in seagrass "*state*" on the Reef. It also considered ways to quantify any "*impact*" changes in seagrass would have on the values of the Reef and our ability to determine the effectiveness of management "*responses*". Organising indicators in this way is referred to as the **DPSIR** framework because it categorises an indicator as providing information on a ***driver*** or ***pressure*** that causes a change, the ***state*** of an organism or habitat, the ***impact*** that has on other values and possible management ***responses*** to mitigate harm (Figure 1). The application of the DPSIR framework was made in the context of delivering resilient seagrass ecosystems in the Reef region, recognising the diversity of seagrasses throughout the Reef and the wide range of ecosystem services they provide.

Three key resources were used to identify management needs and priorities for different types of knowledge as they relate to seagrass on the Reef:

1. *The Reef 2050 Long-Term Sustainability Plan* (Reef 2050 Plan);
2. Market research to determine stakeholder information needs and expectations (Enhance Research 2017); and
3. Interviews with Reef managers to identify management needs, to inform the Program Design of the Reef 2050 Integrated Monitoring and Reporting Program (Udy 2017).

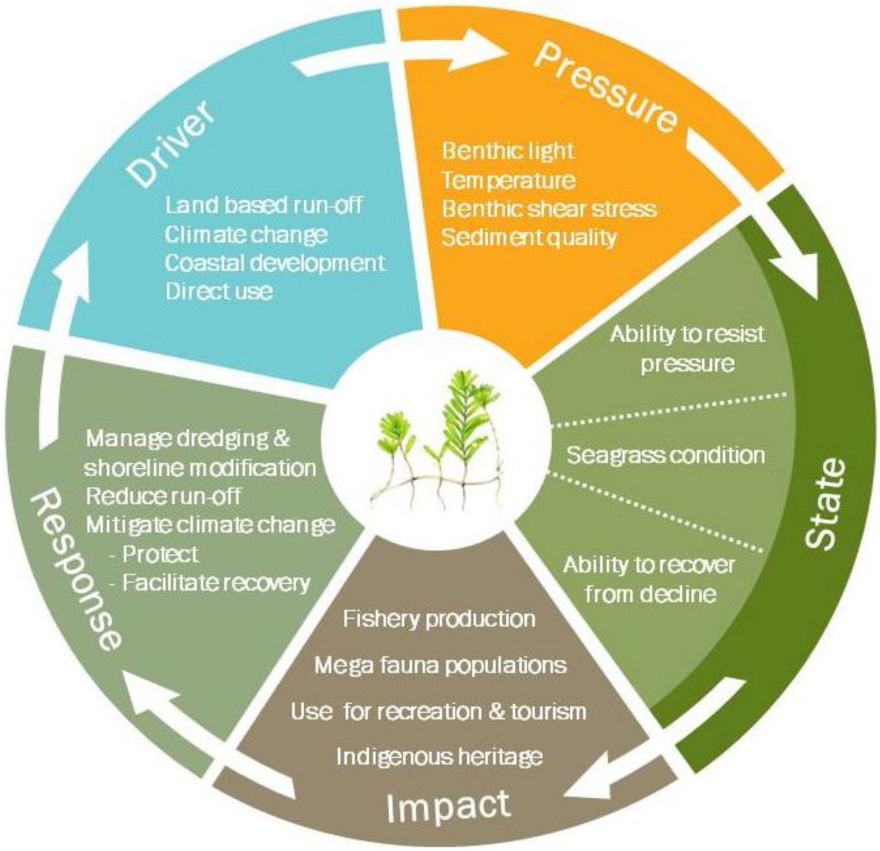


Figure 1. Components of a DPSIR framework as they relate to seagrass.

The recommended monitoring program has been developed to provide information that will enable tracking of progress towards relevant targets and objectives in the Reef 2050 Plan, satisfy most expectations of stakeholders (Enhance Research 2017) and meet current managers' needs (Udy 2017). We have recommended a statistically robust design process be conducted to ensure information can also be applied to new management questions and priorities, in recognition of the fact that government priorities can change, and because the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) is expected to provide managers with relevant information for many years.

1.1 Objectives of the Reef 2050 Integrated Monitoring and Reporting Program

The Reef 2050 Plan provides an overarching strategy for managing the Reef. It contains actions, targets, objectives and outcomes to address threats and protect and improve the Reef's health and resilience, while allowing ecologically sustainable use. The Reef 2050 Plan has been developed in consultation with partners, including Traditional Owners and the resource, ports, fishing, agriculture, local government, research and conservation sectors.

A key component of the Reef 2050 Plan is the establishment of RIMReP, which will provide a comprehensive and up-to-date understanding of the Reef — the values and processes that support it and the threats that affect it. This knowledge is fundamental to informing actions required to protect and improve the Reef's condition and to drive resilience-based management. *The Great Barrier Reef Outlook Report 2019* (Great Barrier Reef Marine Park Authority, 2019) reported on progress in meeting Reef 2050 Plan objectives and will be updated every five years in future outlook reporting.

There are currently over 90 monitoring programs for various physical and ecological attributes operating in the World Heritage Area and adjacent catchment. These programs have been designed for a variety of purposes and operate at a variety of spatial and temporal scales. The comprehensive strategic assessments of the World Heritage Area and adjacent coastal zone — both of which formed the basis of the Reef 2050 Plan — identified the need to ensure existing monitoring programs align with each other and with management objectives. RIMReP will fulfill this need.

RIMReP will provide information across the seven themes that make up the Reef 2050 Plan Outcomes Framework. The themes are ecosystem health; biodiversity; water quality; heritage; community benefits; economic benefits and governance. The seagrass monitoring recommended in this report will contribute most heavily to the ecosystem health and biodiversity aspects of the Outlook Framework, but will also contribute information to water quality as well as the social and economic components.

The intent of RIMReP is not to duplicate existing arrangements but to coordinate and integrate existing monitoring, modelling and reporting programs across disciplines. For example, the Reef 2050 Water Quality Improvement Plan underpins the Reef 2050 Plan's water quality theme and its Paddock to Reef 2050 Integrated Monitoring, Modelling and Reporting Program will form a key part of the new integrated program.

As the driver of resilience-based management under the Reef 2050 Plan, RIMReP's primary purpose is to enable timely and suitable responses by Reef managers and partners to emerging issues and risks, enabling the evaluation of whether the Reef 2050 Plan is on track to meet its outcomes, objectives and targets.

RIMReP's vision is to develop a knowledge system that enables resilience-based management of the Reef and its catchment. This will provide managers with a comprehensive understanding of how the Reef 2050 Plan is progressing (Figure 2). Accordingly, the seagrass monitoring proposed here has a key focus on understanding and predicting resilience of seagrasses, something which has not previously been well understood or monitored for within the Reef.

Three goals for the knowledge system are that it is:

- ***Effective*** in enabling the early detection of trends and changes in the Reef's environment, inform the assessment of threats and risks, and drive resilience-based management.
- ***Efficient*** in enabling management priorities and decisions to be cost effective, transparent, and based on cost-benefit and risk analyses.
- ***Evolving*** based on the findings of Great Barrier Reef Outlook Reports, new technologies and priority management and stakeholder needs.

RIMReP will be central to ensuring decisions regarding the protection and management of the Reef are based on the best available science, consistent with the principles of transparency and accountability, and underpinned by a partnership approach.

To support these goals the recommendations for future monitoring of seagrass on the Reef include a tiered approach that incorporates aspects of the two existing monitoring programs, the Marine Monitoring Program and the Queensland Ports Seagrass Monitoring Program (Ports Monitoring), while also incorporating new national standards in relation to the design of marine monitoring programs (Foster et al. 2018). The linking of monitoring at different scales improves the effectiveness of change detection, makes RIMReP more efficient and ensures the monitoring programs on the Reef continue to evolve by incorporating new knowledge, technological developments and national guidelines. The changes in seagrass monitoring recommended in this document will also improve the defensibility of knowledge available to managers when identifying management options and prioritising actions.

Figure 2. RIMReP program logic: Each of the three goals has associated development and implementation objectives as well as foundational inputs.

1.2 Information needs for the Great Barrier Reef Outlook Report and other reporting requirements

Reporting is critical in supporting existing Reef management and decision making (**Figure 2**) as well as being one of the categories of management uses for information identified in Udy (2017; **Figure 4**). For the purposes of this document, information required to support reporting has focused on reporting within the World Heritage Area by the Authority and Queensland Government departments. However, it is also intended to support local information needs of Natural Resource Management (NRM) groups, local councils, and community groups. The design of this monitoring program has considered Outlook reporting and the regional/catchment report cards, including information provided through websites, as the primary reporting tools that will be used to communicate and report information.

Report cards, future outlook reporting and government websites will rely on information collected as part of RIMReP to report on the trends in seagrass condition and resilience on the Reef. In addition, it will be critical to collect the information necessary to report on the *pressures* on seagrass as well as management actions being taken to reduce the *impact* of these *pressures* on both seagrass and the values of the Reef that rely on seagrass habitats. Incorporating existing seagrass monitoring data into Outlook Report 2019 as well as regional and Reef-wide report cards has been problematic due to an unbalanced sampling design across the Reef and differences in monitoring methodology between programs. This report addresses both these issues. We have also assumed that future reporting requirements for seagrass ecosystems will be linked to assessing the condition and resilience of these habitats and their ability to support critical processes that sustain the ecosystem services provided by the Reef, as well as tracking the effectiveness of management actions to protect them. The categories of the Outlook Report that will require information relating to seagrass include:

1. **Ecosystem Health** of seagrass meadows
2. **Biodiversity** of seagrass habitats
3. Factors that influence the ability of seagrass to support **Regional Values**
4. **Existing Management** to protect seagrass
5. **Resilience** of seagrass meadows and their associated fauna
6. **Risks** to seagrass that are not or cannot be managed

The above categories of managers' information needs, including information required for report cards and websites, will be met by providing the following information products:

1. Maps showing the spatial distribution of *pressures* that threaten seagrass, the *state* of seagrass across the Reef, as well as management *responses* that have been taken to protect seagrass and reduce *impacts.*

2. Trend analysis showing changes over time in *pressures* and *state* of seagrass on the Reef including its resilience (ability of seagrass to resist decline and/or recover following a disturbance).

3. The processes that link seagrass condition with both *pressures* and its *impact* on community values of the Reef.

1.3 Relevant *Reef 2050 Long-Term Sustainability Plan* targets, objectives and outcomes

The Reef 2050 Plan has eight categories of actions intended to achieve targets (2020), objectives (2035) and outcomes (2050) by certain dates. Managers will require various forms of information/knowledge to report progress towards these objectives. To effectively monitor seagrass on the Reef, it will be necessary to sample at different spatial and temporal scales. These three scales have been defined as *habitat assessment*, *health assessment* and *process monitoring*. To link with the monitoring design, discussed later, the knowledge each scale of monitoring will provide and its link to the most relevant Reef 2050 Plan objectives have been summarised in **Table 1**.

Aligning seagrass monitoring to the knowledge goals for RIMReP

Managers of the Reef identified three types of knowledge they require to manage the assets of the Reef efficiently and effectively (spatial, temporal and process knowledge) (Udy 2017).

To ensure the recommended seagrass monitoring program addresses all the requirements of managers it has been designed to measure at three spatial and temporal scales, with each scale focused on addressing one of the manager's knowledge requirements (**Figure 3**).

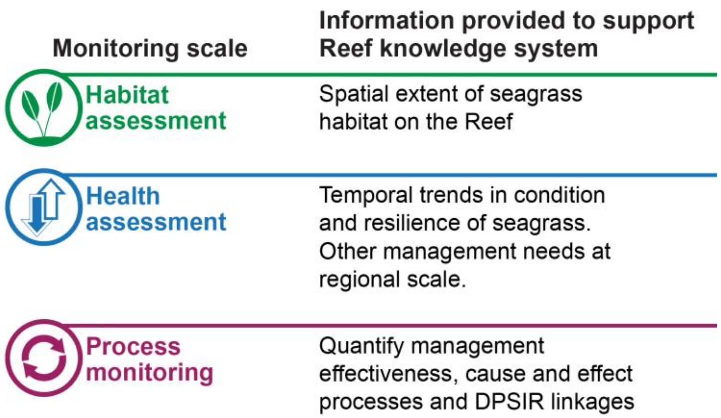


Figure 3. Three scales of seagrass monitoring

There are also important cross linkages between each scale with the *process monitoring* scale providing process-scale understanding for the other two scales. While the spatial (Habitat) and temporal (Health) scales provide a context for the application of knowledge gained at all scales.

Table 1. Type of monitoring required for relevant objectives in the Reef 2050 Plan

Relevant objective in Reef 2050 Plan	knowledge that each type of seagrass monitoring will provide towards Reef 2050 Plan objectives		
	Process monitoring	*Health assessment*	*Habitat assessment*
Objective EH02 The World Heritage Area retains its integrity and system functions by maintaining and restoring the connectivity, resilience and condition of marine and coastal ecosystems.	Quantifying the role of seagrass within the Reef and connection between meadows. Quantify the system functions and buffering services that support healthy Reef ecosystems.	Key indicator of seagrass condition, including attributes of a meadow that inform managers about the trend of a meadow (stable, recovering or declining) and its resilience to future disturbance.	Reef-wide assessment of the condition of seagrass within different habitat types, including species of seagrass present in a habitat and the above ground seagrass abundance.
Objective EHO3 Trends in the condition of key ecosystems including … seagrass meadows … are	Process understanding will enable managers to choose the appropriate management actions if	Higher resolution sampling and additional indicators will inform managers on trends in	Stable, recovering or declining trends will be estimated every five years for seagrass species and

improved over each successive decade.	seagrass meadows are not improving.	seagrass condition and resilience.	abundance across the 12 seagrass habitats for the Reef.
Objectives BO5, BO4 Reef habitats and ecosystems are managed to sustain healthy and diverse populations of indicator species across their natural range, with Indices of biodiversity in good or very good condition at Reef-wide and regional scales.	Provide an assessment of biodiversity across multiple Reef ecosystems and identify management actions needed if good or very good biodiversity is not achieved.	Representative meadows will improve detection of changes in species composition and biodiversity of "indicator" seagrass meadows. Detect the impact on biodiversity recovery from extreme weather and cyclones.	Detect changes in species diversity of seagrass across the large latitudinal range of the Reef, due to climate change or shifts in ocean currents.
Objectives WQO1, WQO2 Over successive decades the quality of water entering the Reef from broad scale (WQ01) and point source (WQ02) land use has no detrimental impact on the health and resilience of the Reef.	This scale provides the mechanistic understanding that supports predictive modelling of expected outcomes for seagrass from changes in water quality.	Changes in the condition and resilience of seagrass meadows in response to flood plumes and improvements in water quality will be detected at this scale.	Reef-wide land use impacts can be linked to likelihood of seagrass being present and to trends in seagrass abundance.

1.4 Information needs for Great Barrier Reef management (modified from Udy 2017)

Despite varied responsibilities of the different organisations managing the Reef (government and non-government), the information needs and types of knowledge products were common across all groups (**Figure 4**; Enhance 2017, Udy 2017). The recommended seagrass monitoring program was developed to ensure it would contribute information products that support a management knowledge system with the following attributes:

- Ability to go from a simplistic summary to obtaining the underlying detailed information/data in a relatively short period of time.
- Spatial representation of information with the ability to scale from the area of the entire Reef to a specific reef or bay – while also providing easy access to information on processes relevant to management decisions.
- Provide current information to managers appropriate to the timescale of management decisions – e.g. tactical/response (days or weeks), strategic (years).

- Links between human actions, condition of the Reef and the impact this has on how current and future generations are able to use the reef and obtain benefits from it – this cause and effect understanding needs to be clearly and simply communicated.
- Provide information on the range and location of habitats and species existing within the Reef and show the interconnectedness of these habitats through key processes.
- Spatially represent risks to the Reef to facilitate prioritisation of management actions

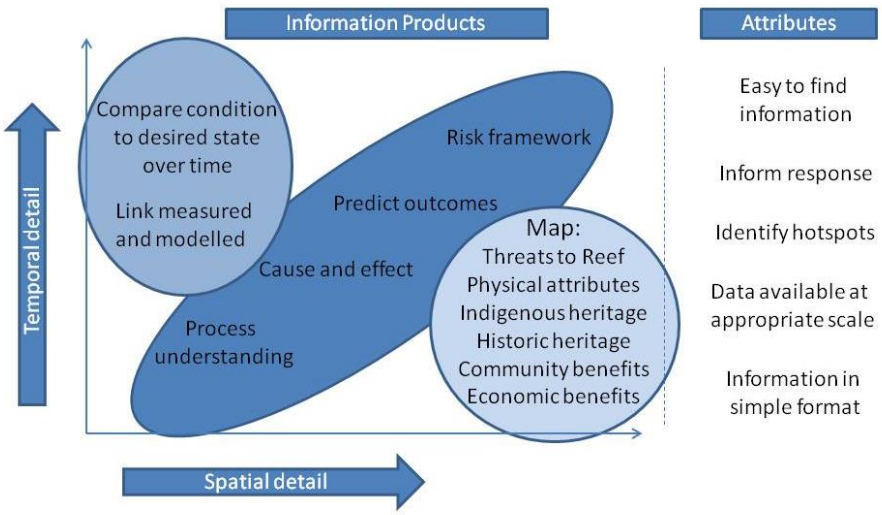


Figure 4. Summary of information products and attributes of knowledge required by managers (from Udy 2017).

To ensure that the appropriate spatial and temporal scale of information is provided to managers, the various management activities were separated into five categories (Udy 2017). Seagrass related information products provided by the three different spatial and temporal monitoring scales have been summarised against each category of management in

Table 2.

Table 2. Information from seagrass monitoring that will support a Reef knowledge system (modified from Udy 2017).

Scale of monitoring	Category of management				
	Tactical	Operational	Strategic planning	Quantifying effectiveness	Reporting
	How information will be used to manage seagrass on the Great Barrier Reef				
Habitat assessment Maps of seagrass condition (species, abundance)	Habitat maps will inform the initial response to acute risks and threats by providing managers with likely values that need to be protected. Also assist with prioritisation of resources.	Identifying sources of cumulative pressures on seagrass will inform management approaches to protection (e.g. modify permits and other actions)	Habitat maps will inform future strategic plans and highlight importance of resources within different zones. Also prioritise protection and recovery actions.	Monitoring condition of seagrass in different habitats will inform effectiveness of past actions at a large spatial scale.	Seagrass habitat maps will be used to communicate with stakeholders and community on the threats to seagrass and how they are being reduced.
Health assessment Trends in seagrass condition and resilience for each NRM and habitat	Will provide a baseline for determining the impact of acute threats and pressures (e.g. oil spills, dredging).	Regional trend analysis will identify areas that require protection or assistance to recover (e.g. permits/high anthropogenic use).	Identifying past responses of seagrass to various pressures will inform strategic plans on the level of intervention required to protect natural capital.	Quantifying the regional response of seagrass to pollutant loads will inform on the effectiveness of past actions and also prioritise future actions to protect / restore.	Use of trends in seagrass condition and resilience to report both the state of seagrass and the efficacy of management actions.
Process monitoring Predict likelihood of recover and outcome of management actions	Will be used to prioritise when and how to take remedial action following an acute or chronic decline in seagrass	Will enable cost benefit decisions for prioritisation of resources by understanding processes of connectivity and resilience.	Will provide planning tools that improve planning across the Reef to mitigate impact of events and the likelihood of successful implementation.	Will be used to assess proposed actions against benefits and set realistic targets and objectives for completed actions to ensure intended outcomes were achieved.	Can be used to report progress towards targets/objectives i.e. actions completed and outcomes achieved.

2.0 Current understanding of seagrass systems and status on the Great Barrier Reef

2.1 Seagrass Systems on the Great Barrier Reef

2.1.1 Importance of seagrass species, meadow form and habitat type

Seagrasses on the Reef are from three distinct evolutionary lineages and employ different modes of resilience to resist or recover from environmental or stochastic pressures. Hence, multiple types of information and actions are required to manage such a diverse group of marine plants exposed to very different pressures. There are three critical attributes that affect the resilience of seagrasses: (i) seagrass life history, (ii) meadow form, and (iii) physical habitat, and the combination of these attributes should inform the monitoring and policy required for effective management, as discussed in further detail in Kilminster et al. (2015).

The design and recommendations of RIMReP have adopted the seagrass functional groups and forms of seagrass meadows described by Kilminster et al. (2015) and applied these to the Reef seagrass model in Waycott et al. (2007) (Figure 5).

<u>Attribute 1: Seagrass life history</u>

Life-history traits of seagrasses, such as shoot (or ramet) turnover, genet persistence and sexual reproduction characteristics, enable a functional classification at the individual species level, which varies substantially among species. To be consistent with the DPSIR framework we have adopted a form-function model that groups species by their response to *pressures* (**Figure 5**). Broadly, we categorise species as having either persistent or colonising traits based on their ability to resist or recover. Colonising species have low physiological resistance and rapid ability to recover, while persistent species are slow to recover but have high physiological resistance. Species with a mixture of these traits are categorised as opportunistic (as described in Kilminster et al. 2015) (Figure 5).

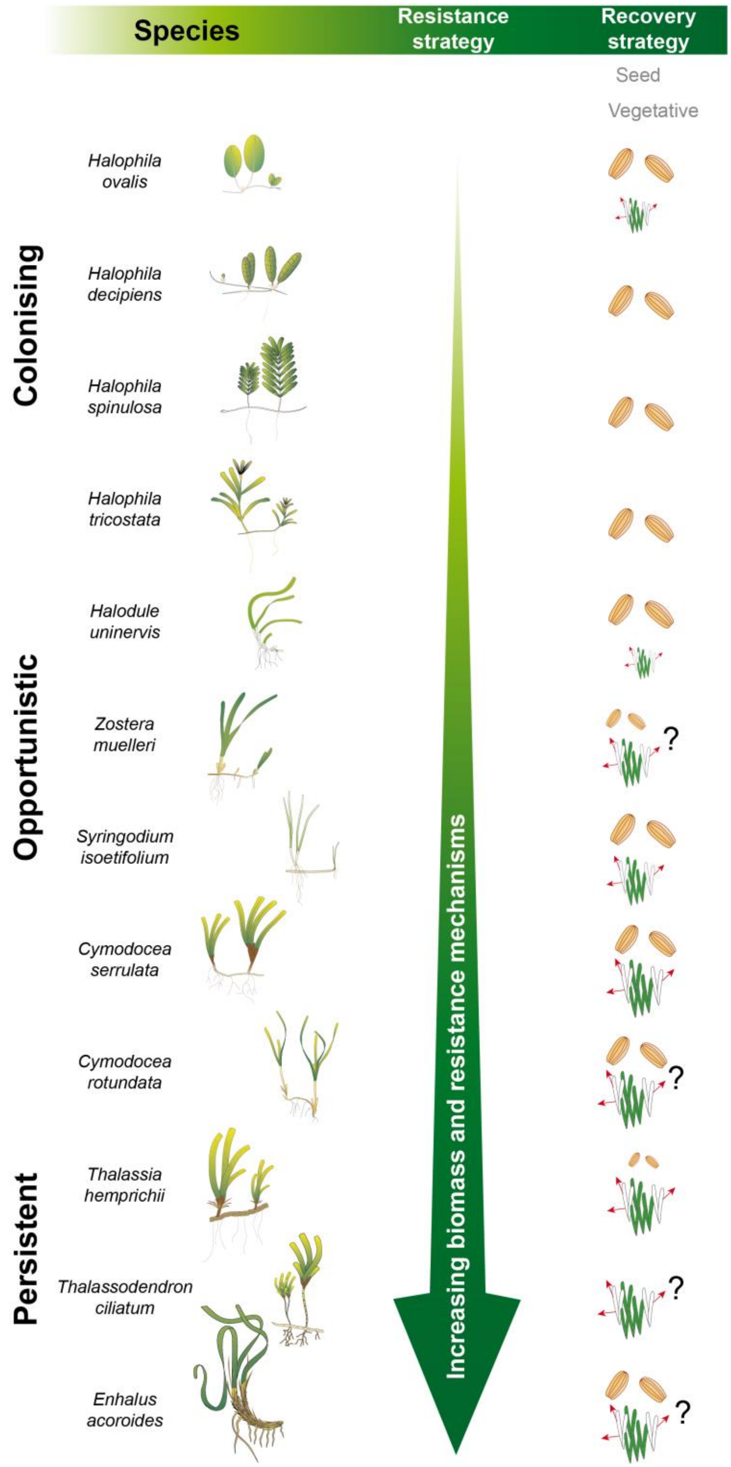


Figure 5. Dominant traits of seagrass species that occur on the Reef and their relative colonising, opportunistic and persistent characteristics (Modified from Waycott et al. 2007).

<u>Attribute 2: Meadow form</u>

Seagrasses grow in natural units we refer to as ‘meadows’. The functional definition of a meadow is the area in which seagrass can grow continuously, which shares the same environmental *drivers*, and that responds to those *pressures* in an integrated way. We acknowledge that this definition means some uncertainty when taking any single point as a reference however, in practice, the areas which make up seagrass meadows are variable in size and composition. Seagrass meadows will be typically within an area influenced by the same hydrological forces, although more than one meadow may be immediately adjacent. Meadows would typically be at the scale of hundreds of metres to tens of kilometres (*sensu* O’Brien et al. 2017). Meadows may be comprised of multiple patches, where seagrass does not occupy the area continuously, and in some circumstances meadows may be small (i.e. less than hundreds of metres). Added to the complexity of seagrass meadow types, in the Reef there are a diversity of species and habitats with varying overall community composition and ability to resist change (Carruthers et al. 2002). We have developed an extended framework for assessing this variation in the following section of this report. Finally, in the context of monitoring, when we refer to a 'site' we refer to a specific area sampled within seagrass meadows, as defined above.

Seagrass on the Reef can occur in either enduring or transitory meadows. Enduring meadows are persistent over time, although they may vary temporally in species composition, biomass, area and phenology. All species and functional groups can form enduring meadows, with the seasonal variation often being greater for enduring meadows of opportunistic and colonising species. The large coastal *Zostera muelleri* subsp. *capricorni* meadows that commonly occur from the Wet Tropics south and a number of the reef platform communities such as occur at Green Island, consisting of the genera *Cymodocea*, *Thalassia* and *Syringodium*, are examples of this meadow type (Figure 6a). In places where they have been monitored for long periods of time (over 10 years) these meadows are generally present despite variations in abundance from year to year (McKenzie et al. 2017, Wells and Rasheed 2017, York and Rasheed 2017). The management priority for these meadows is to prevent/mitigate loss as they may be slow to recover, especially where recruitment opportunities are limited.

Transitory meadows are not persistent over time. At some time periods, seagrass is present and at other times seagrass is absent (**Figure 6**b). Like enduring communities, transitory meadows can show variation in species composition and abundance over time, however only colonising and opportunistic species can form transitory meadows. These meadows are not expected to be present all the time and need to be managed to maximise the likelihood of recovery. An example of this type of meadow are the *Halophila decipiens* meadows found in waters deeper than 10 metres in the Reef lagoon (Rasheed et al. 2014, York et al. 2015). Where observed, abundance and spatial footprint changes markedly between sampling events (York et al. 2015, Chartrand et al. 2018). This extreme variability in abundance and spatial footprint presents challenges for effective monitoring, especially given the large area of Reef lagoon where transitory meadows potentially occur. To resolve this patchiness in distribution many observations need to be made across large areas of the Reef. Seagrass in transitory meadows die back when environmental conditions, such as temperature or light, shift outside the species tolerance range. Due to the colonising nature of the species that make up these meadows they are often highly susceptible to rapid loss from short-term acute impacts

(Chartrand et al. 2018). Meadows may then re-establish from seed when favourable conditions return. As the loss of seagrass biomass and subsequent recovery from seedbank or remnant vegetative fragments is expected in transitory meadows, this needs to be incorporated into both the definition of a desired state for these meadows and the selection of seagrass attributes to monitor. It is essential when managing and monitoring transitory meadows that information on the potential recovery mechanisms of these meadows is understood; this can only be provided by incorporating key elements of resilience into future monitoring.

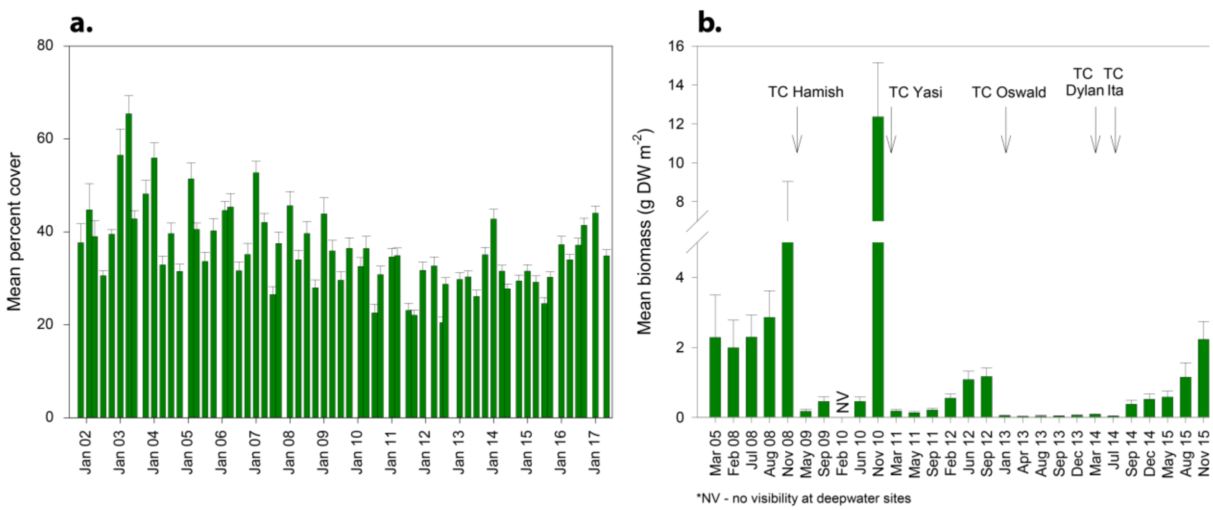


Figure 6. Examples of enduring and transitory seagrass meadows from long-term monitoring. a) abundance (per cent cover) in enduring *reef subtidal* meadow dominated by *Cymodocea* and *Thalassia* at Green Island (McKenzie et al. 2018); b) transitory *coastal deep* meadow near Abbot Point (McKenna & Rasheed 2017).

Attribute 3: Habitat type

The habitat in which seagrasses grow is the final attribute that needs to be considered for effective monitoring and management. Definitions of seagrass habitats have been proposed by a number of authors (for example, Carruthers et al. 2002, 2007, Short et al. 2007, Waycott et al. 2004, 2014 and Kilminster et al. 2015). Each habitat is impacted by different pressures that influence the physical environment (for example, amount and variability of light, nutrients, substrate type, fresh water input and hydrodynamic conditions). The seagrass habitats of the Reef, for the purpose of the current report, have been categorised into 12 habitat types (Figure 7). Habitat types were defined according to two primary factors: (i) Proximity to the mainland and resulting impact on water quality from run-off — water body types used were either plume affected (estuarine, coastal, reef) or non-plume affected (offshore), (ii) water depth — intertidal (areas that experience some tidal exposure), subtidal (never exposes and shallower than minus 10 metres mean sea level and deep (deeper than minus 10 metres, mean sea level) (Figure 7). A range of spatial data sets were compiled to create 12 potential seagrass habitats (**Figure 8**). The 12 habitat types were further sub-divided based on NRM regions to ensure that the spatial design of future monitoring locations would consider the management needs at the regional (NRM) scale as well as the Reef-wide scale (Carter et al., in prep).

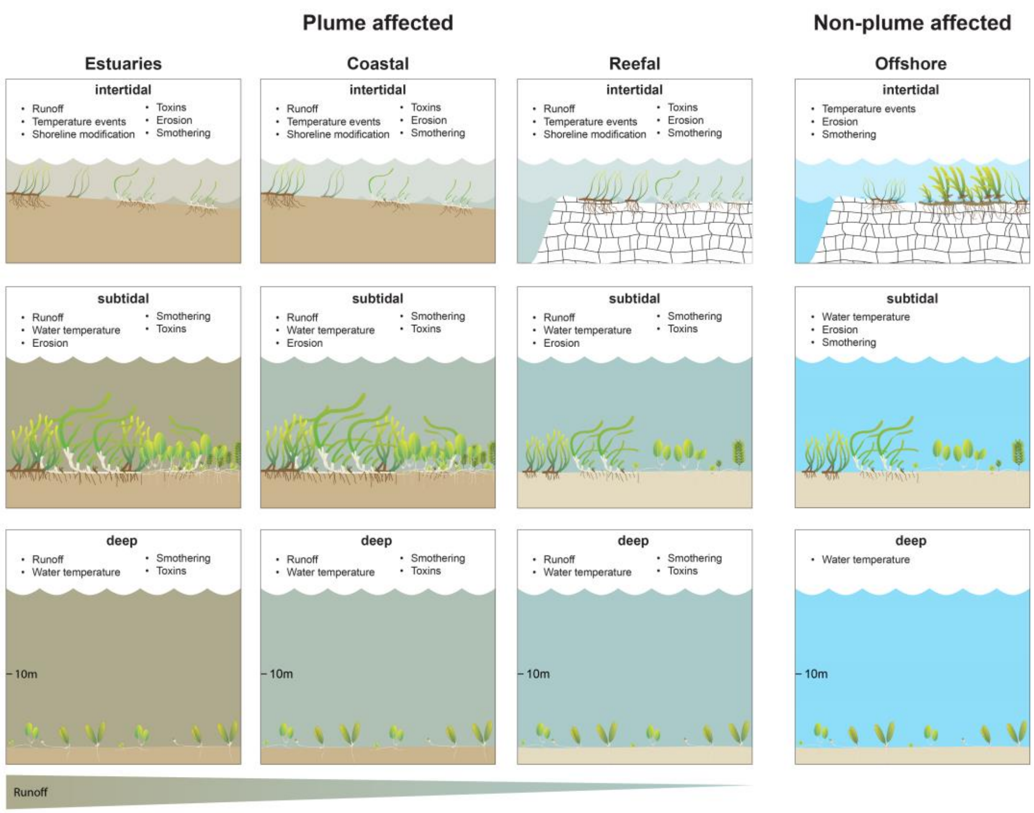


Figure 7. Twelve seagrass habitat types on the Great Barrier Reef. Small text indicates assessed dominant pressures in each habitat.

Within the 12 habitat types, different species assemblages occur that respond differently to pressures on seagrass and provide different services (Attribute 1 above). We also examined the major species assemblages that occur within each habitat type using the composite seagrass data for the Reef collected as part of the National Environmental Science Program's Tropical Water Quality Hub Project 3.1 (Carter et al. 2016a). The full results of this are presented in Appendix 1. The final sampling design for the Reef will need to consider representation of key species assemblages within a particular habitat type to ensure adequacy of the final design for management applications. The example presented in

Table **3** is for the Coastal intertidal habitat type in the Mackay-Whitsunday NRM region and shows that while meadows dominated by *Halodule uninervis* are the most common (67 of 110 mapped meadows), meadows dominated by *Zostera muelleri* subsp. *capricorni* (21), *Halophila ovalis* (13) and *Cymodocea serrulata* (14) also occur. These species span a cross-section of the life-history attributes, and an appropriate Reef-wide understanding of the various community types that occur within each habitat type will be required to ensure adequate representation of each assemblage within the monitoring design.

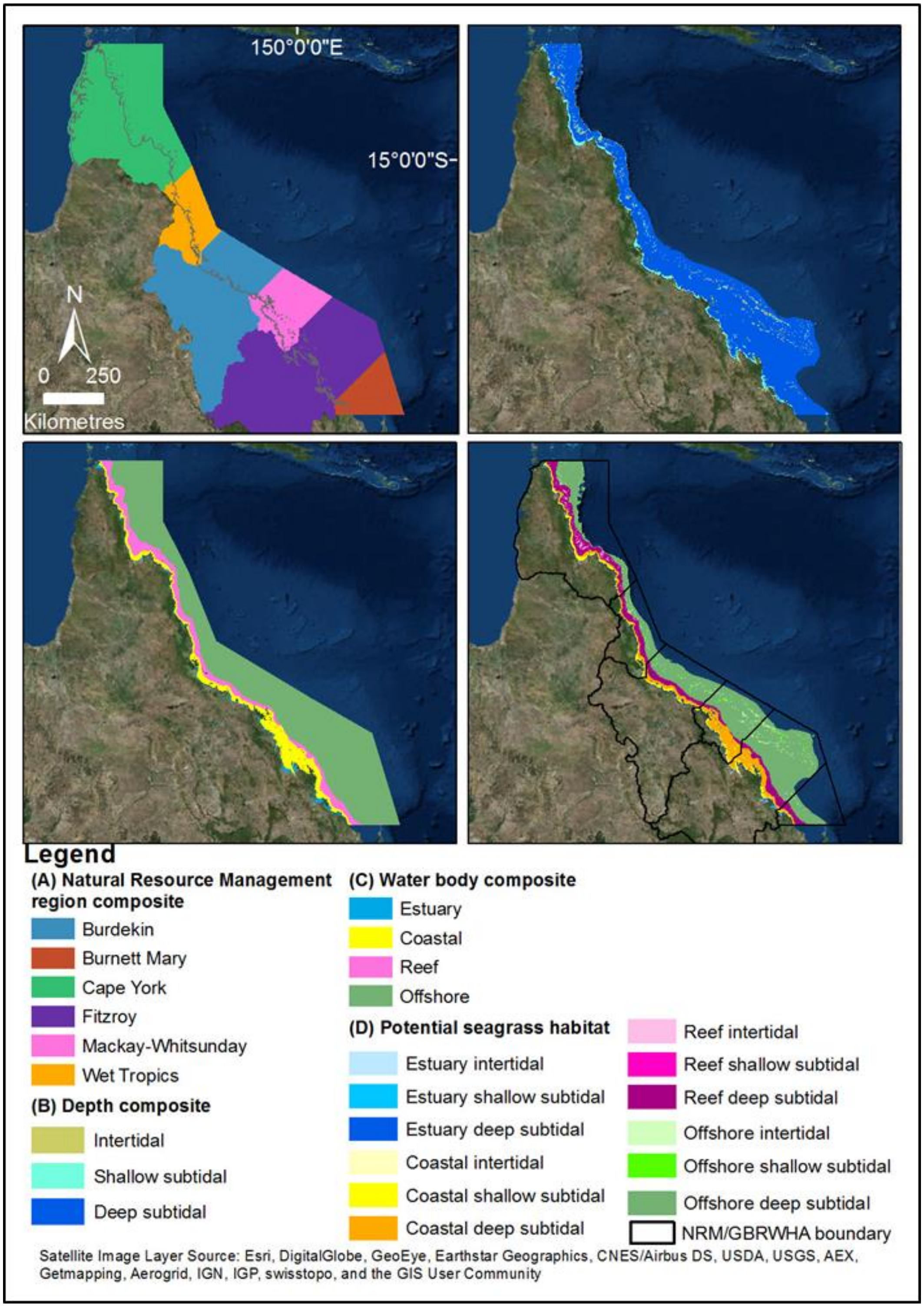
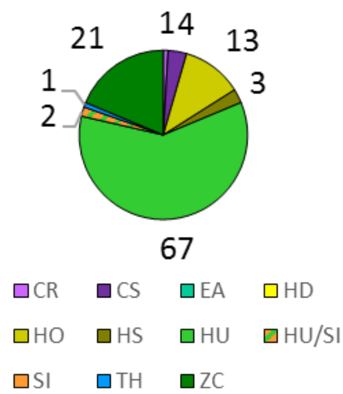


Figure 8. Spatial data included in assessment of potential seagrass habitat within the World Heritage Area.

Table 3. Meadow species assemblages in the Coastal Intertidal Habitat of the Mackay-Whitsunday NRM Region n = 112 meadows (more examples in Appendix 1).

Habitat type	Dominant meadow community types (and number of meadows)	Seagrass species present
Coastal intertidal		CR- *Cymodocea rotundata* HD- *Halophila decipiens* HO – *Halophila ovalis* HS – *Halophila spinulosa* HU – *Halodule uninervis* SI – *Syringodium isoetifolium,* TH – *Thalassia hemprichii,* ZC - *Zostera muelleri subsp. capricorni* CS - *Cymodocea serrulata*

2.2.2 Spatial Distribution of Pressures

Risks to seagrasses are not spatially uniform across the Reef (**Figure 9**). Where risks to seagrass accumulate there is generally an increased management need for information on seagrass condition. Spatial assessments of where multiple anthropogenic pressures occur in the Reef have found that the majority of areas with the highest cumulative risk to seagrass occur in the southern two thirds of the Reef, and are focused around areas of high coastal development. These areas often contain commercial ports, as well as many other coastal development pressures and are influenced strongly by flood plumes (**Figure 9**; Rasheed et al. 2007, Grech et al. 2011). Much of the current seagrass monitoring on the Reef is therefore focused in these high risk areas. However, these past assessments have focused on catchment run-off and anthropogenic threats to seagrasses, with less importance placed on future pressures associated with climate change (e.g. severe storms, ocean acidification and high temperature events). Additional monitoring efforts, spatially representative across the entire Reef, will be necessary to inform managers on the scale of change and seagrass responses to these pressures. The impact of these climate related pressures are predicted to become more severe and more frequent due to climate change, requiring better information for managers to meet the demands of a changing Reef and deliver on the objectives of the Reef 2050 Plan.

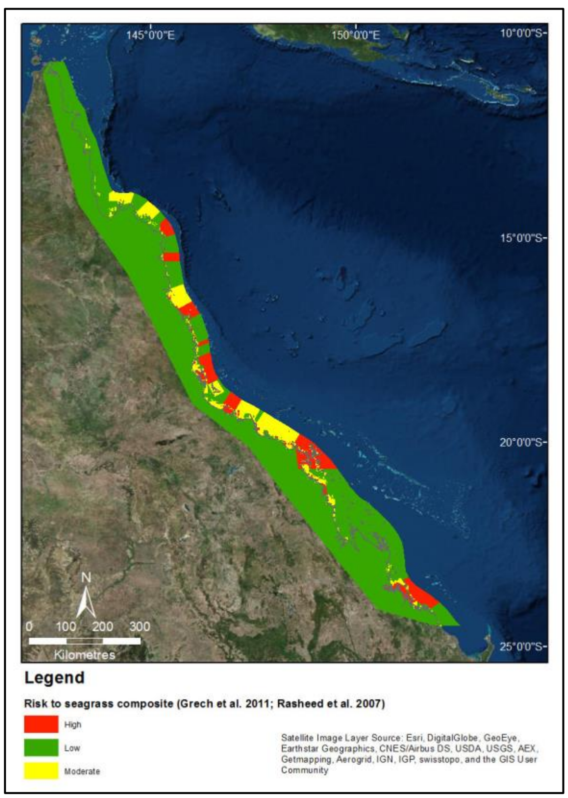


Figure 9. Cumulative risk to seagrass. Composite risk levels defined as low, moderate and high (from Grech et al. 2011 and Rasheed et al. 2007)

As well as the cumulative pressures on seagrass changing with proximity to urban centres (**Figure 9**), the relative impact of different *drivers* and *pressures* vary across the different seagrass habitats on the Reef (represented schematically in Figure 10). Turbid catchment run-off, often including toxins (such as herbicides), nutrients and sediment has a greater influence on habitats close to the mainland in the plume-impacted areas of the Reef (estuaries> coastal >reefal), but has little or no impact on offshore seagrass (Waterhouse et al. 2017). In contrast, many of the climate change related pressures (for example, high temperature events, frequency and severity of storms) impact across the Reef, with offshore seagrass as likely to be impacted, and possibly more impacted, than inshore seagrasses that have more protection from land. The depth at which the seagrass meadow occurs also modifies which *pressures* impact on it. Intertidal and shallow subtidal habitats are more likely to be affected by temperature events and rising sea levels, while the deep subtidal habitats will be more susceptible to small changes in water clarity or longer-term changes in ocean temperatures.

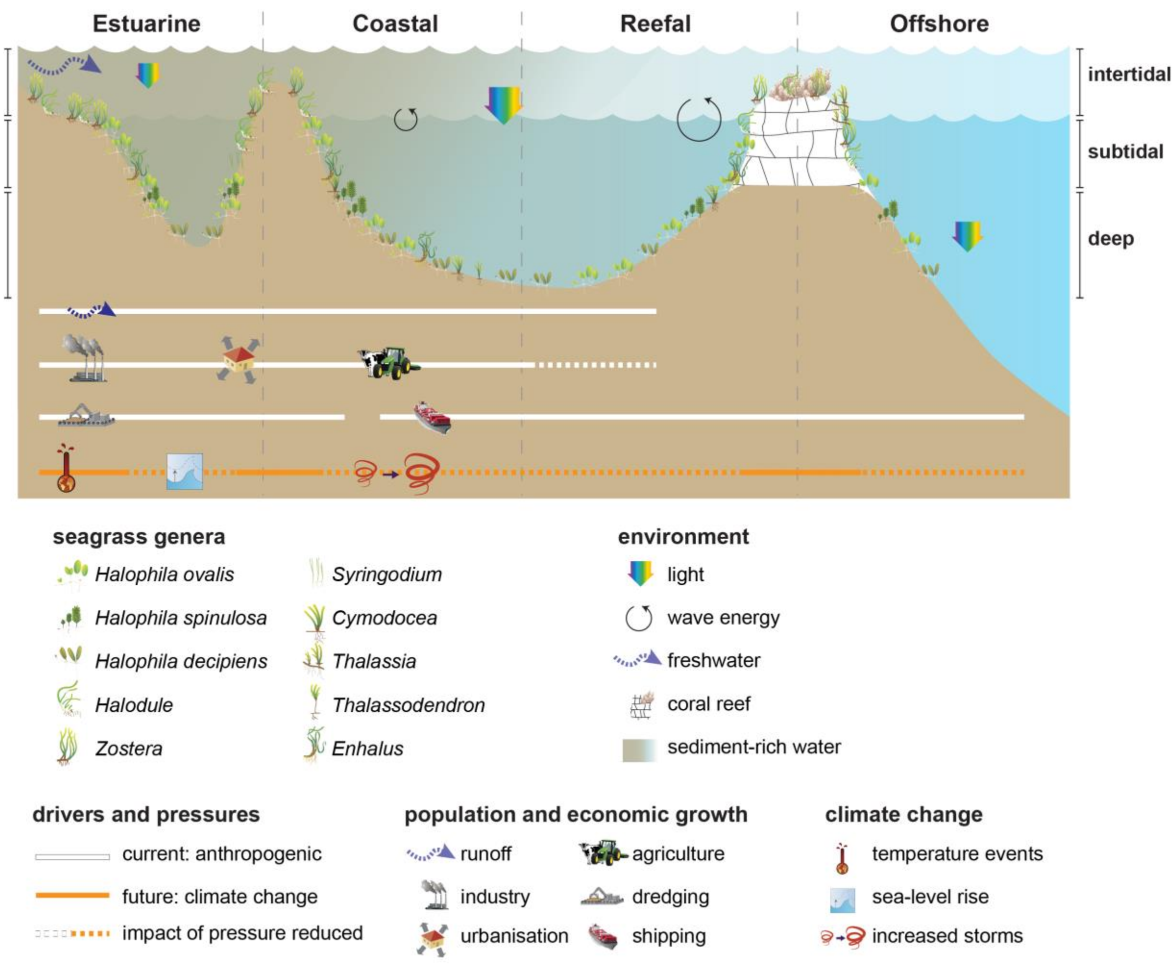


Figure 10. *Drivers* and *Pressures* and their relative impact on different seagrass habitats on the Great Barrier Reef.

2.2.3 Understanding seagrass resilience

Incorporating resilience into management frameworks is increasingly recognised as critical to halt the degradation of our nearshore ecosystems, and resilient ecosystems are clearly identified as an important component of the Reef 2050 Plan. A framework identifying the important aspects of resilience for seagrass ecosystems has recently been proposed (Unsworth et al. 2015). This includes features of a resilient seagrass system such as genetic diversity or continuous habitat, as well as biological (for example, connectivity) and biophysical (for example, water quality) features of the supporting ecosystem. Within the seagrass system, the ability of seagrass to resist or recover from a disturbance varies and is linked to the different life-history strategies of the species (Kilminster et al. 2015, O'Brien et al. 2017). The features necessary to understand resilience have been identified, but to embed resilience into a monitoring program for seagrass, as required here, a more complete understanding of interactions and responses of seagrass meadows to the pressures is necessary.

Globally, no standard approach exists to measure or predict resilience of seagrass meadows. Different tools have been reported to predict resilience such as using Bayesian models (Maxwell et al. 2015, Wu et al. 2017) or utilising estimates of metapopulational persistence as a surrogate for resilience (Hanski and Ovaskainen 2000, He et al. 2018). A recent review of the ecological attributes that have been applied in conservation and restoration programs provides a preliminary framework to establish decision support tools for ecosystem management (Timpane-Padgham et al. 2017). However, these models are limited in application largely due to current knowledge gaps or testing inferences as a result of interactions. Monitoring programs on the Reef do not explicitly measure resilience at this time. Some seagrass metrics being collected contribute to evaluating resilience, but there are critical elements missing. Here we summarise the information required to measure and predict seagrass resilience on the Reef (**Figure 11**), and how we will embed and assess these attributes within an integrated seagrass monitoring framework.

Resilient seagrass meadows can be best summarised as having a set of measurable biological characteristics that exemplify seagrass meadows' resistance to pressures and the essential mechanisms for recovery (**Figure 11**). Further, these measures can be utilised as indicators when expected outcomes can be defined in the resilience framework and are measurable. We propose a set of these characteristics that may be applied as indicators appropriate to predict expected responses of seagrass meadows across the Reef. As a monitoring tool it is critical to include components of both resistance and recovery, and to have an expectation for outcomes that exhibit a measureable response to changes. For seagrass meadows, all seagrass species are able to grow vegetatively, as well as recruit from propagules (seeds and seedlings) making it even more critical to understand both resistance and recovery. Mild disturbances, where there is no disruption to the environmental conditions that might limit normal vegetative growth, should see rapid recovery (Collier and Waycott 2009). This is observed in many of the ongoing monitoring programs across the Reef (for example, McKenzie et al. 2018). However, rapid recovery from large scale losses is only feasible when there are many sources of propagules, including seeds (Collier and Waycott 2009).

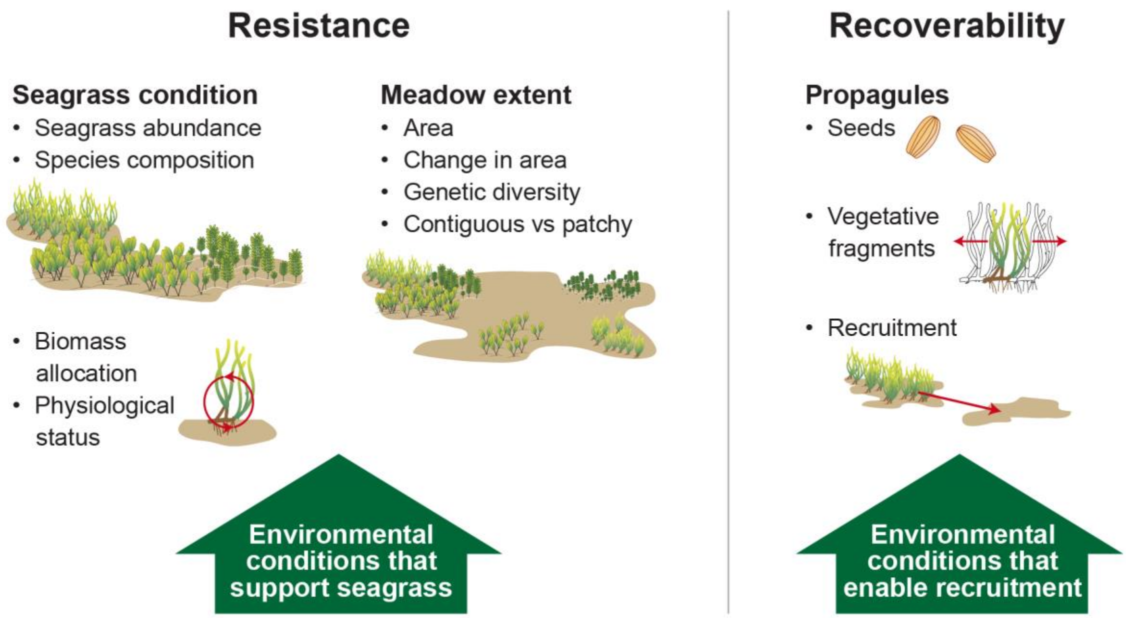


Figure 11. Resistance and recoverability attributes that can be monitored to manage for seagrass resilience on the Great Barrier Reef.

Feedback processes that impact on seagrass resilience *(Adapted from Maxwell et al. 2017)*

The interactions between seagrass plants and environmental conditions can result in non-linear relationships between increasing *pressures* and the ecosystem *response*, resulting in hysteresis in both seagrass degradation and recovery. These feedback mechanisms (loops) can confound our understanding of causal mechanisms behind seagrass dynamics and limit the effectiveness of management actions that desire to protect or restore seagrass.

Stabilising feedbacks play a role in helping seagrass resist increasing *pressures*. These result in limited ecosystem responses being observed prior to the stabilising feedback being overwhelmed. However, once overwhelmed a sudden decrease in seagrass condition and/or extent normally occurs, often taking managers by surprise.

Protection and conservation of seagrass meadows traditionally focused on successional based, passive approaches that assume that re-establishing the historical abiotic conditions that existed prior to degradation will return the system to its original *state*. However, achieving environmental conditions following a disturbance similar to those that occurred before the disturbance may be impossible or very slow when feedbacks have been disrupted. To predict the impact a management action will have and prioritise which management actions will be beneficial it is important to account for feedbacks in the conceptual understanding of the systems dynamics. Monitoring feedback processes that influence the response of seagrass ecosystems may help identify the conditions that aid resistance to *pressures* and those that could prevent recovery, thereby increasing the effectiveness of future management actions and prioritisation of management options.

2.2.4 DPSIR cause and effect relationships

Seagrass ecosystems form a critical link between environmental factors (*pressures*) and the *impact* these *pressures* have on many of the outstanding universal values of the Reef. The role of feedback loops in modifying the *pressure* at which seagrass will decline or how they will impact on seagrass recovery is poorly understood. In addition, the *impact* of seagrass decline on commercial and recreational fisheries, threatened species, tourism and other human uses of the Reef, while understood in a qualitative manner, has limited quantitative examples. The recommendations in this monitoring program provide an integrated process for making progress on the highest priority knowledge gaps.

2.2.5 Current Status of Seagrass Systems on the Great Barrier Reef

Where seagrasses are currently monitored in the Reef there has been a general trend of increases in seagrass abundance and meadow area since 2011. These increases follow large scale declines at most monitored locations in the southern two thirds of the Reef between 2009 and 2011, caused by climate related impacts, including multiple years of above average rainfall and an extreme weather event in early 2011 (McKenna et al. 2015, Rasheed et al. 2014). This seagrass loss had significant flow-on effects for dugong and green turtle populations, which are highly dependent on seagrass as their primary food supply (Meager and Limpus 2012). Initial recovery of seagrass meadows typically resulted in species shifts, with fast growing colonising species initially dominating meadows, followed by a gradual return of opportunistic and persistent species (McKenzie et al. 2016).

Despite this general trend, contrasting recovery outcomes have been observed between different monitored locations within an NRM region (McKenna et al. 2015, McKenzie 2017) and between different meadow/habitat types at a single location (Rasheed et al. 2014). This variation likely reflects the degree to which meadows were initially impacted as well as local differences in the availability of propagules (remaining seagrass patches, seed banks or availability of recruits) to aid recovery. These differences have resulted in some seagrass areas recovering relatively rapidly, such as Cleveland Bay/Townsville (Wells and Rasheed 2017, McKenzie et al. 2017), through to extreme cases with no recovery at all for the foundation species, such as Mourilyan Harbour (Reason et al. 2017) and Dunk Island (Mckenzie et al 2017), both occurring in the southern Wet Tropics. The current monitoring programs provide limited information to assist in identifying and prioritising management actions that could improve the likelihood of a seagrass meadow successfully recovering. It is intended that the new monitoring program proposed in this report will address this through a focus on aspect of seagrass resilience and links to management actions that can facilitate resistance and recovery.

The most recent publicly available reports from the Marine Monitoring Program (seagrass monitored during 2015-16) and the Queensland Ports monitoring (seagrass monitored in

2016) provide scores of seagrass condition. Many locations remained in poor condition, but there were generally condition improvements from the previous year with some locations returning to good condition (for full details of program results see McKenzie et al. 2017; McKenna et al. 2017, McKenna and Rasheed 2017, Reason et al. 2017, Wells and Rasheed 2017, York and Rasheed 2017). Variable environmental conditions during 2016 and 2017 mean recovery continued at some monitoring locations, while recovery stalled at locations impacted by extreme events (e.g. marine heatwave and Tropical Cyclone Marcia) (JCU, in prep; McKenzie et al. 2018, in review).

Seagrasses on the Reef have shown a generally high level of resilience and/or capacity for recovery (Coles et al. 2015). This reflects, for most species, their life history strategies of relatively rapid clonal growth (Rasheed 1999; 2004) and a likelihood of highly connected meadows through dispersal of propagules (Grech et al. 2016). Despite this, disturbances and events over the last decade have shown that for many meadows in the Reef this capacity has been tested and we are starting to see evidence of shifts that may not be so easily reversed through natural processes. With the La Niña climate patterns and frequency of severe storms likely to increase under modelled climate change scenarios, this capacity for recovery and resilience of seagrass on the Reef may be exceeded in the future (Waycott et al. 2007; Rasheed & Unsworth 2011).

3.0 Priority indicators to monitor seagrass on the Great Barrier Reef

The proposed seagrass monitoring program recommends that integrated monitoring take place across three spatial and temporal scales (**Figure 12**). Each scale is linked to inform the other scales and increase a manager's confidence in the knowledge on which they base their decisions. In addition to the important linkages between the temporal and spatial scales of monitoring, each scale of monitoring is target to address the following management knowledge requirements:

1. Seagrass **habitats** that occur across the Reef.
2. The trends in seagrass **health** at representative sites within defined regions.
3. **Process** understanding to help prioritise management actions, inform management effectiveness and develop models to predict seagrass responses to future pressures.

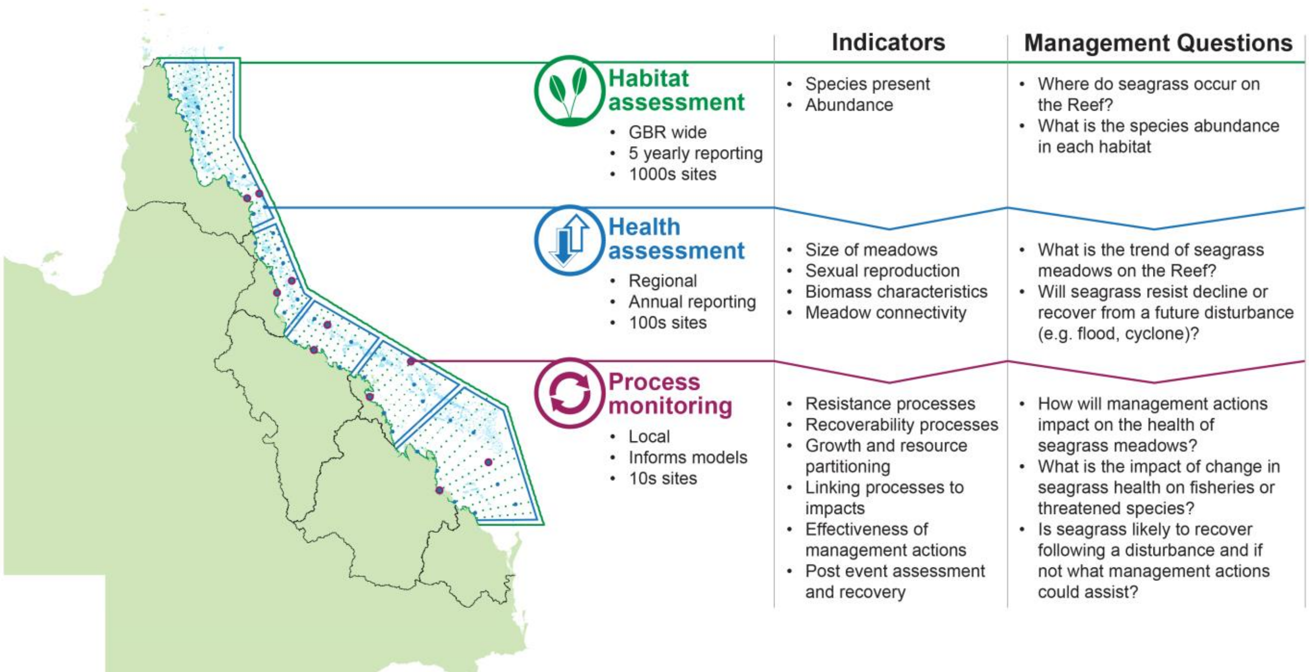


Figure 12. Three scales of monitoring required to address different management questions.

3.1 Cross-scale linkages

All three scales of monitoring are required to adequately provide the package of management information and knowledge system required to manage and report on the World Heritage Area. The three scales are nested with the information collected and knowledge available to managers increasing at each subsequent scale. At the broadest monitoring scale *habitat assessment*, information collection needs to be rapid to allow for a large number of sites to be assessed; therefore less detailed information is able to be captured. This scale has been optimised to provide managers with a good spatial understanding of the condition of seagrass within the different habitat types across the Reef, so temporal frequency is minimised (once every five years) to provide better spatial representation. The *health assessment* scale provides more frequent annual or biannual data at a subset of these locations to inform trends within that five-year timeframe, as well as more detailed information on smaller scale spatial changes in the extent and resilience of meadows, to inform both regional and Reef-wide assessments. This scale also provides more detailed information in areas of high cumulative anthropogenic risk. The *process monitoring* scale is undertaken at the fewest number of sites, as it measures processes and cause-and-effect relationships that require intricate measurements or frequent sampling. The complexity of monitoring these indicators limits the number of sites where they can be measured. These assessments provide critical information required to interpret the indicators used at the two broader levels of monitoring including cause and effect pathways, feedback loops and validating the assumptions of the other indicators, but are only needed at fewer representative demonstration sites. Statistical design will be required across all three scales to ensure the information from each scale can be efficiently summarised or interpolated to provide maximum benefit to managers and ensure a robust multi-purpose monitoring program that informs a scalable knowledge system for the Reef.

Preliminary advice has been provided to the group by DATA 61[1] on statistically robust principles of optimal monitoring design. The following recommendations have been based on this advice.

It is important that monitoring programs are designed so that the information collected is fit for purpose and the resulting data are representative of the 'population' under investigation. Representative samples are typically selected through the process of randomisation. In contrast, samples selected in an opportunistic or haphazard way lead to data that may be efficient to collect, but cannot be used to make inference about the population as a whole. However, simple randomisation is not the most efficient (cost-effective) form of random sampling, with research in this area leading to spatially balanced designs. A spatially balanced design can be seen as an extreme form of stratification (Stevens and Olsen 2004) that aims to reduce the frequency of placing samples close to each other (relative to simple randomisations). The efficiencies of spatially balanced designs can be further improved by increasing the probability of selecting sampling locations where the sampling variable is thought to have greater variance.

……………………………………

[1] *DATA 61 is affiliated with the CSIRO and provided input to the group under a separate contract with the Great Barrier Reef Marine Park Authority.*

A spatially balanced sampling design incorporating varying inclusion probabilities for the 12 seagrass habitat types as well as existing legacy sites should be used to develop a spatial/temporal monitoring design for seagrass on the Reef. This approach is consistent with national standards for the design of marine monitoring programs, recently released by the National Environmental Science Program Marine Biodiversity Hub (Foster et al. 2018).

Here we identify criteria that should be considered when identifying where to sample for *habitat assessment* and *health assessment*:

1. areas that should be excluded or given a low priority for sampling due to excessive depth (greater than 80 metres) or strong bottom shear stress, as a result of tidal currents or wave energy,
2. geomorphology and sediment characteristics,
3. pressures (cumulative risks) that seagrass are exposed to,
4. seagrass species composition and community types present on the Reef,
5. reporting scale requirements for management outputs and organisations (for example, level of detail required for Report Cards, NRM regions, local government or port areas).

The relative proportion of sampling effort that is allocated to each sampling zone will be determined in consultation with managers — taking into account the importance of spatial and temporal resolution in undertaking management tasks and the ability for monitoring information to change or trigger a management response.

A second important consideration in reducing the uncertainty in monitoring data is reducing the unexplained variation in the data. This requires measurement techniques and protocols that are repeatable, with two observations at the same site (a GPS location) and time likely to be similar. The number of observations taken at a sampling site needs to be such that temporal comparisons of change reflect a true change in condition of the indicator, rather than being an artifact of measurements being conducted in a spatially variable seagrass habitat. While this is not the focus of this report, these aspects of variability in seagrass meadows will need to be considered in the development of standard sampling protocols for each of the spatial/temporal sampling scales. Statistical analysis of existing data, as well as assumptions relating to the spatial and temporal variability, will need to be undertaken to identify the optimal number of observations and size of a seagrass monitoring 'site', as well as frequency and timing of data collection. The likelihood that two adjacent samples return a similar result, as well as the temporal variability (including seasonality) of attributes, will be critical to consider in the monitoring design. The spatial tools available from existing long-term monitoring and the NESP Reef seagrass synthesis data (Carter et al. 2016a) provide valuable tools that can inform and be used to test the new design.

Habitat assessment

For managers to obtain information on the condition of seagrass habitats at the scale of the Reef a new monitoring design is required which embeds the current understanding of seagrass ecology, an area that has advanced substantially since the current seagrass monitoring programs were established. A modern monitoring design will provide critical information to future Outlook reports and other documents that need to track progress towards objectives and outcomes in the Reef 2050 Plan. Implementation of a new spatially balanced monitoring design will enable the Authority and others to report on the condition and trend of seagrass within the 12 different seagrass habitats that occur on the Reef. This style of design is consistent with international monitoring best practice as well as national standards for the design of marine monitoring programs, recently released by the National Environmental Science Program (Foster et al. 2018).

The *pressures* impacting on the 12 seagrass habitats (Figure 7, Figure 10) are different, as is the ability for management actions to influence and modify these *pressures*. Hence, there is a strong rationale for the prioritisation of sampling efforts depending on the benefit higher resolution data will provide to managers and the likelihood of information collected through monitoring resulting in a change in management *responses*.

4.0 Priority *habitat assessment* indicators

To answer management questions relating to seagrass at the scale of the Reef, an extensive area needs to be sampled. The operational logistics of monitoring sites over such a large spatial area (228,000 square kilometres; Appendix 1) limits the amount of time that can be spent at a site, and requires that the travel time to reach each site is minimised. This limits sample collection at this scale to seagrass or environmental attributes that can be quickly and easily collected in a repeatable manner — a rapid assessment. It is also recognised that there are likely to be numerous sampling teams collecting the same information in different regions of the Reef. This will require establishment of various quality controls and data standardisation protocols to ensure that data is comparable across regions. All indicators recommended at the *habitat assessment* scale have been chosen because they are observable or able to be inferred from a photograph/video (

Table 4, Table 5). This ensures that the time taken collecting the data is short and enables the development of quality assurance and control protocols to validate data from multiple observers.

Table 4. *Habitat assessment* indicators recommended for assessing seagrass condition across the Reef.

Priority Indicator	**Justification for selection**	**Management Link** (Reef 2050 Plan objectives represented by their code)
Seagrass presence and abundance	Seagrass presence and an estimate of above-ground abundance provide an indication of seagrass condition and a meadows ability to deliver important ecosystem services.	Tactical, Operational, Strategic Planning, reporting, EH02, EH03, WQ01, WQ02
Seagrass Species or genera	Seagrass species provide an indication of the stability of a seagrass meadow as well as the meadows resilience and ecosystem services.	Tactical, Operational, Strategic Planning, reporting, B04, B05, EH02, EH03, WQ01, WQ02

Table 5. Complimentary environmental indicators recommended to measure at all *habitat assessment* sites

Priority Indicator	**Justification for selection**	**Management Link** (Reef 2050 Plan objectives represented by their code)
Sediment Type	Sediment type has a strong influence on water turbidity and the impact that strong currents (tidal or flood) and dredging will have. Knowing the sediment type in an area informs managers on the impact different pressures are likely to have on seagrass and other nearby habitats.	Tactical, Operational, Strategic Planning, Management effectiveness, reporting, EH02, EH03, WQ01, WQ02
DPSIR linkages	The seagrass measurement can be combined with outputs from eReefs and other Reef-wide spatial tools to present the information on seagrass *state* as well as assess likely *pressures* and *impacts*.	Tactical, Operational, Strategic Planning, Management effectiveness, reporting, EH02, EH03, WQ01, WQ02

4.1 Statistical Design Required

A design approach consistent with the recommendations in the NESP 'Survey Design Methodology' report (Foster et al. 2018) is strongly recommended. Aspects of the survey design approach have been included below in the sections relating to frequency of measurement, key design considerations and scale and size of sampling unit. This scale of the seagrass monitoring will focus on a spatial and temporal sampling strategy that will enable the Authority to report on the condition of seagrass across the 12 seagrass habitats (defined in this report) every five years as part of the Outlook Report. In addition, it will contribute information on temporal trends across the Reef that can be used by regional report cards and for more frequent updates on the Authority's website. Although historical records will not have been sampled at this same scale and methodology (Carter et al. 2016a) it will also be possible to conduct comparative historical evaluations, albeit at local or regional scales rather than the whole Reef.

4.2 Frequency of measurements

It is anticipated that a small percentage of sites would be visited annually with the balance of sites visited once every five years. The exact design would need statistical examination to determine the optimal frequency of sampling and number of sites that would need to be visited annually to be fit for purpose for the priority management questions. The composite of Reef seagrass monitoring from National Environmental Science Program Project 3.1 (Carter et al. 2016a), and the habitat classification (Appendix 1) provides an initial data source to aid in design. Adaptations to the monitoring design can be made as additional information is collected during the initial phase of implementing this broad level of monitoring. The annually-examined sub-set of sites will provide an indicator of annual trends within the five-year sampling period, while additional monitoring conducted at the *health assessment* locations, nested within this spatial design, will provide further interpretive power.

4.3 Key design considerations

While typical spatially balanced designs such as Balanced Acceptance Sampling and Generalised Random Tessellation Stratified designs maximise the efficiency of sampling (in terms of lowest variance for a given number of sites), the large distance between sites can make this method logistically challenging and cost-prohibitive, depending on the number of sites being sampled and area covered. One way to improve this is to select the spatially balanced sample in two stages, where the first stage represents the central site (with fewer sites selected) and then within a certain radius of that site a large number of additional sites can be selected in a spatially balanced manner. This means that multiple sites can be sampled in a given area, reducing large traverses between sites and making the sampling design more appropriate for the application of new technologies (for example, survey robots). This design approach is also likely to work well for capturing the spatial variability of seagrass meadows.

4.4 Scale and size of sampling unit

The principles of a spatially balanced design rely on the concept of a site representing a location in space defined by its latitude and longitude. The number of observations required to accurately quantify what is present at a site will be determined by sampling method and small scale spatial heterogeneity. The key to collecting information across the large number of sites required to complete a broad scale *habitat assessment* is to keep the site size small and the sampling methodology simple, so that many sites can be sampled. During the spatial design phase (not yet funded) it will be important to balance the statistical benefits from having more sampling sites vs reducing the sampling error from small scale spatial heterogeneity. This is especially important given the large operational area across which *habitat assessment* will occur, and need to optimise the sampling design while incorporating the operational costs related to visiting each site (also see text on spatial heterogeneity of seagrass in *health assessment*).

4.1 Contribution towards reporting

The *habitat assessment* scale of monitoring provides the majority of information on condition and long-term trend of seagrass in the World Heritage Area for future Outlook reporting. This monitoring also provides a critical input to the annual regional Report Cards, with additional information being contributed from the *health assessment* indicators, collected at representative sites for each habitat type.

Seagrass health is determined by combining seagrass abundance (per cent cover, biomass) measured as part of *habitat assessment*, with an assessment of resilience. The *resilience* of a seagrasses meadow is determined by its *resistance* and *recoverability*; hence a resilient seagrass meadow has a greater ability to persist over time when exposed to a range of pressures and disturbance events (for example, cyclones, floods, dredging, warming, and dugong grazing). The ability of a seagrass meadow to resist and recover is dependent on attributes relating to the seagrass itself, including the spatial extent of seagrass, species diversity, genetic diversity of the population (for example, clonal diversity, population structure), the condition of the seagrass (including, sexual and vegetative reproduction and stored energy within the plant) as well as attributes beyond the seagrass meadow of interest (for example, connectivity or dispersal of propagules between meadows) (**Figure 11**,

, **Error! Reference source not found.**).

4.1.1 Quantifying resistance and recoverability

Meadows' resistance to pressures is primarily dependent on abundance and species diversity, (included in *habitat assessment*), spatial extent, stored energy within the plant and the distribution of patches or fragmentation of the meadow (

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Recovery of a meadow following degradation triggered by exposure to a pressure or disturbance event is facilitated by the presence of a seed bank or vegetative fragments as well as the ability to recruit propagules from other meadows. At the *health assessment* scale the recoverability of seagrass habitats will be assessed by quantifying the seed bank and presence of reproductive structures at representative locations within each habitat type as well as connectivity with other meadows. The more time consuming and complex measures of resistance and recruitment will only be measured at the *process monitoring* sites (**Error! Reference source not found.**).

5.0 Priority *health assessment* indicators

To determine the resilience of seagrass at the *health assessment* scale we need to combine the resistance attributes (seagrass abundance, species composition, spatial extent of representative meadows, seagrass condition) with the recoverability attributes (seed bank, presence of reproductive structures, connectivity of meadow). These metrics provide managers with information relating to meadow *resistance* (likelihood of persisting) and *recoverability* (likelihood of recovery following an event) (Table 6, Table 7, Figure 11, and Figure 13).

Table 6 *Health assessment* indicators – representatively sampled across habitat types:
These will inform managers on critical components of resilience at the regional scale

Priority indicator	Justification for selection	Management Link
Seagrass abundance (at higher spatial resolution than *habitat assessment*)	Seagrass above ground abundance provides an indication of seagrass condition as well as a meadow's ability to provide important ecosystem services. Monitoring at this scale provides higher resolution of information needed to inform on variability within a meadow.	Tactical, Operational, Strategic Planning, Management effectiveness, reporting EH02, EH03, WQ01, WQ02
Seagrass species (at higher spatial resolution than *habitat assessment*)	Seagrass species provide an indication of the stability of a seagrass meadow as well as meadow resilience and ecosystem services. Greater diversity of species will increase resistance potential and likelihood of fragments remaining or seed banks being present following an event. Monitoring at this scale provides higher resolution of information needed to inform on variability within a meadow.	Tactical, Operational, Strategic Planning, Management effectiveness, reporting B04, B05, EH02, EH03, WQ01, WQ02
Spatial extent of key and/or representative meadows Measuring change in meadow area or patchiness by mapping meadows at a higher spatial resolution	Changes in the spatial extent of a meadow have a direct impact on its resistance, and the ecosystem services it provides. Changes in the edge of a meadow or its patchiness provide additional information on the resilience of the meadow and likely pressures that are impacting on the seagrass.	Tactical, Operational, Strategic Planning, Management effectiveness, reporting EH02, EH03, WQ01, WQ02
Sexual reproduction: 1. Seed Bank 2. Reproductive structures	The number of seeds in a meadow provide a strong indication of recovery potential (for species that produce seeds). Quantification of presence/absence of reproductive structures during the peak season also provide an indication of seagrass meadows' resilience.	Tactical, Strategic Planning, reporting EH02, EH03, BO5, BO6, WQ01, WQ02

Table 6: Continued

Priority indicator	Justification for selection	Management Link
Seagrass condition 1. Biomass allocation (morphology, above/below), 2. Stored metabolites (e.g. carbohydrate)	Allocation of resources within a seagrass plant (biomass, morphology and metabolites) influence the meadow's resistance to decline. Biomass Allocation: The relationship between above ground and below ground biomass can change by more than 10 fold depending on environmental conditions. Knowing the ratio at specific meadows and how it has changed over time will inform managers about past environmental conditions and the likely future resilience of a seagrass meadow. Stored Metabolites: The storage of metabolites informs managers on how seagrass has responded to previous environmental stresses and its resilience to future pressures.	Tactical, Operational, Strategic Planning, Management effectiveness, reporting EH02, EH03, BO5, BO6, WQ01, WQ02
Connectivity (likelihood for dispersal between meadows)	The ability for external inputs of seeds or other vegetative or reproductive propagules to reach a meadow increase a meadow's recoverability and contributes to maximum potential values for a meadow's population structure, clonal and genetic diversity. The quantification of a meadow's connectivity with other meadows is only required once and uses both hydrological models as well as in-situ measures or water flow and genetics to predict past connectivity. This needs to be undertaken during site establishment – then only repeated if there is a dramatic change in seagrass distribution or local hydrodynamics (velocity of tidal currents or wave energy impacting a meadow), following major disturbance events.	Tactical, Strategic Planning, reporting EH02, EH03, BO5, BO6, WQ01, WQ02

Table 7. Complimentary environmental indicators at *health assessment* monitoring sites

Priority indicator	**Justification for selection**	**Management Link** (Reef 2050 objectives represented by codes)
Habitat and/or environmental suitability 1. Benthic light, 2. Temperature 3. Benthic shear stress 4. Sediment quality	Seagrass resistance or recovery requires that abiotic conditions remain within an acceptable range. To inform managers of useful responses, if seagrass decline is detected, it is important to know the environmental conditions as these will influence vegetative growth rate and propagule recruitment success. These are a combination of *in situ* measures and computer-generated predictions provided by other aspects of RIMReP. Collecting this information at the same time and location as seagrass metrics is critical for interpretation. All of these attributes can be measured by taking a sample (sediment quality) or *in-situ* sensors (benthic light, temperature, benthic shear stress). Benthic shear stress can be measured accurately *in-situ* using an ADCP, or estimated using relatively cheap low technology options (rate at which a block dissolves/erodes).	Tactical, Operational, Strategic Planning, Management effectiveness, reporting EH02, EH03, WQ01, WQ02
DPSIR Linkages 1. Flood plume frequency 2. Pollutant loads 3. Impact from cyclones	These are attributes that quantify the pressure on seagrass meadows, but are likely to be measured by other groups — increasing the interpretive power of the seagrass monitoring.	Tactical, Operational, Strategic Planning, Management effectiveness, reporting EH02, EH03, WQ01, WQ02

Considerations in statistical design

As with *habitat assessment*, the appropriate spatial scale of a sampling 'site' and number of observations required to account for small scale spatial variability will require further statistical analysis. Consideration should be given to the scale required to monitor each indicator to provide a robust representation of the seagrass attributes, having regard to its ecological relevance and impact on management decisions. In addition, the scale at which information is required to support local, regional or Reef-wide management and reporting needs will influence the prioritisation of sampling resources. For example the *health assessment* scale of monitoring is where monitoring in areas with high cumulative risk will continue to occur (for example, monitoring currently undertaken for the Marine Monitoring Program and Ports monitoring).

Sampling will occur either annually or bi-annual, depending on management questions and priorities. Seasonality of seagrass distribution and abundance requires that the time of sampling be considered to ensure specific management questions can be answered. The following factors need to be considered when selecting sampling times:

- The largest seagrass abundance generally occurs between September and November. Sampling at this time of year provides an annual maximum of seagrass extent and abundance, and improves the likelihood of determining multi-year trends in seagrass condition.
- If managers need to understand the impact a specific wet season has had on seagrass condition, then sampling between March and May is required.
- Sampling twice during a year will provide a more robust inter-annual assessment of change and additional information on the condition of seagrass following a wet season, enabling quantification of the impact its associated storms and cyclones had.
- If sampling occurs only once per annum, RIMReP will have approximately a nine-month delay before it can report on any change in seagrass following a severe wet season.

RIMReP also needs to capture meadows of special value and high risk, including:

- sources of seeds for recolonising following a catastrophic loss;
- known areas of importance to dugong and turtle populations;
- important fisheries habitat;
- rare species that may have a higher risk of regional or Reef-wide extinction; and
- high cumulative anthropogenic risk sites that require a more intensive level of monitoring to meet local management requirements.

5.1 Frequency of measurements

Temporal and spatial scale of monitoring — incorporation of legacy sites

It is envisaged that a site at this level of monitoring may be larger than at the *habitat assessment* scale, to capture the inherent variability that we know is a feature of seagrass meadows on the Reef. This scale is also where the majority of legacy sites from existing monitoring programs (Marine Monitoring Program and Ports monitoring) will be incorporated.

We have recommended that the monitoring design include legacy sites within a spatially balanced design, where relevant, as this has been demonstrated to improve the detection of trends and reduce uncertainty due to inferences (Foster et al. 2017). It will also ensure that locations with existing data (up to 20 years in some areas) providing a historical context of expected seagrass *state* including variability are maintained within the new program (see Figure 15 for existing monitoring locations).

Foster et al. (2017) make the distinction between legacy sites and iconic sites, where the former have previously been chosen as a result of randomisation from some historical monitoring and the latter chosen based on specific traits (for example, high biodiversity, adjacent to high cumulative pressures). Care should be taken in selecting appropriate sites to use as legacy sites in the seagrass monitoring framework with sites considered on an individual basis. Estimates of status and trend using data from sites which are closer to the definition of iconic may not be representative of the broader area they are expected to represent.

5.2 Contribution towards reporting

Health assessment indicators will be reported annually at the regional scale and predominantly inform management at the NRM and sub-regional scale. The health assessment indicators also provide information at smaller scale (for example, ports, and bays) with appropriate consideration during sampling design. These indicators provide a robust base on which to establish a scoring system for use in report cards and other reporting documents. This informs on the resilience component of seagrass *state*, as well as management actions that could be taken to assist seagrass recovery following a significant decline or loss.

Process monitoring

PROCESS MONITORING AIMS TO ELUCIDATE THE UNDERLYING MECHANISMS WHICH INFLUENCE SEAGRASS CONDITION AND RESILIENCE. THIS INFORMATION HAS MANY USES. IT CAN PROVIDE CONFIDENCE TO INDICATORS USED AT HIGHER SCALES (FOR EXAMPLE, RESILIENCE); PROVIDE MODELS OF SEAGRASS PRODUCTIVITY; ESTIMATE ENERGETICS OF SEAGRASS AS FOOD RESOURCES FOR KEY CONSUMERS (DUGONG AND TURTLE); QUANTIFY AND TEST THRESHOLDS FOR DECLINE AND RECOVERY OF SEAGRASS MEADOWS; QUANTIFY CRITICAL PROCESSES; AND, IMPROVE MANAGERS' UNDERSTANDING OF CAUSE-EFFECT RELATIONSHIPS (

Table 8, **Figure 14. Component of resilience monitoring measured at *habitat, health and process monitoring* scales.**

Table 9). *Process monitoring* is split into two types: *routine* and *post-event*. Routine *process monitoring* should occur at a subset of the sites monitored for seagrass *health assessment*. *Post-event* monitoring will occur in response to a disturbance event (for example, cyclone or flood) which has decimated seagrass. Both scales of monitoring will provide critical information on rates and processes useful for model development.

Routine process monitoring will require a high temporal frequency to capture seasonal patterns, or sampling methods that are either too costly or time-consuming to be carried out at all locations monitored for seagrass health. *Post-event* monitoring will quantify the recovery response following an extreme event, and will be carried out at fewer sites. Data collection will be focused on for this monitoring scale.

6.0 Priority *process monitoring* indicators

6.1 Routine monitoring

Routine monitoring will be undertaken at a randomly selected subset of sites from the seagrass *health assessment* sites, and focus on collecting data that informs:

1) Resilience attributes of seagrass plants or meadows that require too much time or resources to include in *health assessment*. Both resistant and recovery aspects of resilience that could be measured at this scale at shown in
2)
3) .

4) Processes that are thought to be a dominant feedback mechanism or important in the DPSIR framework, including the:
   - impact of herbivory on seagrass (mega fauna, fish and micro grazers);
   - sub-lethal response of seagrass to changes in water quality;
   - role of seagrass biomass in trapping sediment particles and improving benthic light;
   - quantification of environmental and ecological thresholds and tipping points; and
   - role of genetic diversity of a meadow to inform resilience and connectivity assessments.

Characterising feedback processes that influence the response of seagrass ecosystems may help identify the conditions that prevent recovery and allow those to be addressed through targeted management actions (Maxwell et al. 2017). Feedbacks are not usually directly considered in monitoring and management programs, however, monitoring feedbacks is necessary as they directly affect seagrass ecosystem structure and function.

Of the 17 feedbacks that have been demonstrated in seagrass ecosystems globally, we propose that four are included in RIMReP (

TABLE 8). Feedbacks are also a critical component of understanding a seagrass meadow's resilience to different pressures as they modify the environment and severity of the pressure (see

).

Positive features of resilient seagrass meadows *(assume per unit time)*

Highly resistant	***Rapid recovery***
Meadow area (Ha & abundance m^{-2})	
Large area >100's m	Small area <10's m
Continuous becoming patchy	Patchy becoming continuous
Species diversity (# spp m^{-2})	
Mixed meadow of persistent spp.	Mixed meadow of colonising spp.
Seagrass condition (e.g. %C g^{-1} m^{-2} or above:below ground biomass)	
High storage of %C	Low storage but rapid accumulation of %C
High above:below ratio	Low above:below ratio but changing
Population genetic structure–spatial, clonal and genetic diversity (# alleles $site^{-1}$)	
Moderate to high clonal diversity	Moderate to low clonal diversity
Genetic diversity moderate	Moderate to low genetic diversity
Genets mixed across site	Genets rapidly expanding and mixed
Connectivity and dispersal (# migrants $site^{-1}$)	
Dispersal away from site	Dispersal to site
High connectivity locally and regionally	High connectivity from source site
Propagule supply (# seeds/fragments $site^{-1}$)	
Seeds or fragments supplied at grreater than replacement rate to maintain continuous meadow	Seeds or fragments greater than loss due to predation or lost viability over time
Propagule survival (recruitment success # seeds/fragments $site^{-1}$)	
Survival maintains meadow	Survival leads to expansion of meadow
Meadow expansion rate (patch size m^{-2} $site^{-1}$)	
Patches maintained as continuous	Patches expanding
Environmental modifiers/feedbacks e.g. sediment composition, bed shear stress or light regime (Kd etc.)	
Environmental conditions that support seagrass	Environmental conditions that enable seagrass recruitment

Figure 13. Indicators of a resilient seagrass meadow. Resistant features to the left, recovery features to the right, for each potential indicator.

Table 8. Routine *process monitoring* indicators — this includes measures that are too costly to monitor at all *health assessment* sites, but in combination with *health assessment* indicators will provide an understanding of resilience and feedbacks.

Priority indicator	**Justification for selection**	**Management Link** (Reef 2050 objectives represented by codes)
Meadow characteristics and condition 1. Areal extent 2. Abundance 3. Patchiness 4. Biomass allocation (morphology and above/below) 5. Stored metabolites (C:N:P, carbohydrates)	Tracking seasonal change in meadow characteristics at a subset of sites monitored in the seagrass *health assessment* scale. Many of these measures inform the resistance attribute of seagrass resilience. These measures will inform predictive models and also enable measures made less frequently in *habitat assessments* and *health assessments* to be adjusted for seasonal variation.	Tactical, Operational, Strategic Planning, Management effectiveness, reporting EH02, EH03,BO4, BO5, WQ01, WQ02
Connectivity and population structure	Connectivity (the ability for propagules to disperse from one meadow to another) is a critical component in recoverability (the potential for a meadow to recover from a disturbance). The likelihood for external inputs of propagules to the affected area, therefore influences clonal diversity, population structure and genetic diversity. Due to cost and effort required, it is unlikely this attribute could be monitored effectively at all seagrass health sites. However, connectivity works at a larger scale than generally considered within this *process monitoring* — so has been included as an indicator in both sections, it is likely a baseline survey will be adequate with event response sampling and periodic evaluation of sites.	Tactical, Operational, Strategic Planning, Management effectiveness, reporting EH02, EH03,BO4, BO5
Meadow diversity 1. Species diversity 2. Clonal diversity	Understanding the spatial distribution of individuals (species or genotypes) across a seagrass landscape (within and between meadows) provides information on both resistances of meadows to pressures and likelihood of recovery. Other aspects which may be desirable to understand include population structure and genetic diversity, but these are currently not highlighted as priorities to measure.	Strategic Planning, Management effectiveness, reporting EH02, EH03,BO4, BO5
Recoverability: Routine measures	Resistance and recovery of a meadow is determined by its ability to grow and recover faster than seagrass is lost through natural attrition and extreme events. These measures are time	Tactical, Operational, Strategic Planning, Management

1. Sexual reproduction (seed bank, seed viability, seedling numbers, reproductive structures) Non-routine 1. Vegetative growth rate 2. Recruitment success (Propagule and Seedling) 3. Rate of expansion of fragments 4. Seedling survival rate to adult-hood	consuming and may require more frequent sampling, but they provide a direct measure of seagrass resilience. Sexual reproduction may be difficult to measure effectively at the seagrass health scale due to seasonality of reproduction falling outside the targeted sampling period or challenges in identifying reproductive features (for example, too time-consuming to carry out at all locations). Therefore, we propose that these more detailed measures of recoverability are undertaken at a subset of the seagrass health sites. They directly quantify resilience processes and support predictive model development as well as provide validation and confidence in the reproductive measures collected at the broader seagrass health scale. A range of other measures are also considered important for resilience understanding and are listed here as non-routine. These may also be considered important to monitor at some locations when managers require additional information on meadows likely recovery.	effectiveness, reporting EH02, EH03,BO4, BO5, WQ01, WQ02
Herbivory: 1. Direct observations 2. Exclusion sites 3. Explicit mapping of feeding scars	Herbivory, particularly from large herbivores such as dugong and turtle, can have a profound effect on seagrass state. Herbivory pressure is not constant; quantifying this change at representative sites is a key to defining cause and effect in seagrass change. A decline in seagrass may have nothing to do with water quality or anthropogenic direct impact at a site, but be caused by large herbivores. Simple exclusion cages at key sites are an effective way to understand the impact of herbivores and integrate with threatened species monitoring across the Reef.	Tactical, Operational, Strategic Planning, Management effectiveness, reporting EH02, EH03,BO4, BO5, WQ01, WQ02
Controlling feedback mechanisms 1. Sediment trapping/preventing resuspension 2. Density-dependant hydrodynamic effects 3. Sediment oxygenation to prevent sediment toxicity 4. Grazing-induced enhancement of nutrient uptake	Seagrass resistance or recovery requires an understanding of the feedback process that can help seagrass resist or recover from environmental or anthropogenic pressures. These four feedback mechanisms should be measured to establish a baseline at key sites and provide a comparison with sites where declines or slower than expected recovery is occurring. This will help prioritise management actions to facilitate resilience. Points 1 and 2 require sediment traps and ADCP; point 3 microprobes and point 4 as part of herbivory (above).	Tactical, Operational, Strategic Planning, Management effectiveness, reporting EH02, EH03,BO4, BO5, WQ01, WQ02
DPSIR Linkages	To be effective the indicators measured here need to be developed across expert themes (for	Strategic Planning, Management

<table>
<tr>
<td>Abiotic from other groups:

1. Flood plume frequency
2. Pollutant loads
3. Impact from cyclones

Additional indicators to measure:

- Requires discussion between group leads.</td>
<td>example, Water quality, Seagrass, Megafauna, Human dimension).

It is important that pressures are measured at the same sites as seagrass state and impacts. Site for the purpose of this component may have a larger spatial definition to accommodate spatial and temporal variability of the pressure or value that is being impacted.

Indicators to possibly include:

- Tracking condition of seagrass at sites most influenced by anthropogenic pressures
- Estimating grazing pressures and ‘total’ sum of seagrass available in each habitat type every five years or annually in some locations.</td>
<td>effectiveness, reporting

EH02, EH03, BO4, BO5, WQ01, WQ02</td>
</tr>
</table>

Description of feedback mechanisms (more detail provided in Maxwell et al. 2017)

1. Sediment trapping/preventing resuspension: Meadows with higher density and species of a larger structure trap water column sediment, improving water clarity. This has a positive impact on seagrass growth, which can increase seagrass depth range and the maximum depth limit of a meadow. This feedback is important in habitats with higher benthic shear stress (currents or wave action) and/or small particle size suspended sediment. Canopy height and leaf density both affect flow velocity, so feedback strength may be estimated from the values for ‘meadow characteristics’ in *process monitoring* as well as seagrass abundance, species and condition from *health assessment* sites, but in some cases direct measures of the feedback loop will be required to inform managers of a meadow’s resilience to future threats (de Boer, 2007; Carr et al., 2010; Hansen and Reidenbach, 2012).

2. Density-dependent hydrodynamic disruption: High-density seagrass reduces near-bed water currents (shear stress), reducing physical stress on seagrass plants. Low-density seagrass patches or meadow edges locally increase turbulence, possibly resulting in erosion and scouring. Reduced near-bed currents trap more sediment, which leads to better conditions for seagrass growth at the meadow scale. However, increases in near-bed currents, following the loss of seagrass, reduces sedimentation and can lead to erosion. This can reduce the resilience by preventing successful recovery of seagrass meadows following large biomass declines (Fonseca and Koehl, 2006; Van Katwijk et al. 2010).

3. Sediment oxygenation to prevent sediment toxicity: High-density seagrass puts more oxygen into the sediment (rhizosphere), reducing sulfide concentrations. This improves sediment conditions for seagrass growth or reproduction. This feedback is most important in areas with high organic sediment loads and impacted by reductions in benthic light, which limits the potential for oxygen production by the seagrass (Borum et al., 2005; Brodersen et al, 2014).

4. Grazing-induced enhancement of nutrient uptake: increasing seagrass nutrient uptake (e.g. turtles and dugongs): Hence megagrazer activity can alleviate the negative effects of eutrophication by stimulating seagrass production and nutrient uptake. This feedback is most important in areas where eutrophication is high and there are active megaherbivores. If grazing decreases this can have a direct impact on the resistance of seagrass by making them more susceptible to high nutrient loads and possible overgrowth by epiphytes or macroalgae (Christianen et al. 2012).

6.2 Post-event monitoring

Following an event that causes significant seagrass loss it will be necessary to initiate *post-event* monitoring to assess if factors are present that will enhance or inhibit recovery, as well as track the recovery rate of representative meadows (**Error! Reference source not found.**). It w ill improve predictive models and validate the estimates of resilience provided by the *health assessment.* Specifically, we propose that following a disturbance of concern, a rapid assessment of recovery potential be carried out (for example, number of fragments, presence of seedbank and habitat suitability). This first assessment provides information as to whether the meadow is likely to recover by itself and over what time period, or if active intervention may be necessary. If recovery is considered likely, an ongoing *post-event* monitoring program will confirm recovery is progressing according to estimates. This program needs to be scaled appropriately to the disturbance and consider kinetic and seasonal aspects of recovery.

Figure 14. Component of resilience monitoring measured at *habitat, health and process monitoring* scales.

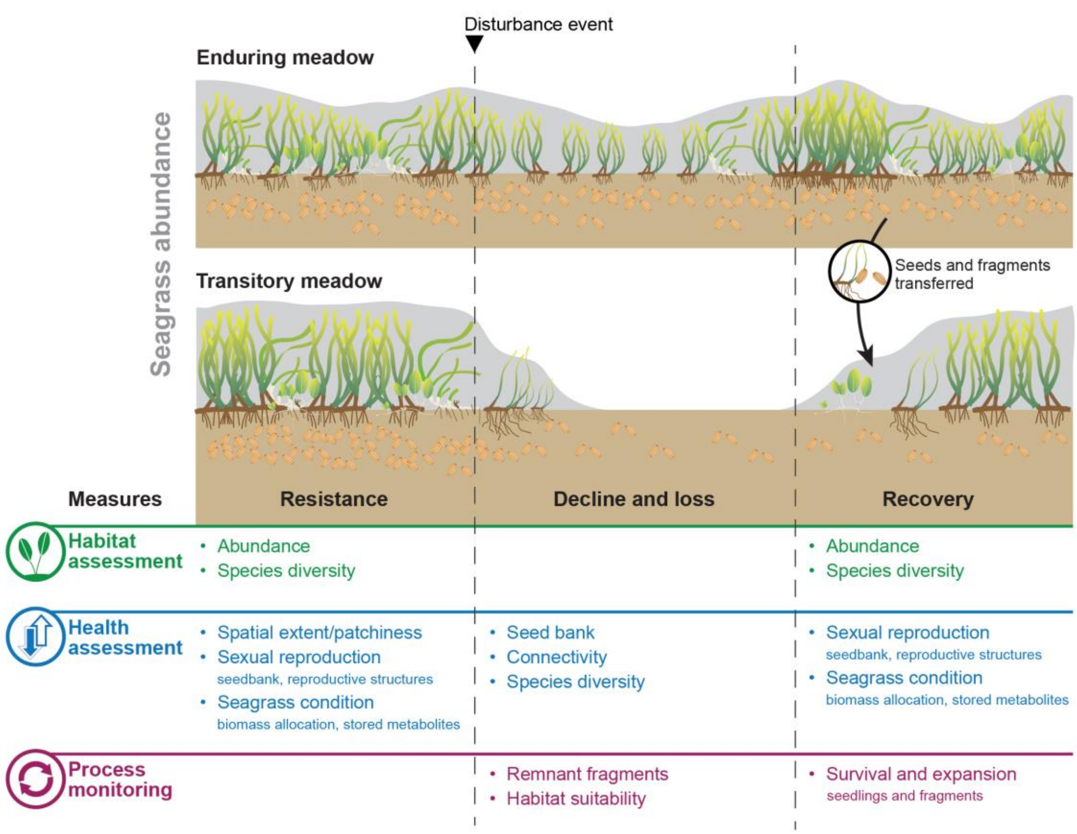


Table 9. *Post-event* Process Understanding indicators – to quantify recovery processes

Priority Indicator	**Justification for selection**	**Management relevance** (Reef 2050 Plan objectives by their code)
Recovery potential (rapid assessment) 1. Seed bank 2. Remnant fragments 3. Species diversity	This first assessment provides managers with information as to how severe the disturbance was. It enables prediction of recoverability i.e. whether active intervention may be necessary or if the meadow is likely to recover by itself.	Tactical, Operational, Management effectiveness, reporting EH02, EH03,BO4, BO5, WQ01, WQ02
On-going *post-event* monitoring 1. Seagrass abundance 2. Species diversity 3. expansion of fragments 4. Sexual reproduction (seed bank, propagule production) 5. Biomass allocation	Recovery of a meadow is determined by its ability to grow and recover faster than seagrass is lost through natural attrition or the next extreme event. These measures directly quantify recovery processes and can be used to provide managers with predictions of recovery rates for a meadow, inform model development and validate surrogate measures, which may be quicker to collect. These attributes will only be measured at a few sites within an impacted region, so sites should be selected to be representative. Other attributes contributing to recovery not given priority to measure here are: fragment expansion, propagule recruitment success rate, vegetative growth rate and seedling survival rate to adulthood.	Tactical, Operational, Strategic Planning, Management effectiveness, reporting EH02, EH03,BO4, BO5, WQ01, WQ02
Habitat suitability Sediment quality and characteristics of meadow area	Recovery of a meadow is determined by the suitability of the sediment to allow seed germination or propagule growth. Sediment suitability can change following a disturbance, hence sediment suitability for recovery is critical to inform management response and expectations.	Tactical, Operational

6.3 Considerations in statistical design

Site selection for *process monitoring* needs to consider multiple factors. It will need to be nested within the random spatially balanced sampling design developed for the *habitat assessment* and *health assessment* to ensure the information can be interpolated beyond a specific location. Legacy sites will be included to maintain long-term trends in aspects of seagrass condition and resilience measured in the current programs. This scale of monitoring is expected to provide information needed to statistically assess the relationship between seagrass resilience and seagrass responses to environmental pressures. It is likely at this scale of monitoring that the statistical design may vary over time and/or between sites as management priorities change and knowledge gaps are progressively filled.

6.4 Frequency of measurements

Routine sampling frequency will be specific to the indicator, but is likely to range from monthly to quarterly. *Post-event* sampling will take place as soon as possible following an event. The scale of event needed to initiate *post-event* sampling will be set by managers, and will need to be based on environmental information provided through linkages with other themes within RIMReP.

6.5 Contribution towards reporting

This scale will be critical for quantifying cause and effect linkages and demonstrating management effectiveness. The information collected at this scale will often be site-specific, so will not always be able to be extrapolated to all seagrass meadows in a NRM region or Reef-wide. However, this scale will provide the majority of information to inform broader predictive tools that will support future management decisions and prioritisation of actions.

7.0 Evaluation of the adequacy of current monitoring of seagrass on the Great Barrier Reef

7.1 Synopsis of existing monitoring programs

Seagrass on the Reef is currently monitored by either the Marine Monitoring Program, managed by the Authority, or the Queensland Ports Seagrass Monitoring Program (Ports Monitoring), funded by numerous Port Authorities. These programs were developed collaboratively by the Australian and Queensland governments, James Cook University (JCU) and industries to meet specific management needs. The focus for both programs is to monitor the condition and trend of seagrass meadows in nearshore waters with varying levels of anthropogenic pressures. The Ports Monitoring focuses largely on habitats that occur within port limits, and the Marine Monitoring Program was designed primarily to examine a range of seagrass habitats impacted by declines in inshore water quality caused by flood plumes and sediment resuspension. Across both programs, 98 per cent of monitoring effort occurs at intertidal or shallow (less than minus 10 metres, mean sea level) subtidal meadows impacted by flood plumes. Within these same habitat types the Marine Monitoring Program recently expanded the spatial extent of sampling by including existing participatory science monitoring sites (Seagrass-Watch) and new drop camera monitoring sites, undertaken by Queensland Parks and Wildlife Officers at shallow subtidal habitats.

All seagrass monitoring activities on the Reef focus on assessing the species of seagrass present and the above-ground abundance (percentage cover or biomass). Sampling occurs either quarterly, thrice, twice or once every year, enabling the identification of seasonal and annual trends in seagrass species, abundance and quantification of changes in the spatial extent of seagrass, within defined sites or meadows. Additional data relating to the resilience of seagrass is also collected at some sites/locations, including the presence of reproductive structures, density of seed bank, tissue nutrient content of leaves, dugong feeding activity, macro-algae abundance, epiphyte cover and relevant environmental conditions (for example, benthic light and temperature).

There are many similarities between the seagrass monitoring programs that occur on the Reef, but the monitoring designs and information collected differ sufficiently that it is difficult to combine the data at a regional or Reef-wide scale (**Figure 15**). The method for estimating above-ground abundance and the scale at which sampling is conducted differ between the two major programs. The Marine Monitoring Program has 45 sites at 21 locations across the Reef where it measurements abundance (per cent cover from 33 observations in a 50 by 50 metre area) and maps the landscape features of seagrass (patches and scars) across 5.5ha of a meadow (Figure 16**Error! Reference source not found.**). This provides an ability to detect c hanges in seagrass abundance at a site with high statistical power but may limit capturing seagrass variability at larger scales (bay, region), particularly where spatial variability in abundance is high. The Ports Monitoring occurs at eight locations within the reef where it maps the boundary of entire meadows (between five and 14 meadows per location). It measures abundance at the meadow scale through a visual assessment of above-ground biomass at multiple sites spread throughout a meadow (three observations made at each site and the number of sites within each meadow is determined by power analysis, based on the site variability within a meadow) (Figure 16). This provides an estimation of variability and change in spatial extent and abundance across an entire meadow. However, as both current monitoring programs lack random spatial design for site selection it restricts the ability to extrapolate changes observed to a representative habitat type on the Reef. In addition to these two major programs, the Queensland Parks and Wildlife rangers and Seagrass-Watch provide additional information on the percentage cover at a further 20 sites.

The different approaches of the programs have created challenges for reporting the data sets in an integrated way. Despite this, seagrass data from both programs has been combined with an interim method to produce seagrass condition scores in NRM regional reports (Carter et al. 2016b), but this requires refinement. Hence, the recommendations in the current report have been developed to ensure future synthesis of information on the condition and resilience of seagrass on the Reef will be easily condensed into regional report cards and Reef-wide reports, such as the Outlook Report.

Data collected by the current seagrass monitoring programs is currently reported and utilised in several different products, with only limited crossover or combination of the two data sets. The Marine Monitoring Program is a critical component in the Paddock to Reef monitoring modelling and reporting program that tracks changes in regional water quality and its impact on the Reef, as land management practices are improved. Results from the three seagrass indicators are scored for the annual Reef Plan report card which was developed by the Authority, using advice from expert working groups and the Paddock to Reef Integration Team. The monitoring program receives thorough independent statistical analysis and review every five years and results undergo extensive external independent review annually. As a consequence, findings are not publically available until 12 to18 months after each monitoring period. The Ports Monitoring results are summarised through a report card that was developed in consultation with the Gladstone Healthy Harbour Partnership to report on seagrass condition for the Gladstone region, and has since been implemented across all the Ports Monitoring locations (since 2014). An annual report for each of the Ports monitoring locations is publically available approximately 6 months after the monitoring surveys, with the shorter turnaround in data making it more useful to managers and as a communication tool.

Data from both the Marine Monitoring Program and Ports Monitoring are integrated and incorporated into the current network of regional report cards for the NRM regional partnerships that develop scores for marine and estuarine health (Mackay-Whitsunday Healthy Rivers to Reef Partnership; Wet Tropics Healthy Waterways Partnership; Gladstone Healthy Harbour Partnership).

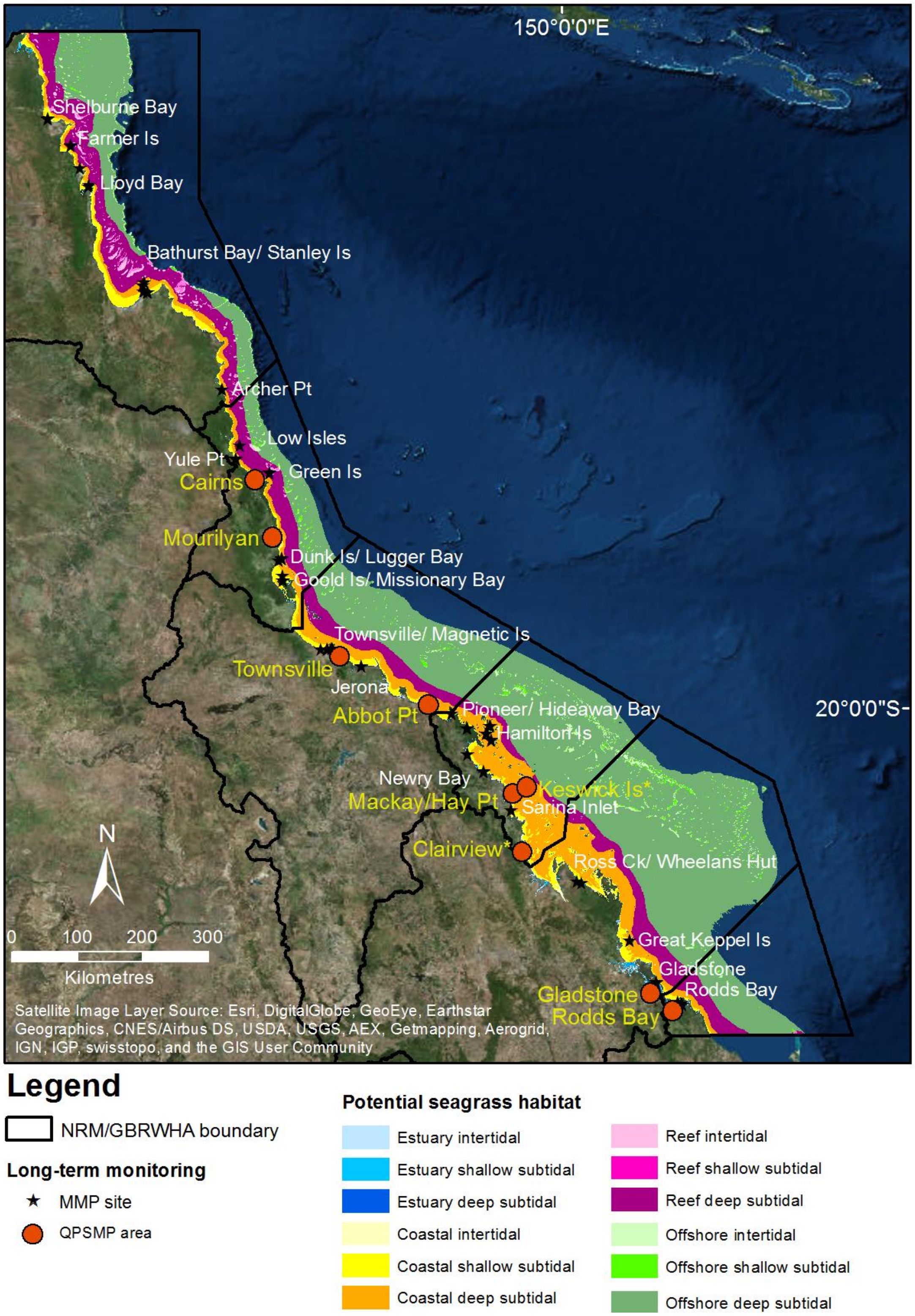


Figure 15. Location of Marine Monitoring Program sites (MMP) and areas where the Queensland Ports Seagrass Monitoring Program (QPSMP) are currently sampled, overlaid on the 12 seagrass habitat types.

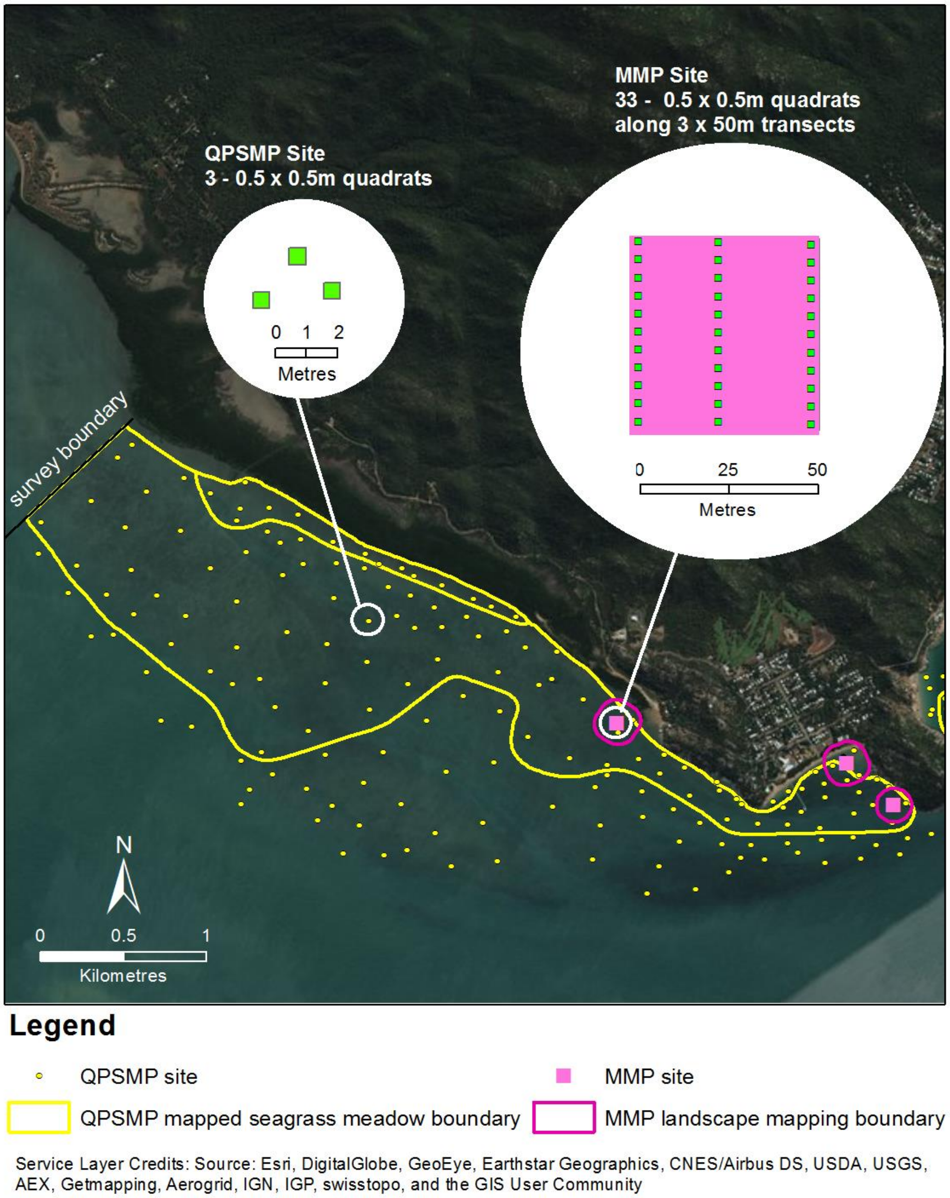


Figure 16. Sampling scale of the Queensland Ports Seagrass monitoring Program (QPSMP – yellow) and the Marine Monitoring Program (MMP – pink) on a seagrass meadow in Cleveland Bay. The green squares represent an observation in both programs.

7.2 Adequacy of existing monitoring programs

The existing seagrass monitoring programs have focused on intertidal and shallow subtidal seagrass meadows in areas with the highest cumulative anthropogenic risk (**Figure 15**; refer to Appendix 1). This provides an excellent foundation to understand seagrass condition and trend in regions close to anthropogenic pressures. It also provides an ability to detect change, but provides little or no information to provide a baseline for offshore seagrass meadows (intertidal, shallow sub-tidal) or those in deep water (coastal, reef, offshore). Changes and trends observed at these locations cannot be extrapolated to seagrass in other locations on the Reef, due to the lack of random site selection in the monitoring design. This means that the current programs will not be able to report appropriately on progress towards Reef 2050 Plan targets, objectives or outcomes that aim to report "at the Reef-wide and regional scales". To achieve the reporting requirement of the Reef 2050 Plan and meet other management information needs, it is necessary to develop a spatially balanced design that maintains elements of the historic sites in an expanded program.

Despite spatial limitations with the current programs, it is important to acknowledge that on a global scale the monitoring effort on the Reef has been described as "among the most extensive and longest running seagrass monitoring programs in the world" (Coles et al. 2015). The current programs provide excellent long-term historical information at the site or meadow scale. This includes long-term datasets of change, required to understand cause and effect relationships and processes that influence seagrass condition, including some attributes of resilience, in specific locations of the Reef (exposed to high anthropogenic pressures including catchment land use activities).

7.3 Overlap with proposed new monitoring design

Current seagrass monitoring programs on the Reef have many characteristics of the proposed new program. Monitoring on the Reef already adopts spatial and temporal scaled approaches. The Ports Monitoring provides reliable spatial assessments of specific seagrass meadows by having many sites spread over a large spatial area, where limited data is collected. The Marine Monitoring Program also expands its spatial coverage of monitoring by collaborating with other government departments (Queensland Parks and Wildlife Services) and participatory science programs (Seagrass-Watch). This approach of developing multi-agency and participatory/citizen science collaborations to maximise the spatial coverage of parameters that can be photographed or are simple to measure, will be expanded in the new program to achieve the spatial sampling intensity that will be required, especially in the *habitat assessment* scale.

The temporal scale of sampling ranges in the current programs from twice a year, to capture seasonal variability, to revisiting meadows/locations annually or every 3 years. This is a similar range in temporal frequency that is recommended for the *health assessment* (twice a year) and *habitat assessment* (once every 5 years with a subset annually).

At present the equivalent of the *process monitoring* is undertaken intermittently at only a few locations, when research funding is available (e.g. recent projects funded by the Australian Research Council, the Great Barrier Reef Foundation, and the National Environmental Science Program).

The programs currently measure all the priority indicators identified for *habitat assessment* and many of the priority indicators for *health assessment* (Table 10, Table 11). Some of the indicators proposed for *process monitoring* are also assessed in the existing programs, in a limited capacity (Table 12, **Table 13**).

7.4 Overlap in indicators between existing monitoring and *habitat assessment*

Habitat assessment at the Reef-wide scale will require development of a spatially balanced design incorporating the 12 habitat types defined in the current report, with an option to stratify sampling effort further based on additional management priorities. Sampling at or near some legacy sites (Marine Monitoring Program, Ports monitoring) are likely to be incorporated to improve detection of temporal trends.

Table 10. Seagrass indicators monitored as part of existing seagrass monitoring programs that will be incorporated into *habitat assessment* of the new program.

Indicator	MMP indicator	QPSMP indicator	New integrated Program
Estimates of above ground abundance	Yes (visually measure per cent cover)	Yes (visually measure above-ground biomass)	All the indicators collected from existing programs are compatible with the recommended new program. The only change required is development of a new spatially balanced sampling design and standardisation of the method used to quantify seagrass abundance.
Species Composition	Yes Per cent of abundance	Yes Per cent of abundance	
Sediment type	Yes (visual)	Yes (visual)	

7.5 Overlap in indicators between existing monitoring and *health assessment*

Health assessment at the Regional scale will use data collected at the Reef-wide scale as well as collecting additional data from representative sites within each habitat type. The spatially balanced design for *habitat assessment* will retain its integrity when sub-sampled at the NRM region scale (using the 12 habitat layers for each NRM region, provided in the current report). Within this design a few sites will be identified for additional sampling. This will provide information on seagrass resilience of the 12 habitat types, within each NRM region. Where possible, sites where resilience information is collected will incorporate existing sites to ensure continuation of temporal data at these locations. However, as current monitoring does not sample all 12 habitat types, it will be necessary to identify new sites to capture all habitats. It may also be necessary to stop sampling at some of the existing sites or reduce the weighting of information from existing sites to provide an unbiased Reef-wide assessment of seagrass condition.

Table 11. Seagrass indicators monitored as part of existing seagrass monitoring programs that will be incorporated into *health assessment* of the new program.

Indicator	MMP indicator	QPSMP indicator	New integrated Program
Seagrass above-ground abundance	Yes (visually measure per cent cover)	Yes (visually measure above-ground biomass)	Sampling design will ensure that all sampling conducted at the *habitat assessment* scale can be sub-sampled to inform Reef managers at a regional scale. This information on species composition and abundance, within each habitat type, will provide information for report cards by enabling the regional detection of trends in seagrass condition and a component of resilience.
Seagrass Species Composition	Yes Per cent of abundance	Yes Per cent of abundance	
Spatial extent of key and/or representative meadows	Yes Landscape patches/scars mapped within a 5.5ha area	Yes Entire meadows mapped annually	Determining change in spatial extent of seagrass meadows requires mapping of entire meadow boundaries. This will be achieved through direct mapping of meadow boundaries where they are visible (intertidal or clear water). Additional spatial intensity may be required at sub-tidal meadows near the edge to infer the location of boundaries. This information on meadow area change, within each habitat type, will provide information for report cards.
Sexual reproduction	Yes Seed density and reproductive effort	Yes Only some measures.	More detailed measures covering aspects of seagrass resilience will be measured at a sub-set of representative sites for each habitat type (number of sites will be determined during statistical design, based on the scale of information managers need). The new design will incorporate legacy sites where feasible, but will also require new sites to be sampled.
Seagrass characteristics	Yes Only some measures.	No	
Connectivity	No	No	
Habitat suitability	Yes Only some measures.	Yes Only some measures.	Abiotic pressures will be expanded as part of DPSIR framework to ensure critical pressures are measured across representative sites in each habitat type.

7.6 Overlap in indicators between existing monitoring and *process monitoring*

The *process monitoring* requires sites along causal gradients of pressure (anthropogenic or climate change drivers). Sites from existing monitoring programs will be incorporated to improve the temporal information provided by each site. There will also be the need to select new sites to represent habitat types not currently monitored or to capture the full range of *pressures* on seagrass and their *impact* on key processes and values.

Table 12. Seagrass indicators monitored as part of existing seagrass monitoring programs that will be incorporated into *process monitoring* of the new program.

Indicator	MMP indicator	QPSMP indicator	New integrated Program
Meadow characteristics and condition 1. Areal extent 2. Abundance 3. Patchiness 4. Biomass allocation (morphology and above/below) 5. Stored metabolites (C:N:P, carbohydrates)	Yes Needs to be standardised Biomass allocation and stored metabolites not routine	Yes Needs to be standardised Biomass allocation and stored metabolites not routine	Statistical design of spatial and temporal sampling along with a standardised methodology will be funded as an additional project.
Connectivity and population structure	Partially	Partially	The assessment of connectivity for seagrass across the various habitats will be developed as part of the statistical design (additional project).
Meadow diversity 1. Species diversity 2. Clonal diversity	Yes Only some sites and conducted as research project components	No	A spatially balanced sampling design will be conducted to improve our understanding of population structure in representative meadows within each habitat type. Temporal frequency for this measure can be over multiple years.

Table 12: Continued 1

Indicator	MMP indicator	QPSMP indicator	New integrated Program
Recoverability *Routine* measures 1. Sexual reproduction (seed bank, seed viability, seedling numbers, reproductive structures) Non-routine 1. Vegetative growth rate 2. Recruitment success (Propagule and Seedling) 3. Seed viability 4. Rate of expansion of fragments 5. Seedling survival rate to adult-hood	Yes Reproductive structures and seed banks measured routinely, some other attributes measured occasionally	Yes Seed banks measured routinely, some other attributes measured occasionally	A spatially balanced and temporally representative sampling design will be used to quantify these attributes of resilience for each habitat type along the longitudinal gradient of the Reef (replicate sites in NRM regions would be ideal)
Herbivory 1. Direct observations 2. Exclusion sites 3. Explicit mapping of feeding	Yes Limited routine measures of direct observations	Yes Limited number of sites, all measures	A more strategic and representative approach will be developed to inform the impact of herbivory on seagrass condition across the habitat types and NRM regions.
Controlling feedback mechanisms 1. Sediment trapping/preventing resuspension 2. Density-dependant hydrodynamic effects 3. Sediment oxygenation to prevent sediment toxicity 4. Grazing-induced enhancement of nutrient uptake	No/Yes Megaherbivore pressure (4) documented occasionally	No/Yes Megaherbivore pressure (4) documented occasionally	Need to design this component of the monitoring program to provide managers with information on feedback mechanisms and their influence on seagrass resilience.
DPSIR linkages	Yes	No	Developed in collaboration with the other themes.

Post-event monitoring on the Reef is currently haphazard and dependent on disaster relief funding or an organisation's ability to redirect resources to the recently impacted seagrass meadows. This fails to provide a timely assessment of the condition of the seagrass habitat, and managers often don't have the information they require to decide if intervention is required or would be beneficial. We recommend that following a large disturbance (flood, cyclone) thought to have caused loss or decline in seagrass, there should be a dedicated monitoring effort to collect information on key attributes of seagrass meadows with the zone of impact. This will inform managers of the likelihood of recovery and their options regarding interventions. Some of the attributes suggested in this component of the monitoring program are currently measured as part of existing programs, but this has not previously been linked to providing managers or modellers with information on critical processes relating to recovery of seagrass following a major disturbance.

Table 13. Seagrass indicators required to establish a *post-event* monitoring program — none of the measures are collected routinely in current programs.

Indicator	MMP indicator	QPSMP indicator	New Integrated Program
Rapid assessment of recovery potential 1. Seed bank 2. Remnant fragments 3. Species diversity	No Some indicators are measured. Current programs do not have a defined post-event response plan	No Some indicators are measured. Current programs do not have a defined post-event response plan	Standard protocols and activation processes will be established for post-event monitoring. This will ensure managers receive a rapid assessment of seagrass recovery potential following any event "of concern".
On-going *post-event* monitoring 1. Seagrass abundance 2. Species diversity 3. Expansion of fragments 4. Sexual reproduction (seed bank, propagule production) 5. Biomass allocation	No Some indicators are measured. Current programs do not have a defined post-event response plan	No Some indicators are measured. Current programs do not have a defined post-event response plan	A spatially balanced and temporally representative sampling design will be used to quantify recovery across the impacted area during the recovery process.
Habitat suitability Sediment quality and characteristics of meadow area	No	No	A spatially balanced sampling design will be used to quantify these attributes across the impacted area.

7.7 Gaps in current monitoring effort

While the current monitoring programs collect information directly relevant to the RIMReP, their focus on particular habitats and locations leads to gaps in the overall monitoring coverage. These gaps will need to be filled using a spatially balanced sampling design before RIMReP can detect trends relevant to the Reef 2050 Plan or accurately assess seagrass condition relevant to regional NRMs. To quantify the spatial and temporal representativeness of current monitoring we examined three historical seagrass spatial data sets in relation to the potential seagrass habitat distribution shapefile (called 'habitat shapefile' from here on). The available seagrass data sets provide an excellent guide for location of seagrass within the World Heritage Area and include:

(1) The site composite seagrass shapefile (approximately 66,200 sites surveyed between 1984 and 2014 including Ports monitoring sites; Carter et al. 2016a; Figure 17).
(2) The meadow composite seagrass shapefile (approximately 1,200 meadows mapped between 1984 and 2014 including Ports monitoring meadows; Carter et al. 2016a).
(3) The Marine Monitoring Program and affiliated programs shapefile (65 sites; McKenzie et al. 2018).

Consideration was given to the spatial extent of potential seagrass habitats as well as existing seagrass knowledge within those habitats and NRM regions within the Reef. This resulted in 72 potential habitats (the 12 habitat types across 6 different NRM regions). However, only 62 of these combinations cover more than 10 square kilometres of the Reef, with four of them not being present at all (Appendix 2).

For intertidal and shallow subtidal seagrass, good historical information is available on spatial extent, species and abundance for coastal habitats and, in some NRMs, reef and estuarine habitats (see Appendix 2). This data was suitable for quantifying total areas of particular seagrass habitat types and examining spatial representativeness of current seagrass knowledge and monitoring. However, no routine monitoring occurs on offshore seagrass (intertidal, shallow subtidal, deep).

Current monitoring programs only routinely monitor deep seagrass habitats at two relatively small locations (Hay Point and Abbot Point). In other areas of the Reef, data has been collected infrequently or only once. This data suggests that deeper areas of the Reef are dominated by relatively low coverage and/or transitory *Halophila* species. This historic data also shows that deep seagrass is present across a broad area of the Reef lagoon including our coastal, reefal and offshore water body types. This suggests deep seagrass is an important ecological resource that contributes to sustaining the processes and values of the Reef, but is currently underrepresented in the Reef's two monitoring programs.

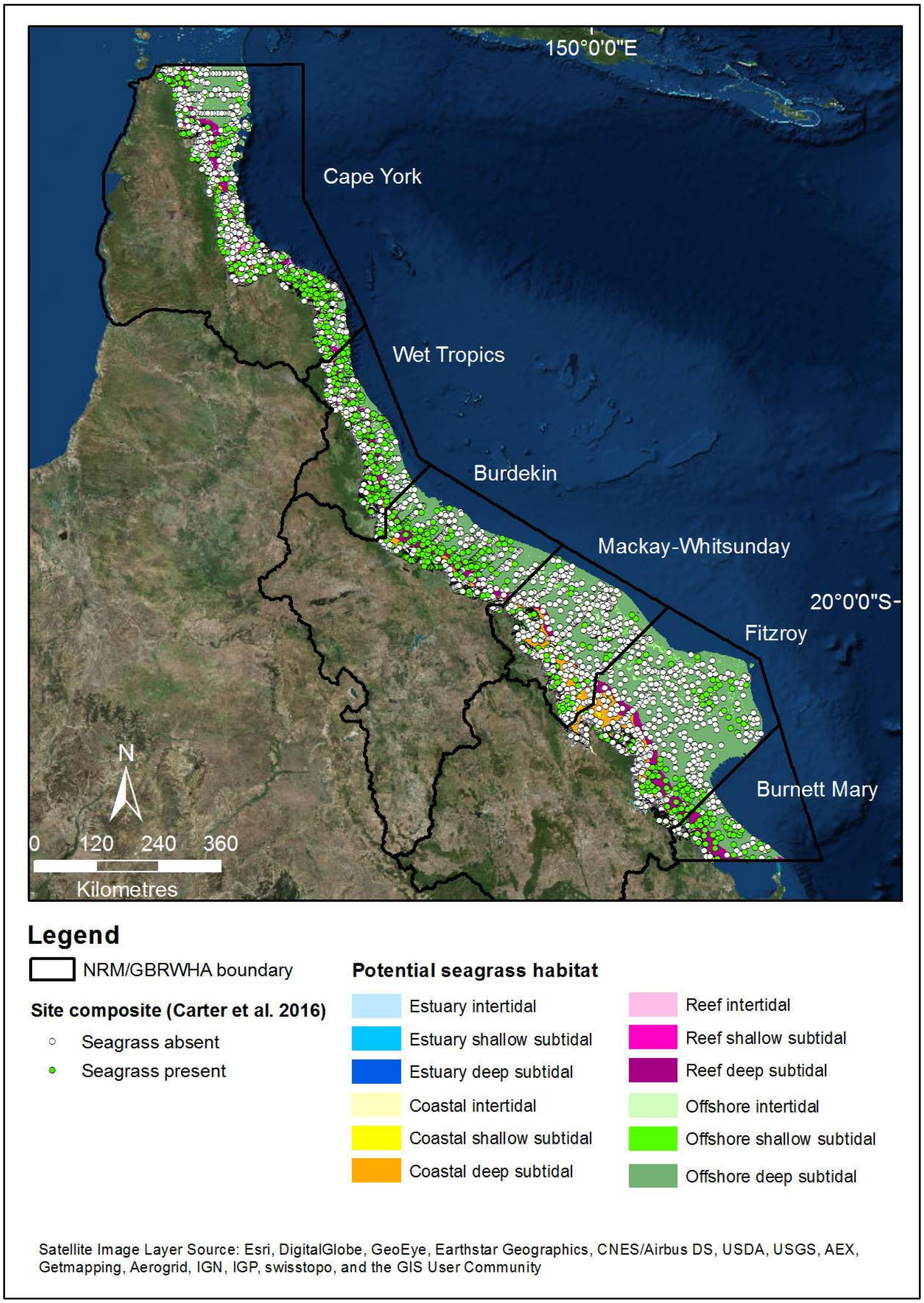
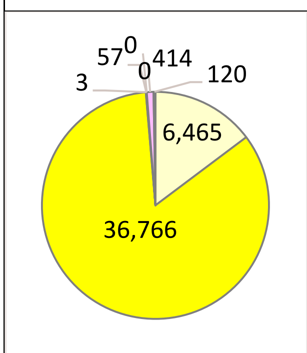
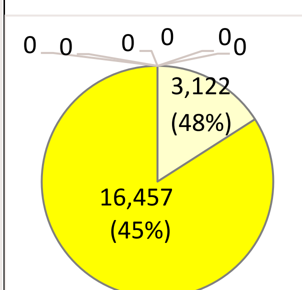
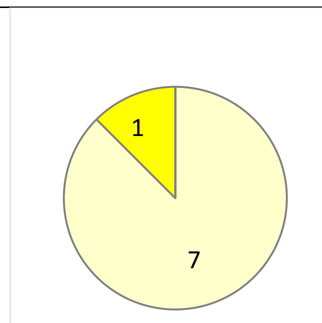
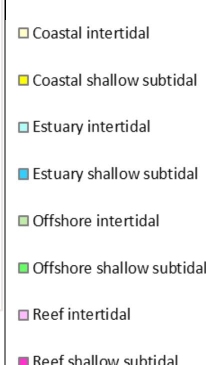


Figure 17. Seagrass presence/absence (seagrass site composite, 1984-2014; Carter et al. 2016a) within the World Heritage Area relative to NRM boundaries and the 12 seagrass habitat types.

The seagrass dataset was then examined to assess how well current monitoring efforts cover the total known extent of seagrass habitats, NRM regions, and areas of high cumulative anthropogenic risk within the World Heritage Area. Many NRM regions had relatively good coverage with existing monitoring, covering as much as 50 per cent of the total described area for some habitat categories. The Burdekin region for example has 45 to 48 per cent of the total mapped coastal seagrasses monitorined every year (**Table 14**; Full details for all NRM regions and habitats are presented in Appendix 2). However, this was not uniform for all habitat types or NRM regions with many seagrass habitats poorly represented and some NRM regions, such as Cape York, having poor monitoring coverage for the majority of seagrass habitat types.

Both of the existing monitoring programs sample only 14 of the 68 possible habitat types. Annually, the Ports monitoring focusses on coastal meadows only in the Burdekin and Mackay-Whitsundays, on estuarine meadows only in the Fitzroy and Burnett Mary, and on a mix of estuarine and coastal meadows in the Wet Tropics. The Marine Monitoring Program focusses on intertidal and subtidal reef and coastal sites only in Cape York and the Wet Tropics, coastal sites only in the Burdekin and Mackay-Whitsundays, and a mix of estuarine and coastal sites in the Fitzroy and Burnett-Mary regions.

Table 14. Burdekin NRM intertidal and shallow subtidal seagrass monitoring coverage by habitat type. (a) Area (ha) of meadows mapped (Carter et al. 2016a); (b) meadow area (ha) covered by annual QPSMP with per cent spatial coverage of QPSMP relative to total meadows mapped; (c) number of MMP sites.

(a) Meadows mapped (ha)	(b) QPSMP meadows (ha)	(c) MMP monitoring sites (#)	Legend
			

Areas with the highest cumulative anthropogenic risk to seagrass generally were well covered in each NRM by the existing monitoring programs which were designed to specifically examine these areas in detail (**Figure 9**; **Figure 15**). High risk areas covered by current monitoring include Archer Point in Cape York (MMP), Cairns to Green Island (QPSMP and MMP) and between Dunk and Hinchinbrook Islands (MMP) in the Wet Tropics, Townsville (QPSMP and MMP) in the Burdekin, Whitsunday Islands and Newry Bay (MMP) and Mackay-Hay Point (QPSMP) in Mackay-Whitsunday, and Gladstone Harbour (QPSMP and MMP) in the Fitzroy. High risk areas not currently covered by monitoring include Cape Flattery (Cape York NRM), Port Douglas (Wet Tropics NRM), the Fitzroy River/Port Alma (Fitzroy NRM), and Hummock Hill Island (Burnett Mary NRM).

This initial analysis of gaps and coverage revealed that for many shallow habitats good spatial coverage exists and could provide a foundation for the spatially balanced sampling design recommended in the current report. The spatial tools available and existing datasets utilised in this gap analysis provide a valuable tool to inform and test the new design to ensure it has the statistical resolution to meet management requirements.

8.0 New technologies for monitoring seagrass on the Great Barrier Reef

Technological advances during the last two decades have dramatically changed the options available to scientist and managers for the collection, processing, storage and retrieval of information (Table 15). In line with these changes, communities' expectations in relation to access to data, including the time between data collection and it being available, have changed. We have organised new technologies into three categories that should be considered, including those that:

1) facilitate data collection;

2) enable improved data processing and/or storage; and,

3) enhance the data users experience by improving access and visualisation.

Table 15. Potential new technologies that could improve different aspects of monitoring.

Category	New technology	How it would help monitoring
Data collection	New satellite and remote sensing products	The resolution and wavelength of remote sensing products is constantly improving. The potential applications of remote sensing advances to benthic habitat surveys have recently been reviewed by the University of Queensland. At present the low coverage of many intertidal seagrass meadows and poor water visibility near the coast reduce potential applications of this technology to seagrass habitats at inshore areas of the reef, but they may have applications in some areas.
Data collection	Robots, Remotely Operated Vehicles (ROVs) - Robots, ROVs and drop cameras available to use at present	A new robot called 'Rangerbot' has been developed by the Queensland University of Technology and trialed on the reef near Cairns and in the Swains. It was designed to undertake underwater visual surveys of benthic habitat (seagrass and coral). The robot can travel approximately 14 kilometres on a single battery charge, collecting video or still photographs of benthic habitat. Software could be developed to auto process the visual images to provide an estimate of seagrass abundance. The robot relies on vision to navigate, requiring water clarity of at least one to two metres. In clearer waters, it could collect visual data across large spatial areas in a matter of days (surveying approximately 32 kilometres of benthic habitat in an eight-hour day). Robots also remove the need for people to enter the water, reducing occupational health and safety concerns. The use of ROVs and drop cameras has also improved significantly over the last decade. These provide the ability to rapidly collect visual data of seagrass meadows where distances between sites are greater that the robot can navigate.

Table 15: Continued 1

Category	New technology	How it would help monitoring
Data collection	New DNA tools - tools exist but require development of techniques appropriate to seagrass	Advances in DNA technology provide a previously unavailable source of information for scientists and managers. With modification, tools could be developed that would identify seagrass species and likely seed banks in a meadow, from a sediment sample. This would change methodologies and improve our ability to report on biodiversity in seagrass habitats. This could also dramatically reduce laboratory time when conducting seed bank assessments.
Data collection	Application of acoustic techniques	Acoustic technology finds the low biomass seagrass common to the Reef difficult to detect. Many of the new acoustic tools would be useful in habitat characterisation by providing improved bathymetry and predictions of sediment type that can also be used to interpret benthic shear stress and tidal currents.
Data collection	Sub-lethal seagrass indicators - e.g. 'omics' techniques to identify light stress, Diversity in genome scale	There is a suite of emerging seagrass indicators that provide sub-lethal link to pressures including 'omics' techniques such as transcriptomics and metabolomics. When available, these omics tools can be used to identify specific stress responses to pressures through measuring up and down regulation of gene expression or the production of particular metabolites specific to the stress. These provide important information to managers and allow management responses to be put in place prior to a catastrophic loss of seagrass. Further development of these indicators will be enhanced in the monitoring program at the *process monitoring* scale or will require specific research and development funding. When developed, they should be incorporated at the *health assessment* scale and possibly *habitat assessment* scale, depending on complexity.
Data collection	Sediment micro-profiling to better understand anoxia and small scale processes.	Micro profiling enables an improved understanding of processes occurring between the seagrass roots and surrounding sediment. This could be applied at the *process monitoring* scale in the new monitoring program to better understand processing of high organic loads from point sources and catchments and the impact on seagrass meadows.

Data collection	Statistical optimisation of sampling	New tools that assist with the optimisation of and spatial design of monitoring programs are now available and should be used by RIMReP. Tools were provided through Commonwealth Government (NESP) funding and would be available free to RIMReP.
Data processing or storage	New data base technologies	The ease of collecting and managing the QA/QC of data from multiple sources to ensure data is fit for purpose has improved exponentially in the last decade. The application of this technology has already started on the Reef with Eye on the Reef. A similar approach to Eye on the Reef could be used to improve the spatial coverage of seagrass data at the *habitat assessment* scale. However, significant changes would be required to ensure QA/QC of the data inputs. A cloud based solution with QA/QC for locations where the data is collected as well as the assessment of seagrass species and abundance would need to be developed. This could manage data input from QPWS, Indigenous rangers, tourist boats, other commercial and recreational boats, high school student projects and other participatory/ citizen science programs (for example, SeagrassSpotter, Seagrass-Watch), with limited human resources required to maintain and run.
Data processing or storage	New ways of processing data that enable the collection of larger data sets and automatic image processing	Developments in artificial intelligence are predicted to change the way people work in most workplaces over the next 10 years. While designing and implementing this program (especially at the *habitat assessment* scale) we have focused on attributes of a seagrass meadow that can be assessed visually. This allows for computers/robots to be trained to identify the patterns that we use to identify species, per cent cover, canopy height and even the conversion of the seagrass abundance to above ground biomass. It is likely that within less than five years, a photo or video of the bottom will be sufficient for a computer to determine these attributes and enter them into a database. This dramatically changes the options available to the Authority in collecting this spatial data.

Improve access and Visualisation	New data base technologies	The ability to store data in the cloud changes both data upload options and access when multiple users and stakeholders are involved. There are still going to be issues relating to the release of data prior to appropriate QA/QC and withholding of sensitive data. But these should be overcome in the implementation stage, with the majority of data collected as part of the new program having a standardised format to facilitate access and use by multiple end users.
Improve access and Visualisation	Improved visualisation tools	The gaming industry has progressed to a point with visualisation tools that it is now common to give people virtual experiences based only on the equivalent of spatial and temporal data. The level to which RIMReP seeks to utilise these tools to make otherwise complex data sets easy to understand needs to be discussed for the entire program — not an individual component, such as seagrass.

9.0 Recommendations for integrated monitoring of seagrass on the Great Barrier Reef

Habitat assessment

Survey methods required to implement the *habitat assessment* components of the recommended new seagrass monitoring program.

Priority Indicator	Survey method	Survey location (spatial)	Survey frequency (temporal)
Seagrass presence and abundance	Method of collection will vary depending on the seagrass habitat being sampled (intertidal, shallow and deep subtidal). At this scale the priority is to capture the seagrass above-ground abundance rapidly at a site/point defined by its latitudinal and longitudinal coordinates. Abundance will be determined by a rapid visual assessment technique suitable across all habitats. The collection needs to be reliable and repeatable by multiple human observers and artificial intelligence (image processor compatible). As a minimum it will include percentage cover, but ideally will account for the three-dimensional change in seagrass abundance rather than just two-dimensional cover.	A balanced spatial design will be developed following submission of this report. The need to collect multiple replicates or sample within a larger site will be investigated as part of the statistical design.	The sampling design will confirm temporal frequency, but it is expected that approx. 95 per cent of sites will be sampled every five years and around five per cent of the sites every year. Abundance and species data collected annually will inform both the *habitat assessment* and *health assessment* components of the monitoring program.
Seagrass species or genera	Identifying the proportion of seagrass abundance represented by each species/genera.		

Habitat assessment

Survey methods for abiotic pressures at the *habitat assessment* scale.

Priority Indicator	**Survey method**	**Survey location (spatial)**	**Survey frequency (temporal)**
Habitat 1. Sediment type	A rapid visual assessment of sediment type should be included as part of the habitat characterisation.		
DPSIR Linkages 1. Nutrient 2. Sediment 3. Surface and benthic light 4. Temperature	Reef-wide assessment by other components of RIMReP. Remote sensing, eReef predictions of total suspended solids and coloured dissolved organic matter.	These will be predominantly computer generated outputs.	Annually to five-yearly assessment.

Health assessment

Survey methods required to implement the *health assessment* components of the recommended new seagrass monitoring program.

Priority Indicator	Survey method	Survey location (spatial)	Survey frequency (temporal)
Seagrass abundance (at higher spatial resolution than *habitat assessment*)	Method will be the same as the *habitat assessment* monitoring but the sampling strategy will be conducted at the scale of the meadow spatial change assessments. This will require an assessment of seagrass abundance at representative sites within meadows to adequately describe change at the meadow scale (likely in the order of 25 to 100 sites/points per meadow).	The survey design will be nested within the spatially balanced design for *habitat assessment* and undertaken as a separate project following submission of this report. The need to collect multiple replicates or samples within a larger site will be investigated as part of the statistical design	Annually as a minimum. If managers require information on recovery or seasonality of seagrass, sampling should occur twice a year.
Seagrass species (at higher spatial resolution than *habitat assessment*)			

Continued: Survey methods required to implement the *health assessment* components of the recommended new seagrass monitoring program.

Priority Indicator	**Survey method**	**Survey location (spatial)**	**Survey frequency (temporal)**
Spatial extent of key and/or representative meadows Measuring change in meadow area by mapping meadow boundaries at appropriate spatial resolution.	Determining change in spatial extent of seagrass requires mapping of the boundaries to occur. This will be achieved through direct mapping of meadow boundaries where they are visible and easily accessed (e.g. intertidal meadows using helicopter/ remote sensed/ on-ground mapping). For subtidal seagrasses where direct mapping of meadow boundaries is not possible, additional spatial intensity of field observations either side of where meadow edges are likely to occur will be undertaken.	The survey design will be nested within the spatially balanced design for *habitat assessment* and undertaken as a separate project following submission of this report. Replicates of representative meadows for each habitat and NRM region will be selected. This will include consideration of increased sampling intensity in areas of high cumulative risk as well as incorporating sites from existing monitoring.	Annually as a minimum. If managers require information on recovery or seasonality of seagrass, sampling should occur twice a year.

Continued: Survey methods required to implement the *health assessment* components of the recommended new seagrass monitoring program.

Priority Indicator	Survey method	Survey location (spatial)	Survey frequency (temporal)
Sexual reproduction 1. Seed Bank 2. Reproductive structures	Seed bank Sampled by collecting small cores (5 cm diameter) from an appropriate number of sites/points in the meadow. For species with large seeds these can be assessed in the field. For species with smaller seeds such as *Halophila* spp these will need to be sampled in the laboratory using magnification and seed sediment separation techniques. Reproductive Structures Assessed by sampling during peak period between August and December (validate sample timing in *process monitoring*).	Seed bank assessments will be conducted at all representative meadows for appropriate habitat types. Presence or absence of reproductive structures will also be assessed at all representative meadows — but detail relating to density of reproductive structures and temporal variability will only be conducted at *process monitoring* locations.	Seed bank and presence of reproductive structures conducted annually or biannually, when sampling spatial extent and abundance. Validation of abundance of reproductive structures sampled monthly between August and December at sub-set of sites (*process monitoring*) to detect temporally variable timing of flowering and fruiting.

Continued: Survey methods required to implement the *health assessment* components of the recommended new seagrass monitoring program.

Priority Indicator	**Survey method**	**Survey location (spatial)**	**Survey frequency (temporal)**
Seagrass condition 1. Biomass allocation (morphology, above/below), 2. Stored metabolites (e.g. carbohydrate)	Biomass allocation Develop a rapid low volume sampling technique to validate above/below model developed as outcome of this project (Appendix 2). Metabolites stored Samples for laboratory analysis can be obtained from the samples collected for biomass allocation.	Small samples of above and below biomass should be collected from each representative meadow in each habitat type to improve the resolution and predictive power of the new above/below biomass model. The same biomass samples can be processed to provide a baseline for metabolite storage in each habitat type.	Annually — validated by seasonal sampling at *process monitoring* locations.
Connectivity (likelihood for dispersal of propagules between meadows)	Connectivity of representative meadows within each habitat and NRM will be determined in collaboration with eReefs or other high resolution hydrodynamic models. Baseline will need to be expanded for strategic species and locations, then ongoing evaluation can be site or event responsive.	Undertaken at each representative meadow for habitat and NRM region.	Required once when establishing the meadow, and reviewed every five years and following events.

Health assessment

Survey methods required to measure abiotic pressures at the *health assessment* scale.

Habitat and/or environmental suitability and complexity 1. Benthic light 2. Temperature 3. Benthic shear stress 4. Sediment quality	As part of the DPSIR framework, simple abiotic pressures will be quantified at each *health assessment* location.	Appropriate replication (as determined by statistical design) for representative seagrass meadows.	Continuous loggers for light, temperature, benthic shear stress. Annually for sediment quality.
DPSIR Linkages 1. Flood plume frequency 2. Pollutant loads 3. Impact from cyclones	The above site-based measurements will be linked with Reef-wide assessment from other components of RIMReP to provide a link between *pressures* and the *state* of seagrass.	Remote sensing, eReefs, Bureau of Meteorology.	Annually

Process monitoring

Survey methods required to implement *process monitoring* components of the recommended new seagrass monitoring program.

Priority Indicator	**Survey method**	**Survey location (spatial)**	**Survey frequency (temporal)**
Meadow characteristics and condition 1. Areal extent 2. Abundance 3. Patchiness 4. Biomass allocation (morphology and above/below) 5. Stored metabolites (C:N:P, carbohydrates…)	More detailed process understanding for sites at risk, sites of high conservation value or where critical habitat through provision of ecosystem services are identified (for example, grazing areas).	Methodology as for *health assessment* scale, with more detailed sampling and designed specific to issue.	Depending on the process being investigated, anything from monthly to bi-annually.
Connectivity and population structure (likelihood for dispersal of propagules between meadows)	Evaluation of hydrodynamic models for actual dispersal of different forms of propagules are needed *in situ* to complement modeling.	Knowledge gaps to be filled at the local and between meadow scale.	Once established - only required if conditions change dramatically.

Continued: Survey methods required to implement the *process monitoring* components of the recommended new seagrass monitoring program.

Priority Indicator	**Survey method**	**Survey location (spatial)**	**Survey frequency (temporal)**
Meadow diversity 1. Species diversity 2. Clonal diversity	Finer scale determination of changing community composition and genetic diversity allows understanding of the shifts in population processes.	Conducted at a fine scale of multiple meadows within a region and habitat types.	Baseline and then only required if conditions change dramatically.
Recoverability Routine measures 1. Sexual reproduction - Seed bank - Seed viability - Seedling numbers - Reproductive structures Non-routine 1. Vegetative growth rate 2. Recruitment success (propagule and seedling) - Seedling survival rate - Rate of fragment expansion	Routine Sexual reproduction. Seed bank: as in *health assessment.* Seed viability: using staining techniques on freshly collected seagrass seeds, seed coats removed and staining with tetrazolium. Seedling numbers and reproductive structures: spatial survey *in situ* between August and December to identify peak time for flowering and fruiting. Non-Routine. Vegetative growth rate and fragment expansion: leaf and rhizome tagging and marking. Recruitment success (seedling survival): determine if seedlings have established and begun to expand by visual observation.	The logistically more difficult and time consuming assessments of seed viability would be conducted at a sub-set of the meadows/sites assessed at this scale according to management need.	Seed bank and viability will be conducted after peak seed production and prior to expected annual germination (December and May). Seedling numbers and Reproductive structures: monthly between August and December. Vegetative Growth Rate: biannually. Recruitment success: measured at time of above sampling (August to May), and requires repeated sampling times.

Continued: Survey methods required to implement the *process monitoring* components of the recommended new seagrass monitoring program.

Priority Indicator	**Survey method**	**Survey location (spatial)**	**Survey frequency (temporal)**
Herbivory: 1. Direct observations 2. Exclusion sites 3. Explicit mapping of feeding scars	Direct observations. Visible cropping or evidence of dugong feeding trails recorded. Exclusion cages (DPSIR link). At representative meadows to quantify herbivory on seagrass. Explicit mapping (DPSIR link). Quantification of dugong feeding trails at key meadows using structure from motion software and mapping techniques.	Conducted at a representative subset of meadow and habitat types. Some targeted assessments in recognised high value megaherbivore feeding areas.	Exclusion studies are year-round and sampled at the time of annual sampling *at health assessment* sites. Mapping of feeding trails quarterly to pick up temporal changes in feeding activity.
Controlling feedback mechanisms 1. Sediment trapping/preventing resuspension 2. Density-dependant hydrodynamic effects 3. Sediment oxygenation to prevent sediment toxicity 4. Grazing-induced enhancement of nutrient uptake	Measuring feedback requires varied techniques: Further information can be provided on these during the statistical design and trade-off phases.	Measurements will require both *in situ* sampling and laboratory time. The scale of monitoring needs to be confirmed during statistical analysis and in consultation with managers.	High frequency sampling (monthly and/or deployment of sensors.
DPSIR linkages	Need to discuss as part of prioritisation process.		

Process monitoring

Survey methods required to implement the *process monitoring* components of the recommended new seagrass monitoring program.

Priority Indicator	Survey method	Survey location (spatial)	Survey frequency (temporal)
Recovery potential (rapid assessment) 1. Seed bank 2. Remnant fragments 3. Species diversity 4. Habitat suitability	Methods as above: This is a sub-set of above indicators that provide a rapid assessment of sites' recoverability — it should occur immediately following an event.	Determined by the scale of event and management priorities.	Within one month of event — inform future responses.
On-going *post-event* monitoring 1. Seagrass abundance 2. Species diversity 3. Expansion of fragments 4. Sexual reproduction (seed bank) 5. Biomass allocations	Methods as above: This is a sub-set of above indicators that should be measured until the seagrass meadow is determined to have stabilised or is not 'of concern' to managers. As well as informing managers during the recovery, it will improve our understanding of critical processes that facilitate recover to assist with future events.	Determined by the scale of event and management priorities.	During the recovery period with decreasing frequency until meadow is stabilised or not 'of concern' to managers.

Process monitoring

Survey methods required to measure the abiotic pressures at the *process monitoring* scale.

Priority Indicator	**Survey method**	**Survey location (spatial)**	**Survey frequency (temporal)**
Sediment quality and characteristics of meadow area	As part of the DPSIR framework abiotic pressures will be quantified at each site where *process monitoring* occurs. This should include as a minimum benthic light, temperature, benthic shear stress due to waves or tides, bottom topography and gradient, sediment type.	This is primarily a site establishment cost with limited ongoing resource requirements. Require approx. four days per site for *in situ* and follow-up work.	On site establishment, repeated every five years or following an extreme event that may alter conditions.
DPSIR linkages	These are ideal sites to investigate linkages between the various values and attributes of the Reef, with indicators selected to represent important linkages in the DPSIR framework.	Need further discussion at integration/ trade-off meetings.	

10.0 Transitioning from the current monitoring program to RIMReP

Both current seagrass monitoring programs on the Reef provide important information to different managers. Hence, it is important that RIMReP maintain all critical information required by managers and provide improved or enhanced information products that are not currently available. One aspect of the current programs that will be important to maintain is the long-term temporal data. It may also be necessary to have a staggered implementation of RIMReP to deal with the many operational and technical issues that are likely to arise from the increase in the spatial scale of monitoring.

To ensure critical information is not lost when transitioning to the new program it is important that a statistically robust spatially balanced design process is undertaken. This will:

1. Confirm managers' priorities for the type and scale of information — this will influence resources allocated between the different monitoring scales.
2. Inform managers on the ability of the new program to detect change, both in comparison to the accuracy required by managers and what is currently achieved.
3. Clarify the likely resources required to meet managers' information needs for both spatial extent of information and their ability to detect temporal changes.
4. Confirm the importance of timeliness of data provision and ensure that expectation for data turnaround (time between monitoring occurring and information being available to managers) are realistic and agreed to by both scientists and managers.

Following these steps it will be possible to develop the operational plan for implementation, including incorporation of appropriate current sampling locations and establishment of new sampling components and locations.

11.0 Assessment of the resources required to implement the recommended design

A statistically-determined spatial monitoring design has not yet been developed (this has been postponed awaiting the integration process), and in its absence it is impossible to accurately predict the quantity of resources required to implement these recommendations. However, the below section of this report provides estimates of the indicative costs to undertake the recommended monitoring activities. It should also be noted that the recommended monitoring approach includes monitoring of many seagrass areas that are not currently monitored by any program as well as integrating existing monitoring programs and improving data storage and access protocols. Much of the improvement could be delivered through cost neutral optimisation of existing resources including through the adoption of new technology, especially as RIMReP procedures for data curation and access are delivered. However, full implementation of our recommendations will require significant additional field resources. This will be the first time a routine monitoring program has attempted to collect representative visual assessments of all seagrass habitats that occur across the Reef. With regard to field resources there are opportunities for Indigenous rangers, new technology (for example, robots that can undertake 14 kilometre-long visual surveys) and participatory/citizen science (for example, SeagrassSpotter and Seagrass-Watch) to assist in filling some of these additional resource requirements, but all these options have considerable constraints and would require their own resource allocation to be implemented successfully. Even if the additional data collection isn’t fully funded by RIMReP there will be additional coordination resources required. It is also likely that many of the new sites will require fully funded professional scientists to visit, due to logistical or operational difficulties in reaching these sites. The loss of information incurred for not implementing this is detailed in Tables 6 to 9.

Habitat assessment

Resources likely to be required to impliment the *habitat* component of the new seagrass monitoring program.

<table>
<tr><th>Priority Indicator</th><th>Explanation of Resources requirement</th><th>Staff (FTE)</th><th>Field Days</th></tr>
<tr><td></td><td>To achieve the spatial coverage recommended there will need to be a significant increase in the project management and coordination of seagrass monitoring on the Reef. This component is likely to require the combination of data from numerous organisations (e.g. citizen science, Indigenous rangers, Queensland Parks and Wildlife Service rangers, Australian Institute of Marine Science (AIMS) research vessels, JCU targeted sampling), hence it will require the allocation of resources toward coordination and QA/QC as well as field work.</td><td>1.5 (coordination)

This is an estimate based on the fact we will be combining two existing programs and also expanding that spatial scale of monitoring – as well as potentially increasing the number of stakeholders who need to be engaged throughout the process.</td><td>Nil — this is coordination component only</td></tr>
<tr><td>Seagrass presence and abundance</td><td rowspan="2">Abundance and species can be assessed visually at the same time or with a digital record of the benthos. Each site should take less than five minutes to sample. Multiple methods and levels of experience exist in Queensland. The statistical design work (still to be completed) will include a cost optimisation for sampling strategies.</td><td rowspan="3">One FTE to conduct visual assessments of imagery, QA/QC of data and data entry.

Ideally use innovative approaches to reduce overall cost in people and field operational expenses.</td><td rowspan="3">50 to 100 sites per day

Variable based on distance, sea conditions and habitat type and sampling equipment used.</td></tr>
<tr><td>Seagrass species or genera</td></tr>
<tr><td>Sediment Type</td><td>Visual assessment collected at the same time as above.</td></tr>
</table>

DPSIR linkages	Developed and costed by other groups or during integration.

Health assessment

Resources likely to be required to impliment the *health* component of the new seagrass monitoring program

Priority Indicator	**Explanation of Resources requirement**	Staff (FTE)	Field Days
Seagrass abundance and species composition (at higher spatial resolution than *habitat assessment*)	Seagrass abundance measurements at this scale will need to be sufficient to capture changes in above ground abundance at the spatial scale of the meadow. This will require analysis of within meadow variability to determine the number of observations required.	These assessments can be combined with the meadow spatial extent sampling where possible, and utilise the same field teams.	Same measure as conducted in *habitat assessment.* Can also use resource of spatial extent (below). Assessment will require spatial design.
Spatial extent of key and/or representative meadows Measuring change in meadow area by mapping meadow boundaries at appropriate spatial resolution	This will require intensive field validation to examine the targeted meadows using a range of techniques depending on the habitat: **Intertidal meadows** helicopter/ remote sensed/ on ground mapping depending on accessibility and size of meadows **Shallow Subtidal meadows** free diving/ remote sensed drop camera/ROV - can determine meadow edges by concentrating field validation points. **Deep Subtidal meadows** drop camera/ROV/robot	It is likely that there will be many of these assessments captured from effort in existing programs, but the balanced design covering all habitats is likely to require additional effort and resources particularly in regions or habitat types that have a poor existing coverage. Field teams must include a minimum of 2 people, with the location and type of	The time taken per meadow is highly variable depending on the size and type of meadow, equipment used and location within the Reef. Further analysis of resources for this task will occur after the statistical design.

		equipment used possibly requiring more.	

Continuation - Resources likely to be required to impliment the *health* component of the new seagrass monitoring program

Priority Indicator	**Explanation of Resources requirement**	Staff (FTE)	Field Days
Sexual reproduction: 1. Seed Bank 2. Reproductive structures	Collection of seed bank data requires *in situ* collection of cores. Large seed species can be assessed relatively rapidly in the field but small seed species from the genus *Halophila* and *Zostera* will need to be taken to a laboratory for sieving and separation and examination under magnification.	Combine with abundance and species monitoring, but requires additional field time for sampling and laboratory time for small seed species — approximately one to two hours per core.	Combine seed banks with abundance and species surveys. Reproductive structures require that sampling occur between August and December
Seagrass condition 1. Biomass allocation (morphology, above/below), 2. Metabolites stored (carbohydrate)	Collection of small biomass cores for above: below biomass assessment and metabolites requires *in situ* collection of cores and follow-up laboratory work.	Combine with abundance and species monitoring, but requires additional field time for sampling and laboratory time. Approximately two to four hours per additional location (depending on replicates required).	Field sampling for biomass allocation and metabolites can be combined with abundance and species surveys. Additional resources will be required.
Connectivity	This would be a one-off cost associated with establishment of the representative sampling sites and require input of tidal,	Cost of field component could be incorporated into meadow assessments, additional cost mainly	Modest additional sampling would be a minor cost – need to

(likelihood for dispersal of propagules between meadows)	wind driven and residual currents from eReefs.	associated with eReef outputs.	cost CSIRO/BoM regarding eReefs.
Habitat and/or environmental suitability 1. Benthic light 2. Temperature 3. Benthic shear stress 4. Sediment quality	These are critical pressure measures that can be collected by seagrass monitoring or others. Involve the deployment of loggers, sediment analysis and data collation, analysis and interpretation at the scale of sampling region.	Additional field sampling time and cost for data management, and to maintain and calibrate sensors. Requirements will be dependent on number of sites, expect 0.5 FTE per region in addition to other activities at this scale.	Cost of purchasing the equipment and time required to maintain equipment and data base, needs further discussion with AIMS.
DPSIR Linkages	Developed and costed by other groups or during integration.		

Process monitoring

Resources likely to be required to impliment the *process* component of the new seagrass monitoring program

Priority Indicator	**Explanation of Resources requirement**	Staff (FTE)	Field Days
Meadow characteristics and condition 1. areal extent 2. abundance 3. patchiness 4. biomass (above/below) 5. chemical measures (C:N:P, carbohydrates…)	These are the same parameters measured as part of *habitat* and *health assessment*. The sampling costs per site would be similar, with costs varying depending on spatial and temporal resolution required and number of observations.	Estimate 0.5 FTE per region to manage this and other general data management for *process monitoring*. Highly variable based on number of sites and sampling frequency (spatial and temporal).	Multiple meadows can have their field work completed in a day – but spatial design of sampling is required to cost.
Connectivity and population structure	This would be a one-off cost associated with establishment of the *post-event* sites and require input of tidal, wind driven and residual currents from eReefs.	Cost of field component could be incorporated into meadow assessments, additional cost mainly associated with eReef.	Modest additional sampling would be a minor cost – need to cost CSIRO/BoM regarding eReefs.
Meadow diversity 1. Species diversity	Baseline assessment for strategic species will require field collections, extraction of DNA, genotyping. Currently, only a limited	0.5 FTE per region In addition to *health*	Modest collection effort in addition to already planned

2. Clonal diversity	amount of data for four species is available at this scale. However, a tight sampling design and analytical approach can be designed to deliver monitoring outcomes.	*assessment* in any single years sampling.	sampling in other sections
Recoverability: Routine measures 1. Sexual reproduction - seed bank - seed viability - seedling numbers - reproductive structures Non-routine 1. Vegetative growth rate 2. Recruitment success (Propagule and Seedling) - Rate of fragment expansion - Seedling survival rate	Dependent on number of samples and site requirements, however, data collection at other scales would contribute. In addition, site specific sampling design would involve in field measurements.	2+ FTE per region Sites determined for sampling by risk or other priority management needs.	*In situ* monitoring in field and lab analysis required.
Herbivory: routine measures 1. Direct observations 2. Exclusion sites	Direct observations conducted as part of abundance assessments recording presence/absence of dugong feeding trails at sites	20+FTE days/ location. Direct observations conducted as part of	Direct observations as part of routine monitoring

3. Explicit mapping of feeding scars	Megaherbivore exclusion cages using the same methods established for current Reef/ARC linkage studies (two by two metre exclusion cages). Compare seagrass inside and outside of cages. Targeted mapping of intertidal dugong feeding using structure from motion software and image analysis (see Rasheed et al. 2017). Image collection from low level photography at low tide using helicopters or drones.	routine abundance assessments Megaherbivore exclusion requires teams of two to three to establish and service quarterly, and can be combined with other reef monitoring activities Mapping of dugong feeding requires a dedicated team for image collection and a spatial analyst for image processing.	Exclusion cages 10 FTE days per location. Mapping of feeding trails 5 FTE days per location.

Continuation - Resources likely to be required to impliment the *process* component of the new seagrass monitoring program

Priority Indicator	**Explanation of Resources requirement**	Staff (FTE)	Field Days
Controlling feedback mechanisms 1. Sediment trapping/preventing resuspension 2. Density-dependant hydrodynamic effects 3. Sediment oxygenation to prevent sediment toxicity 4. Grazing-induced enhancement of nutrient uptake	Given the many different types of measurements and processes included in this group, it will require more detailed discussion with mangers who require the information before the resources required can be estimated.	VERY APPROX!! 0.2+ FTE per location sampled.	10 + per annum per location.
DPSIR linkages	Developed and costed by other groups or during integration.		

Post-event: process monitoring

Resources likely to be required to impliment the *post-event* component of the new seagrass monitoring program

Priority Indicator	**Explanation of Resources requirement**	Staff (FTE)	Field Days
Rapid assessment of recovery potential 1. Seed bank 2. Remnant fragments 3. Species diversity	*In situ,* site-specific sampling design will be required depending on the scale and nature of the event	Included in above Need to allocate an annual response budget	*In situ* monitoring will be needed, as well as field time and lab analysis.
On-going *post-event* monitoring 1. Seagrass abundance 2. Species diversity 3. Expansion of fragments 4. Sexual reproduction (seed bank, propagule production) 5. Biomass allocation	Similar resources required to measuring the same indicators in *health assessment* scale (above).	Included in above Need to allocate an annual response budget	Variable depending on the scale and nature of the event
Habitat suitability Sediment quality and characteristics of meadow area	Incorporated in initial *post-event* site assessment.	Included in above Need to allocate an annual response budget	

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13.0 Report appendices:

Appendix 1: Dominant species assemblages that occur within each of the 12 seagrass habitat types on the Great Barrier Reef, within each NRM region.

Appendix 2: Adequacy of current seagrass monitoring programs – how is current monitoring effort spread across the 12 seagrass habitat types and NRM regions.

Appendix 3: Predicting below ground biomass from above ground biomass – investigating historic data to inform the development of the new monitoring program. What lies beneath: an assessment of seagrass below-ground biomass in northern Australia.

This has been prepared in a separate document as a draft manuscript to support future estimates of below ground seagrass biomass on the Great Barrier Reef - from above ground observations that will dominate future monitoring activities.

Appendix 4: Measuring resilience of seagrass on the Great Barrier Reef – background understanding of resilience models to support the selection of resilience indicators.

Appendix 5: Statistical analysis of reproductive structures and seedbanks – investigating historic data to inform the development of the new monitoring program.

This will be provided in a separate report by Emma Lawrence under a separate contract with the Authority.