DESKTOP SYNTHESIS:
Seagrass Restoration Roadmap For The Great Barrier Reef

COASTAL MARINE ECOSYSTEMS

Emma L. Jackson[1], Alex Carter[2], Catherine Collier[2], Manuja Lekammudiyanse[1], Len McKenzie[2], Andria Ostrowski[1]

[1] Coastal Marine Ecosystems Research Centre, CQUniversity.

[2] TropWater, James Cook University

Report prepared by CQUniversity Coastal and Marine Ecosystems Research Centre and James Cook University TropWater for the Great Barrier Reef Foundation.

EXECUTIVE SUMMARY

The Great Barrier Reef (GBR) faces unprecedented challenges due to climate change, pollution, and human activities. Coastal restoration efforts are critical for preserving this iconic ecosystem. This report presents a comprehensive roadmap for seagrass restoration across the Great Barrier Reef, focusing on assessing the status of seagrass, resilience, availability of infrastructure, baseline research, and partnerships, and is informed by existing available data and published literature and expert opinion. By leveraging this information, we can develop effective strategies to restore and protect the health of the seagrass component of the reef ecosystem.

Approximately 3,464 km² of seagrass is mapped in the inshore Great Barrier Reef (GBR) shallower than 15 meters. Seagrass extends from intertidal areas in estuaries and coasts to depths of 76 meters. Due to challenges in delineating meadow boundaries at depth, extents are modelled. Including deep water (>15 meters), modelled estimates of seagrass area are 35,000 km², representing over half of Australia's mapped seagrass area. Seagrass meadows are vital to the Great Barrier Reef ecosystem, filtering nutrients, serving as nurseries for marine life, and storing carbon as Blue Carbon. Securing the future of seagrass is also critical for supporting dugongs and turtles and maintaining ecosystem services such as fish habitat and carbon sequestration. The Reef 2050 Long-Term Sustainability Plan aims to protect and manage the reef, including seagrass meadows. While Queensland seagrasses have previously been shown to recover naturally from disturbances within relatively short time frames (~1-5 years), recent losses from multiple years of La Niña climate have led to substantial longer-term loss. In some locations, the prognosis for recovery without intervention is poor due mainly to limits on propagule supply and germination. With projected scenarios of more frequent La Niña climate conditions and an increase in the frequency of severe storms, this situation will likely become more common, particularly when combined with other cumulative anthropogenic pressures facing seagrasses.

Here, we highlight the need for restoration and data gaps in assessing seagrass distribution, monitoring, disturbance risk, resilience, and connectivity using existing datasets. We combine restoration needs with existing knowledge of restoration methods. Our aim is to inform stakeholders about vulnerability and restoration priorities for GBR seagrass habitats, identify research needs and partnerships, and recommend scaling seagrass habitat rehabilitation in the GBR.

To synthesise available data to inform seagrass restoration across the GBR, we collated information and data on seagrass distribution, state, and resilience in the GBR, including: compilations of seagrass distribution data (mapped meadows and site data); inshore seagrass Marine Monitoring Program (MMP) and Seagrass-Watch data; Queensland ports monitoring data; seagrass habitat suitability models; relevant published studies with data on change in seagrass condition; information on resilience that may influence how restoration is prioritised or scaled up (e.g., connectivity models); environmental data that could be used to assess risk and prioritise sites; and published maps of broadscale risk to coastal seagrasses from cumulative threats.

Status of seagrass in the GBR

The GBR harbours 15 seagrass species with varying distributions. *Halophila decipiens*, *H. ovalis*, *H. minor*, *H. capricorni*, and *H. spinulosa* are deepwater specialists found across a broad area of the GBR, with *H. tricostata* occurring to a lesser extent and typically in low

abundance. *Halodule uninervis* is widespread, occurring in estuaries, coasts, and reefs to depths over 10 meters. *Nanozostera muelleri* is prevalent in the southern GBR, especially in estuaries and muddy coasts (Figure 2). Other species, including *Cymodocea rotundata, C. serrulata, Halodule pinifolia, Syringodium isoetifolium, and Thalassia hemprichii*, are mainly found in shallow (<15 meters) areas in estuaries, coasts, and reefs. *Thalassodendron ciliatum* is typically found on rocky reefs with strong currents. *Enhalus acoroides* has a limited distribution, mostly occurring in small patches in GBR estuaries and coasts, though it forms dense meadows outside the GBR.

Severe climatic events (e.g., cyclones) causing physical damage and increased turbidity leading to reduced light are the main pressures affecting seagrass abundance along the GBR coast. Additionally, human activities pose threats to seagrass habitats. These include agricultural runoff, urban and industrial runoff, port and infrastructure development, dredging, shipping accidents, and various fishing methods. Climate change exacerbates these risks by altering rainfall patterns, river discharge, and tropical storms. The condition of adjacent catchments and coastal development significantly influences the risk to seagrass habitats from these pressures.

Colonising and opportunistic species are more prevalent in the GBR than those with persistent life history traits. Physical habitat and disturbance modifiers, such as flood events and cyclones, often result in a higher proportion of transitory seagrass meadows—those not persistent over time. These meadows may recolonise via seed banks or the immigration of propagules from nearby patches. Considering species traits and habitats is crucial for restoration efforts in the GBR. Enduring meadows should be managed for protection due to the limitations of natural recovery.

The Great Barrier Reef has a number of valuable seagrass monitoring datasets:

- Queensland Ports Seagrass Monitoring Program (QPSMP)
- Inshore Seagrass Marine Monitoring Program (MMP) for the Reef 2050 Paddock to Reef Program
- Seagrass-Watch
- Monitoring at Clairview by the Mackay-Whitsunday-Isaac Healthy Rivers to Reef Partnership

These initiatives involve collaboration between Traditional Custodians and scientists from different institutions. However, long-term data sets are not yet available. Most monitoring occurs during the late dry season (September to November), when seagrass abundance reaches its annual maximum due to the end of the growth season. Additional monitoring takes place at other times, depending on the location.

Seagrass restoration in the GBR

In recent years, most estuary and coastal community types along the Great Barrier Reef (GBR) have failed to reach their desired state in terms of seagrass biomass. While there has been increased intervention to restore seagrass habitats, a comprehensive review of restoration activities specifically focused on GBR seagrass species is lacking. To address this, we systematically reviewed literature on past and current restoration efforts within and outside Australia. Of the 15 seagrass species found within the GBR, 12 were considered in restoration projects. *Nanozostera muelleri* was the most commonly restored species (45%), primarily using transplanting plugs. Notably, no studies addressed restoration of *Halophila*

minor, *Thalassodendron ciliatum*, or *Halophila capricorni*. The predominant restoration method across all studies was transplanting mature seagrass (94%), followed by seeds (6%) and seedlings (3%). Large-scale restoration trials (≥ 1 ha) are ongoing in Gladstone Harbour, Mourilyan Harbour, and Pioneer Bay, all focusing on *N. muelleri*. However, *H. uninervis*, despite being widespread, lacks restoration studies within the GBR.

Seagrass nurseries

Large-scale seagrass restoration relies on abundant donor material. Seagrass nurseries, like aquaculture systems, enhance seed and plant yields while minimizing impacts on donor meadows and maintaining genetic diversity. These nurseries can produce seeds, grow seedlings, and store native material collected from donor meadows. They are versatile across various seagrass restoration techniques and species. For instance, a study in Gladstone successfully grew wild-collected cores in seagrass nurseries for three months before transplantation.

There are currently three seagrass nurseries in Gladstone, Konomie (North Keppel) Island, and Airlie Beach, and one nursery is proposed for construction in Cairns. To identify existing infrastructure along the GBR region that could be utilised for seagrass nursery operations, we conducted a search of existing seagrass nurseries, marine and aquaculture research centres, aquaria, sea turtle rehabilitation centres, hatcheries, fish and prawn farms, and terrestrial plant nurseries from Cape York to Urangan, Queensland.

Permitting considerations

Seagrass restoration in the GBR region involves site-specific planning and compliance with regulations. These regulations, including provisions from the Fisheries Act 1994 in Queensland, safeguard seagrass beds. For instance, applications for Marine Plant disturbance must adhere to accepted development procedures. However, the involvement of multiple government departments complicates matters. Integrating large-scale coastal restoration into conservation and planning activities could enhance coordination. Additionally, stakeholder engagement with Traditional Owners is crucial to address cultural concerns and ensure sustainable practices aligned with cultural values and heritage.

Prioritising intervention sites

In the GBR region, seagrass restoration decisions rely on historical data. However, identifying permanently lost areas is challenging due to transient seagrass meadows and dynamic distribution. Some areas are unsuitable due to environmental modifications, while others remain unrecorded but potentially suitable. The vastness of the GBR limits monitoring to select sites, leaving significant areas unmapped. Our pragmatic approach prioritised restoration based on disturbance risk and data gaps, recognizing limitations.

Initial steps for selecting restoration locations is based on data availability. Using a decision tree, locations were divided into those with monitoring data (even one-off mapping) and those without any data. Habitat suitability models are available to identify areas suitable for seagrass species. High-suitability areas without data should be assessed for disturbance risk. Locations with both high suitability and disturbance risk should be flagged as a priority for seagrass mapping and monitoring. Low-risk areas with high suitability are not prioritized for restoration or mapping. This pragmatic approach considers limited resources and does not exclude future mapping.

In reviewing data from sites with high-resolution temporal data for declining trends, eleven locations were identified. Loss and degradation of seagrass is found across the GBR, and

these locations by no means represent the only sites of concern for restoration. Rather, these eleven locations are areas where the monitoring data is available at a good enough resolution to make a strong case for targeting these sites for potential restoration activities in the immediate future.

Traditional Owners, including Indigenous communities, have lived in and managed the Great Barrier Reef (GBR) region for thousands of years, possessing a deep cultural and spiritual connection to the land and sea. Their historical and traditional knowledge of the GBR ecosystem, including seagrass meadows, provides a unique perspective on what constitutes a healthy and thriving marine environment. When it comes to seagrass restoration, it is important to recognise that Traditional Owners may have a different baseline for restoration compared to Western scientific or regulatory perspectives.

While the initial focus in prioritising and planning seagrass restoration should begin with understanding where seagrass has been lost or is in decline, many other factors should be considered when considering how to expand restoration efforts and identify new sites. We use a multi-criteria analysis to evaluate sites, weigh, and prioritise them for restoration, and pinpoint where investment is needed to achieve successful outcomes. This analysis is applied to the eleven locations mentioned above, which are in decline and in poor condition but could be applied to other areas where Traditional Ecological Knowledge or local observations suggest the need for restoration.

Assessment Criteria included:

> » Seagrass status, trends and data resolution;
> » Seagrass resilience, using the MMP resilience indicator;
> » Connectivity and Distance to healthy donor meadows;
> » Occurrence of exogenic environmental pressures (external factors that impact ecosystems from outside their natural environment);
> » Occurrence of endogenic pressures, which may need to be managed before restoration is undertaken (e.g. local sources of nutrients and fine sediments, or disturbance by boat anchoring or propellors;
> » The knowledgebase for restoration of the species in the local environment;
> » The species traits (colonising, opportunistic or persistent) and meadow type (enduring or transitory meadows);
> » End users and sustainable funding identification;
> » Associated ecosystem services at the site;
> » Accessibility of the location;
> » Delivery, training and research partner identification and level of existing partnerships; and
> » The available options for establishing infrastructure such as a seagrass nursery.

We applied the MCA, scoring on a consensus basis, on the scores of four of the report authors, to the eleven locations identified as in decline from the review of trend data from high-resolution monitoring. The descriptions demonstrate the application of the approach and the use of the information in terms of the roadmap for scaling restoration, which also inform the key recommendations.

The synthesis identified five key recommendations:

1. Use this report as a tool to discuss aspirations for restoration and mapping with Traditional Owner groups.

2. Increase research and restoration trials on *Halodule uninervis* and *Thallasia hemprichii*
3. Target restoration research and trials in locations with declining trends, based on high temporal resolution data for intervention, using the MCA results to identify knowledge and resource gaps.
4. Target locations with high habitat suitability but no data and high risk for the establishment of mapping, monitoring, and restoration trials.
5. Develop a clear pathway and guidance for the planning and appropriate permitting of seagrass restoration activities.

Contents

Table of Figures

List of Tables

Acronyms

ARC	Australian Research Council
CCTV	Closed-circuit television
CHAS	Coastal Hazard Adaptation Strategies
CMERC	Coastal Marine Ecosystems Research Centre
COP15	Fifteenth meeting of the Conference of the Parties
CQU	Central Queensland University
DAF	Department of Agriculture and Fisheries
DCCEEW	Department of Climate Change Energy Environment and Water
DEA	Digital Earth Australia
DESI	Department of Environment, Science and Innovation
EPBC Act	Environment Protection and Biodiversity Conservation Act
FHA	Fish Habitat Area
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
GBRWHA	Great Barrier Reef World Heritage Area
GIS	Geographic information system
GPC	Gladstone Ports Corporation
GPS	Global Positioning System
Ha	Hectare
ISI	Institute for Scientific Information
JCU	James Cook University
MCA	Multi-Criteria Analysis
MMP	Marine Monitoring Program
MNES	Matter of national environmental significance
MSES	Matter of state environmental significance
MSQ	Maritime Safety Queensland
NESP	National Environmental Science Program
NRM	Natural Resource Managers
OUV	Outstanding Universal Value
QPSMP	Queensland Ports Seagrass Monitoring Program
QPWS	Queensland Parks and Wildlife Service
SPA	Seed Production Areas
SSL	Seagrass-Sediment-Light

TEK   Traditional Ecological Knowledge

TUMRA   Traditional Use of Marine Resources Agreement

1. INTRODUCTION

Seagrasses are in decline globally, largely due to the presence of multiple anthropogenic stressors (Halpern et al. 2019, Turschwell et al. 2021). Human activities, such as coastal development, dredging activities, and pollution, can result in poor coastal water quality, putting tremendous pressure on seagrass habitats and ultimately contributing to large-scale meadow declines (19.1% lost globally since 1880; Dunic et al. (2021). Substantial losses have since prompted increased seagrass restoration efforts since the 1970s (van Katwijk et al. 2016). Although seagrass meadows can naturally recover following disturbance events, intervention (i.e., restoration initiatives) can assist recovery and enhance meadow resilience to future disturbances (Orth et al. 2012, van Katwijk et al. 2016, Statton et al. 2018). If the health of seagrass ecosystems continues to be compromised, it casts uncertainty on their potential to aid in nature-based responses to the climate crisis and the biodiversity decline (Unsworth et al. 2022).

In the UN Decade on Ecosystem Restoration (2021-2030) ambitious targets have been set for restoring degraded marine habitats. Target 3 of the Kunming-Montreal Global Goals for 2050 COP15 is to "*ensure that by 2030 at least 30 per cent of areas of degraded terrestrial, inland water, and coastal and marine ecosystems are under effective restoration, in order to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity*". Assessments of the achievability of global targets for seagrass recovery indicate that protection alone would only provide a 1% gain in seagrass recovery, and that both effective protection and restoration are needed to achieve a 35% gain by 2050 (Buelow et al. 2022).

Seagrass meadows are a significant component of the Great Barrier Reef (GBR) ecosystem, which filters nutrients and sediment between catchment and the Coral Sea, acts as nursery grounds for fish and shellfish, and plays a crucial role in drawing carbon out of the atmosphere and storing it as Blue Carbon. The Reef 2050 Long-Term Sustainability Plan is the Australian and Queensland Government's overarching framework for protecting and managing the Great Barrier Reef to 2050. Under the Reef 2050 Work Area 5, there is a target for no net loss of the extent and a net improvement in the condition of natural wetlands and riparian vegetation that contribute to Reef resilience and ecosystem health. While Queensland seagrasses have previously been shown to recover naturally from disturbances within relatively short time frames (~1-5 years), recent losses from multiple years of La Niña climate have led to substantial longer-term loss. In some locations, the prognosis for recovery without intervention is poor due mainly to limits on propagule supply and germination. With projected scenarios of more frequent La Niña climate conditions and an increase in the frequency of severe storms, this situation will likely become more common, particularly when combined with other cumulative anthropogenic pressures facing seagrasses. Securing the future of seagrass is critical for supporting dugongs and turtles and maintaining ecosystem services such as fish habitat and carbon sequestration.

Scientific reviews agree that successful (self-sustaining) seagrass restoration will require scaling up restoration efforts. Projects focussed on this have commenced within the GBR, but only at limited sites where the science base (needs and approaches), infrastructure, and partnerships exist. Other locations where seagrass is under threat due to continued disturbance and poor recovery either lack the knowledge base or the infrastructure, and partnerships are still developing.

Here, we identify the need for restoration and significant gaps in data to assess this using existing datasets on seagrass distribution, monitoring, disturbance risk, resilience (potential to resist disturbance and recover), and connectivity. Information on restoration needs will be combined with existing knowledge of species and environment-specific restoration methods. Overall, the aims are to inform stakeholders about the vulnerability and broadscale restoration priorities for seagrass habitats in the GBR, identify limiting gaps in the available data, research and partnerships, and provide recommendations for scaling seagrass habitat rehabilitation in the GBR.

To synthesise available data to inform seagrass restoration across the GBR, we followed a staged approach.

1. We collated information and data on seagrass distribution, state and resilience in the GBR, including: compilations of seagrass distribution data (mapped meadows and site data); inshore seagrass Marine Monitoring Program (MMP) and Seagrass-Watch data; Queensland ports monitoring data; seagrass habitat suitability models; relevant published studies with data on change in seagrass condition; information on resilience that may influence how restoration is prioritised or scaled up (e.g., connectivity models); environmental data that could be used to assess risk and prioritise sites; and published maps of broadscale risk to coastal seagrasses from cumulative threats.

2. We applied a multicriteria analysis approach to highlight data gaps and identify key case studies for restoration interventions based on existing long-term trend data. For example, we identify areas with insufficient seagrass condition data where the focus should be mapping and monitoring; areas where monitoring data does not exist, but records of seagrass do or habitat suitability for seagrasses is high; sites where no records of observations exist, but available data suggest habitat suitability for seagrasses is high; and sites where monitoring data show seagrass degradation and low recovery potential.

3. We review past and current restoration activities in the GBR and on GBR-relevant species. We review the available information on restoration techniques for each restoration project. We focus on examples of past and current restoration activities occurring within the GBR and review approaches taken for relevant species in similar environments outside of the GBR.

The synthesis concludes with five key priority actions or recommendations.

2. OVERVIEW OF SEAGRASS IN THE GREAT BARRIER REEF REGION

2.1. Seagrass species and habitats Great Barrier Reef ecosystem

There are approximately 3,464 km^2 of seagrass mapped in the inshore GBR shallower than 15 m (McKenzie et al. 2014, Saunders et al. 2015, Carter et al. 2016, McKenzie et al. 2016); Howley, Unpublished data). Seagrass grows from intertidal areas in the estuaries and coasts

to 76 m deep. Due to the challenges of distinguishing meadow boundaries at depth, extents are modelled. Including deep water (>15 m), modelled estimates of seagrass area are 35,000 km^2 (Coles et al. 2015), which represents more than half of Australia's mapped area of seagrass (McKenzie et al. 2020). Regionally, Cape York contains the most significant area of seagrass overall (32%), followed by Burnett Mary (18%), Burdekin (17%), Fitzroy (17%), Wet Tropics (14%), and Mackay Whitsunday with the least (2%).

Seagrass habitats can be separated into estuary, coastal, reef and deepwater (e.g. inter-reef lagoonal waters) (Carruthers et al. 2002, Carter et al. 2021, McKenzie et al. 2023b; Figure 2). Species assemblages in these habitats are influenced by a complex range of environmental variables, including depth, tidal exposure, latitude, current speed, benthic light, proportion of mud, water type (water quality), water temperature, salinity and wind speed (Carter et al. 2021).

There is higher species diversity in communities closer to the mainland coast (Coles et al. 2009c). There are 15 species of seagrass (Figure 1) in the Great Barrier Reef (Coles et al. 2015) that vary in distribution (Figure 2). *Halophila decipiens, H. ovalis and H. spinulosa* are deepwater specialists that occur across the broadest area of the GBR, and *H. tricostata* to a lesser extent but typically with low abundance, and they are often ephemeral (Coles et al. 2009b). *Halodule uninervis* is the most widespread of the long-bladed species and can be found in estuaries, coasts and reefs and to depths over 10 m. *Nanozostera muelleri*[1] is more common in the southern section of the GBR, especially in estuaries and muddy coasts (Figure 2). The remaining species grow on coasts and estuaries. The remaining species typically occur in shallow (<15m) in estuaries, coasts and reefs. *Enhalus acoroides* has the most limited distribution, generally only occurring in small patches in estuaries and coasts of the GBR (but outside of the GBR it can form dense meadows) (Carter et al. 2021).

Colonising or opportunistic species are relatively more prevalent in the GBR than those with persistent life history traits (Figure 1). Often, physical habitat and disturbance modifiers (e.g. flood events, cyclones) result in a higher proportion of transitory seagrass meadow forms (seagrass meadows that are not persistent over time (Kilminster et al. 2015a). These transitory meadows may recolonise via seed banks or through the immigration of propagules (seeds or vegetative fragments) from nearby patches (McMahon et al. 2014, Weatherall et al. 2016). Consideration of the species traits and habitats of the species of seagrass found in the GBR is an important consideration for restoration. Enduring meadows should be managed for protection due to the limitations of natural recovery.

---

[1] *Zostera muelleri* Irmisch ex Ascherson, 1867 has recently been accepted in the World Register of Marine Species as *Nanozostera muelleri* (Irmisch ex Ascherson) Tomlinson & Posluszny, 2001.

Figure 1 Classification of the 15 seagrass species found within the Great Barrier Reef and the number of restoration studies conducted for each species [Source: Modified from Statton, et al., 2018; Butler and Jernakoff, 1999].
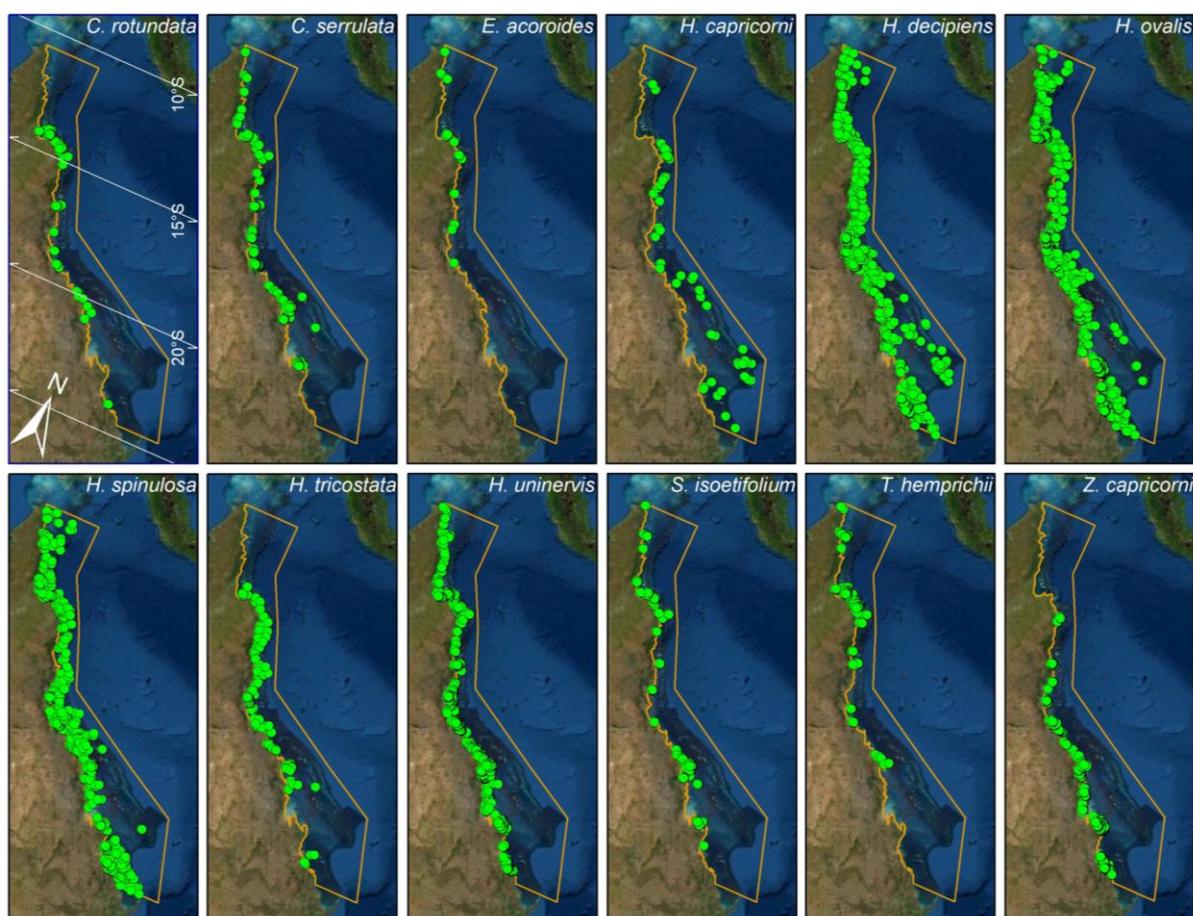
Figure 2 Distribution of 12 seagrass species in the Carter et al. (2021) dataset (green dots) throughout the Great Barrier Reef World Heritage Area (orange boundary) observed in the temporal data synthesis. Sites/points were assessed to a depth of 117 m, but seagrass presence was not recorded to be deeper than 76 m. Satellite image courtesy: ESRI. (From Carter et al 2021). NB: Z. capricorni has recently been revised to Nanozostera muelleri (Sullivan and Short, 2023), and C. serrulata has been revised to Oceana serrulata (Christenhusz et al., 2018).

Seagrass meadows can be comprised of one-to-many individuals due to clonal growth and sexual reproduction (Waycott et al. 2006). For example, *Thalassia hemprichii* in a meadow at Picnic Bay, Magnetic Island, near Townsville was an individual clone, indicating limited connectivity near the margin of this species' range (Collier et al. 2016). The *Nanozostera muelleri* meadow at Pelican Banks in the Port of Gladstone also had low clonal diversity, indicating a high dependency on clonal growth (Collier et al. 2016). Jackson et al. (2021b) undertook a genetic analysis of 352 individuals from 13 seagrass populations across the Port of Gladstone and Rodds Bay and combined with dispersal modelling, and showed that the meadow at Pelican banks had poor retention of propagules.

The resilience of habitats may be affected by genetic composition (Plaisted et al. 2020). For example, plants that perform best at optimum temperatures do not perform as well under high temperatures, so genetic diversity may improve survival during events (Reynolds et al. 2016). Furthermore, some populations have higher heat tolerance than others, such as a *Nanozostera muelleri* population from Midge Point, south of Airlie Beach, that maintained net productivity at 35°C after seven weeks (Collier et al. 2018), while populations further south in Gladstone suffered mortality at lower temperature (33 °C) after seven weeks (Collier et al. 2011). Information on clonality may be needed to understand meadow diversity and

connectivity and determine whether there is a need to enhance resilience through restoration activities.

Some features that distinguish seagrasses from other ecosystems in the Reef:

» They occur throughout coastal areas of the Reef and adjacent estuaries, where there is high pressure from catchment and urban development.
» They grow through sediment, and the majority of plant biomass is below-ground (Collier et al. 2021c). Biogeochemical processes in the sediment affect seagrass and therefore changes to the condition of sediment can act as a pressure (though these processes are not well described in the Reef).
» They are dynamic, both spatially and temporally: decline, species succession and recovery are frequent in many areas. Management of resilience needs to account for and work with these trajectories. Problems occur when pressures worsen, become chronic and exceed thresholds and become especially problematic when habitat change proceeds beyond tipping points.
» Meadow expansion can be maintained only by asexual reproduction of its own rhizomes, however, sexual reproduction sustains the long-term survival of seagrass when vegetative growth is limited. Although the mechanisms that control sexual reproduction in tropical seagrasses are not yet fully understood, stress due to modifications in abiotic factors (e.g. temperature, salinity, light intensity, sediment type and organic matter content) can influence the timing and intensity of the flowering.
» Sexual reproduction is essential to seagrass resilience, and they have unique and varied reproductive and recovery strategies: They grow and colonise through asexual reproduction (rhizome growth and shoot production), as well as sexual reproduction with very diverse strategies. Some species have separate male and female plants (diecious, so both are needed for reproduction), while in others they occur on the same plant (monecious). Some species produce persistent seedbanks while others lack a dormancy period. While some species have relatively predictable reproductive seasons, many others can reproduce throughout the year, yet the reproduction triggers are unknown and cannot be predicted.

Van Katwijk et al. (2021) state that the ability of seagrasses to persist in relatively stressful and unpredictable environments is due to the large numbers of plants in an individual meadow and through metapopulation dynamics. Effective dispersal mechanisms for propagules and vegetative fragments connect different populations, with isolated populations showing lower recovery from disturbance. The Seagrass-Sediment-Light (SSL) feedback, wherein the presence of seagrass encourages sedimentation by baffling wave energy, thereby improving local light availability, which in turn benefits the seagrass, has been well documented (Adams et al. 2016b). Such positive feedbacks depend on large numbers of plants (high density) or areas and is considered to be the reason that large-scale restoration trials are more successful than small-scale trials (van Katwijk et al. 2021), with successful seagrass recovery requiring a large supply of propagules over sustained periods.

2.2. Current threats and challenges facing seagrass in the GBR

The multitude of pressures influencing the Reef drive seagrass declines at some locations and times, while periods with fewer pressures enable recovery (McKenzie et al. 2022a). This

results in dynamic seagrass meadows that are spatially and temporally variable, particularly in inshore habitats.

Severe climatic events (e.g., cyclones) causing physical damage and increased turbidity leading to reduced light are the main pressures affecting seagrass abundance along the GBR coast ((Brodie and Waterhouse 2018, Lambert et al. 2021, McKenzie et al. 2022b)a). They are also threatened by agricultural runoff, urban and industrial runoff, urban port and infrastructure development, dredging, shipping accidents, bottom trawling, boat damage, and other fishing methods (Grech et al. 2011b). Therefore, the condition of adjacent catchments and coastal development significantly influence the risk to seagrass habitats from discharge. These risks will be intensified by climate change (e.g., rainfall, river discharge and tropical storms).

There is a scarcity of studies testing the interactions of pressures (King et al. 2021)) but cumulative impacts from elevated seawater temperatures and reduced light availability (due to increased sediments and nutrients), in combination with herbicide exposure that runs off agricultural land, are threatening seagrass health. The greatest risk from cumulative impacts is adjacent to population centres or farmland areas and in the southern half of the GBR. Industrial ports are heavily regulated but contribute to pressures on seagrass meadows (Coles et al. 2015).

The spatial and temporal scale of pressures or disturbances is significant (O'Brien et al. 2018b). Recovery may occur quickly from small-scale disturbances, such as the patch formation caused by a single anchor scar. Still, widespread pressures such as cyclones or flooding that affect bays or beyond will take longer to recover due to recruitment processes and degradation of processes that maintain the integrity of the habitable area, such as stable sediments. The duration, timing and recurrence time of disturbances are also essential considerations because partial recovery may increase vulnerability to further disturbances (O'Brien et al. 2018a). Management frameworks require understanding how pressures and ecological responses to them at a local scale are nested within those regional, Reef-wide and beyond the Reef's boundaries.

2.3. Importance of seagrass in supporting reef ecosystem health

Blue carbon

Investing in the protection and restoration of coastal habitats offers Nature Based Solutions to mitigate climate change because of the 'Blue Carbon' buried in sediments (UNESCO 2020). There are also opportunities for investment into habitat restoration through Blue Carbon markets. The Australian Government has begun reporting on coastal habitat changes in its National Inventory Reporting, and has begun developing Blue Carbon strategies (Kelleway et al. 2020).

Deep-water seagrass habitats could span tens of thousands of square kilometres in the Reef lagoon (Coles et al. 2009c, Carter et al. 2021) and store organic carbon only 30 percent lower than shallow denser habitats (York et al. 2018). This has potential to contribute significant amounts to the Reef's Blue Carbon inventory together with large stores in mangrove and salt marsh within Reef catchments (Duarte de Paula Costa et al. 2021).

Blue Carbon of GBR seagrass has been estimated from a relatively small number of meadows representing just some of the diverse seagrass community and habitat types of the Reef. Accounting for habitat variability can have a profound influence on blue carbon estimates (Lavery et al. 2013). To accurately assess the contribution of organic carbon burial to carbon storage, it is necessary to account for other processes influencing carbon budgets across

sediment-water-air interfaces, such as carbon lost as CO_2 during calcification (Van Dam et al. 2021)). Advancements in the Blue Carbon economy have focussed on mangrove and saltmarshes, and the information needed in seagrass habitats lags well behind, particularly in tropical Australia.

Fisheries and biodiversity

Seagrass forms habitat for a variety of animals including fish, crab and prawn species that have high socio-economic value (commercial and recreational fisheries) in the Reef (Coles et al. 2015, Hayes et al. 2020). In fact, commercial catches in the Reef are dominated by fisheries species that do not associate with coral reefs, but rather, with shallow inshore habitats, including seagrass (Brown et al. 2020). In recognition of the importance of seagrass to fisheries, the Queensland Fisheries Act 1994 directly protects seagrass in the Reef from anthropogenic damage or disturbance by legislation and codes of practice.

Seagrass and epiphytic algae are critical as habitat and a food source for the Reef's food webs (Jinks et al. 2019), including commercial and recreational fisheries. The most complex habitats appear to be associated with balanced food webs and largest animal biomass ((Jinks et al. 2019)).

Herbivory in seagrass habitats is more resilient when habitats are more connected to each other through a greater number of connections and their spatial arrangement (Jinks et al 2020). Seagrasses are part of interconnected habitat networks with other structural habitats including mangroves, coral reefs, salt marsh (Lefcheck et al. 2019).

The arrangement of seagrass habitats within the Reef seascape and configuration of meadows (including fragmentation) are also key determinants of functionally important associated faunal species in shallow water habitats (Gullström et al. 2008).

Water quality

Seagrasses improve water quality through nutrient uptake, sediment settlement due to lower current velocities and sediment stabilisation (McGlathery et al. 2007). There are feedback processes that maintain seagrass condition. These processes depend on the structural of the habitat, which is in turn influenced by water quality (Adams et al. 2016a). Filtering capacity and nutrient mass balances need to be quantified across the range of seagrass communities and habitat types. This is especially pertinent given the large investments into remediation of Reef catchments to improve water quality entering the Reef.

Traditional values and use

The cultural use and value of the Reef's seagrass ecosystems by Australia's First Nations peoples is poorly recognised and likely underestimated. Aboriginal and Torres Strait Islander people are the Traditional Owners of the Reef, maintaining a close connection spanning millennia. The importance of seagrass ecosystems is predominately in relation to fisheries or in supporting dugongs (*Dugong dugon*) and green turtles (*Chelonia mydas*) which form an important part of the diet and culture of coastal peoples.

It is possible the close connection between First Nations peoples and seagrass ecosystems in the Reef may be similar, to a degree, to indigenous peoples in Melanesia (McKenzie et al. 2021b). For example, opportunistic direct consumption of *Enhalus acoroides* fruits has been reported by peoples from Hopevale (Smith 1987). It is likely that historical use of seagrass ecosystems has changed with the adoption of modern materials and introduction of new fishing techniques. These changes may have also impacted modern use of seagrass ecosystems, with an increase in the number of types of fin fish and crustaceans caught since

the introduction of modern nets and lines and a lower dependence on species traditionally gleaned (Smith 1987).

Likely, many non-material contributions by the Reef's seagrasses have also been overlooked and under-appreciated by decision-makers. A thorough examination of the contributions provided by seagrass ecosystems in the GBR is needed to better understand the importance of seagrass ecosystems to Australia's First Nations' livelihoods and well-being.

2.4. Resilience: Factors influencing the resistance and recovery potential of seagrass habitats

The properties of seagrass resilience include characteristics that enable resistance to environmental pressures and recovery following decline or loss (Unsworth et al. 2015, O'Brien et al. 2018b) such as:

- genetic and species diversity, which increases the range of environmental conditions that the habitat can tolerate and enables succession following impacts;
- seed banks from which the habitat can recover following decline or loss;
- continuous habitat, which increases the capacity of a meadow to withstand disturbances, compared to a fragmented habitat, and is critical in enduring meadows;
- energy reserves, especially in the below-ground rhizomes which sustain seagrasses during periods of metabolic imbalances when the rate of photosynthesis cannot keep up with plant requirements, for example, when water is turbid or temperatures are very high;
- connectivity with other seagrass populations;
- rhizome extension and clonal growth rates enable plants to recover rapidly.

The 15 species of seagrass on the Reef can be allocated to groups that depend on specific resilience characteristics more than others. Placing species on a scale of resistance and recovery traits offers a way to understand and manage trajectories of decline and recovery. The classification of Kilminster et al. (2015b) was developed to simplify complexity in seagrass habitats and facilitate the development of management strategies and monitoring programs. The groups are:

- *Colonising species* have low physiological resistance to disturbances (i.e. low energy reserves), but they flower and seed prolifically and can form a seed bank. They recover quickly from seed and through rapid clonal growth. All *Halophila* species fall into this category, dominating deep water habitats on the GBR (Coles et al. 2009a).
- *Opportunistic species* have all resilience features and can modify their reliance on them to adapt to the conditions in their habitat. They form seed banks for around three years (Collier et al. 2021a), and can proliferate. Still, they can also form stable populations that resist disturbances because of their energy reserves and form dense continuous habitats. Inshore habitats in coastal and estuarine areas of the Reef are often dominated by opportunistic species (Carter et al. 2021).
- *Persistent species* have high resistance capacity, with high below-ground biomass (Collier et al. 2021c) and energy reserves. They grow slowly and form stable habitats (Collier et al. 2021a). However, neither species in the Reef that are 'persistent' (*Thalassia hemprichii* and *Enhalus acoroides*) produce a seed bank.

Depending on the environments and level of disturbance these groups grow, they will either form transitory or enduring meadows. Kilminster et al., (2015) propose that persistent species form enduring meadows, while opportunistic and colonizing species can establish either enduring or transitory meadows. Meadows near their physiological limits or under human impact are more likely to be transitory. Knowing the meadow type helps guide effective management and monitoring strategies. Enduring meadows should be managed and monitored for resistance (e.g. protection, removal of pressures). This is partly due to the challenges of restoring these meadows (slow growth rates, low seed production) and the potential for bi-stable states. Transitory meadows should be managed and monitored for recovery (Kilminster et al. 2015b).

They can also be grouped according to their ecological functions (i.e. the ecosystem goods and benefits they provide (Nordlund et al. 2016); foundational and non-foundational (McKenzie et al. 2021a).

Seagrass habitats are part of a supporting ecosystem that also contributes to resilience. The key attributes of the ecosystem that support seagrass resilience are trophic interactions, connected ecosystems and physical processes (Unsworth et al. 2015):

Trophic interactions

Fauna that graze on algal epiphytes and detritus and top predators (such as sharks) that feed on lower order predators and plant consumers influence the structure and growth rate of seagrass habitats. Algal epiphytes grow on seagrass blades, shading the seagrass and impeding photosynthesis. Herbivorous fish and invertebrates graze on these epiphytes to help maintain seagrass health and growth rate by reducing shading and increasing light availability. By regulating herbivore populations, predators can prevent overgrazing of seagrass and preserve the structural integrity of the meadow.

Mega-herbivores such as turtles, dugongs, and certain fish species consume seagrasses. Moderate levels of grazing can stimulate seagrass growth by promoting shoot proliferation and helping maintain open spaces in the meadow, increasing light availability and nutrient uptake. However, overgrazing can lead to reduced seagrass biomass and even the loss of meadows.

Detritivores such as crabs, sea cucumbers, and worms break down dead seagrass material. This process recycles nutrients back into the ecosystem, promoting the growth of seagrass and other primary producers.

Connected ecosystems

Connected seagrass ecosystems support resilience by moving animals and seagrass propagules that maintain seagrass habitat and increase recovery. Connectivity between meadows, which influences species dispersal, genotypes and recovery, appears to occur over scales of up to hundreds of kilometres based on hydrodynamic models and genetics (Collier et al. 2016, Grech et al. 2016). However, this is likely to vary between regions in the Reef. Specific hydrodynamic modelling has been undertaken in particular areas, for example, Gladstone Harbour (Jackson et al. 2021c), The Whitsunday Islands (Jackson et al. 2021a) and The Keppel Islands (Aiken et al., un published).

The Reef is also an integrated and highly connected part of the northeast Australian seascape. As such, its seagrass ecosystems' resilience is also to some degree dependent on the strength of connections between adjacent marine domains, including Torres Strait, the Coral Sea and the Great Sandy Marine Park. These marine domains are ecologically, socially and culturally connected and contain values of national and international significance (Johnson et al. 2018).

The seagrass ecosystems in each domain are connected by the passive dispersal of propagules and/or vegetative fragments facilitated by currents and hydrodynamic processes. Although the connectivity of seagrass ecosystems across jurisdictions may be generally weak, occurring on ecological (i.e. years to decades) or evolutionary timeframes, it can be necessary for the immigration of propagules to facilitate recovery and maintaining genetic diversity, critical factors in species resilience.

Physical processes

Physical processes and environment, including nearby habitats, affect seagrass habitat suitability, including coral reefs and mangroves. The flow of water through habitats influences nutrient delivery and water quality.

Feedbacks

Resilient seagrass ecosystems rely on feedback processes that absorb impacts and enhance the structural characteristics of the habitat and supporting ecosystem. Seagrass themselves can improve conditions for seagrass growth because feedback processes sustain optimal conditions. Managers can use these principles to increase the success of activities to protect or restore seagrass:

- Seagrass canopies can change water flow regimes locally and cause suspended particulate matter to settle out of the water, reducing turbidity and nutrients (Adams et al. 2016a). Therefore, maintaining or restoring seagrass at densities that can achieve this will improve survival.
- When seagrass photosynthesises, oxygen is pumped to roots and leaked into sediment, preventing sediments from becoming anoxic and uninhabitable (Holmer 2019). Therefore, not colonised sediments may be unsuitable for restoration without prior treatment.
- Seagrass plants and their associated roots and rhizomes stabilise sediments (Infantes et al. 2022). When unvegetated, sediments may become too unstable for colonisation and require stabilising to facilitate recovery or restoration.

These feedback processes can be essential to the survival and resilience of seagrass areas. However, the three examples above may depend on a range of factors, such as water clarity, sediment type, and local hydrodynamics. They may also depend on the functional traits of seagrass species present. Establishing the extent to which they sustain reef habitats is essential to successfully managing The Reef's seagrass habitats.

Tipping points

Protecting or restoring resilience requires feedback processes to be functional. They can influence decline and recovery rates, if and how restoration is required, and underpin needs for habitat creation. There are moments in the trajectory of decline at which abrupt and usually catastrophic changes occur within seagrass ecosystems. These may occur when the feedback processes sustaining habitats break down. These are tipping points.
For example:
- As seagrass meadows fragment into small, isolated patches, the sheer stress on the plants increases disproportionally (currents increase, leading to more scouring of sediment and rhizomes and loss of plants), turbidity may increase, thereby limiting photosynthetic and growth rates, and there is less stable habitat present. When fragmentation exceeds a tipping point, features resisting the breakdown in these feedbacks (e.g. roots and rhizomes stabilising sediments) can no longer sustain the habitat and are lost.

- Under conditions that reduce photosynthetic rates or increase respiration (e.g. turbid water or high-water temperatures), seagrasses may make physiological modifications to optimise these processes, and they can also draw on stored reserves to sustain metabolism and growth. After these modifications have been exhausted and if the pressure remains, the plants reach a tipping point when they decline.

2.5. Monitoring data availability and trends

Seagrass monitoring is undertaken through the Queensland Ports Seagrass Monitoring Program (QPSMP), the Inshore Seagrass Marine Monitoring Program (MMP) for the Reef 2050 Paddock to Reef Program, Seagrass-Watch and monitoring at Clairview by the Mackay-Whitsunday-Isaac Healthy Rivers to Reef Partnership. Several monitoring programs are being established as collaborations among Traditional Custodians and scientists from various institutions, but there are no long-term data sets yet. Most monitoring is undertaken in the late dry season (especially September – November) when seagrass abundance and extent are expected to be at an annual maximum as it is towards the end of the growth season. Some monitoring also occurs at other times of the year, depending on location.

The focus of the long-term monitoring programs is inshore coasts and estuaries, where there is the most significant risk from ports and coastal development (QPSMP) and catchment run-off (MMP), and accessibility and safety, especially for Seagrass-Watch (Figure 3). The spatial extent of monitoring varies among programs.
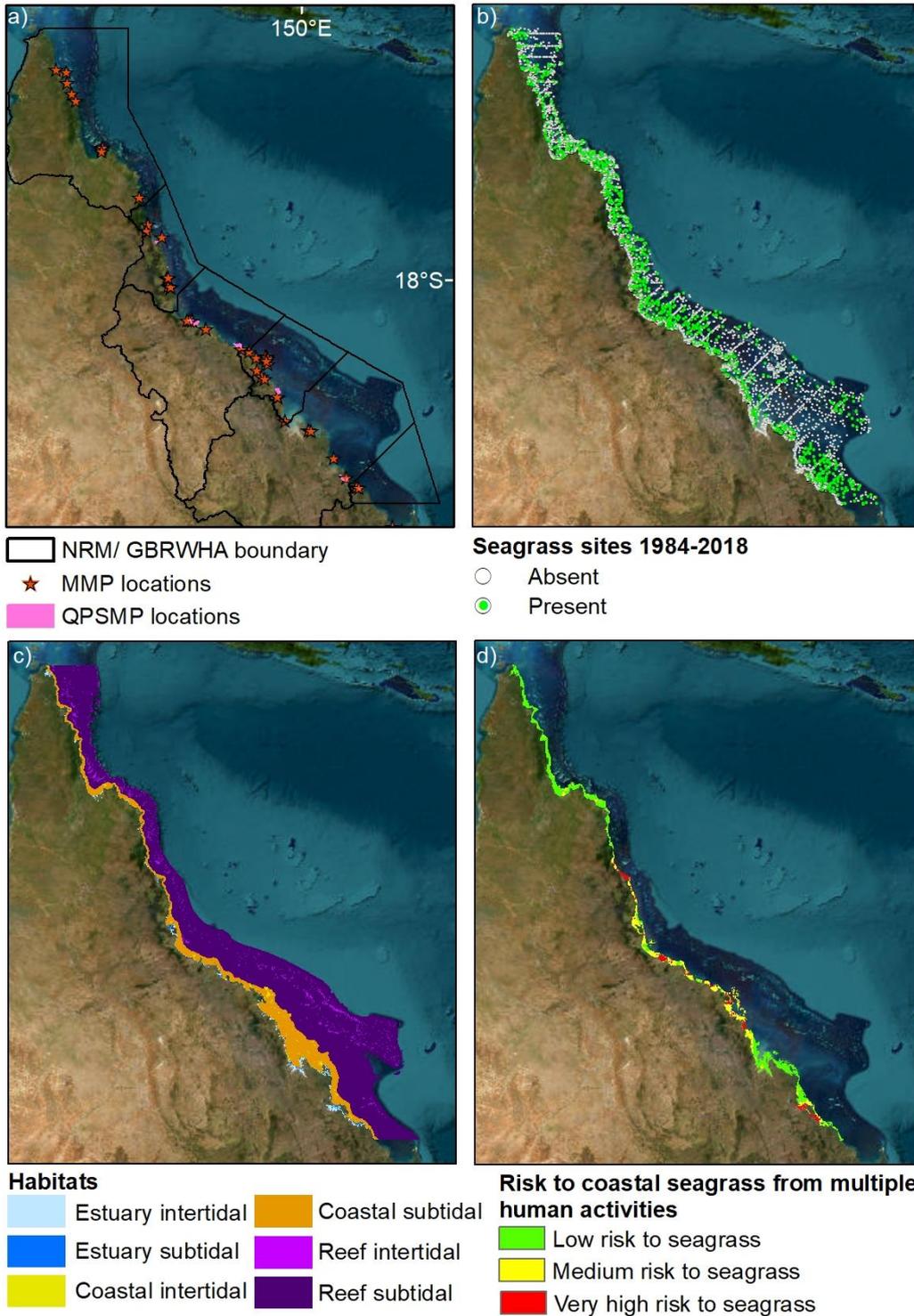
Figure 3 Data sets that are used in the Restoration Roadmap including a) monitoring data (Queensland Ports (QPSMP) and Marine Monitoring Program (MMP)) b) seagrass distribution data (seagrass composite of seagrass presence/absence) (from Carter et al 2021), c) habitats based on water bodies (f1) d) risk assessment (Source: Grech et al. 2011b)
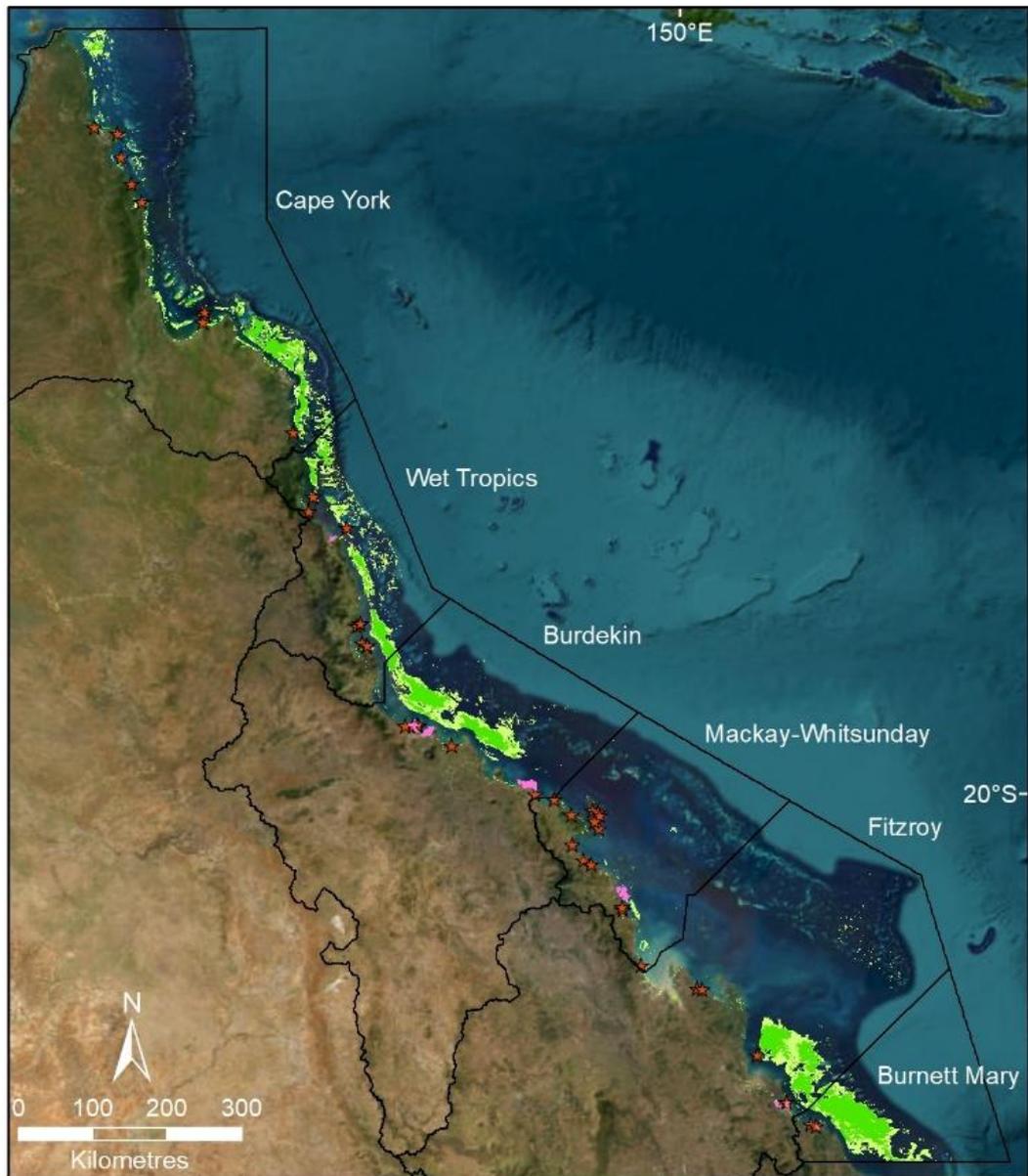
Figure 4 Probability of seagrass (habitat suitability) from 0.6 to 0.8 (light green) and 0.8 to 1.0 (medium green) (Carter et al 2021), QPSMP monitoring area and MMP locations (incorporating RJFMP and Seagrass-Watch sites) in six NRM regions. Full-page images of each panel are in the Appendix.

Queensland Ports Seagrass Monitoring Program

Survey methods follow the established techniques for the TropWATER Queensland-wide ports seagrass monitoring program (see Carter et al 2023). Intertidal meadows are sampled at low tide using a helicopter. GPS is used to record the position of meadow boundaries.

Seagrass presence/absence, biomass, and species composition are estimated from three replicate 0.25 m^2 quadrats placed randomly within a 10 m^2 circular area while the helicopter maintains a low hover. Sites are randomly scattered within each meadow. Shallow subtidal meadows are sampled by boat using an underwater video camera, and van Veen grab. The camera frame serves as a 0.25 m2 quadrat with three replicate quadrats per site, and the video footage is analysed in real-time using CCTV on the boat. Sites are located along transects perpendicular to the shoreline at ~50 - 100 m intervals, or where significant changes in bottom topography occur, and extend to the offshore edge of each seagrass meadow. Annual report cards are produced for all monitoring locations with meadow conditions based on three indicators: meadow area, biomass and species composition.

Inshore Seagrass Marine Monitoring Program (MMP) and Seagrass-Watch (SW)

The MMP includes 47 sites and SW 57 sites across the six NRM regions in estuaries, coasts and reefs. Each site is a 5.5-hectare area intertidally and 3.1 hectares subtidally. In the centre of each site a 50m x 50m relatively homogeneous area (low variability, even topography) in each seagrass meadow is established. Three replicate 50 m long transects are laid parallel, 25 m apart and perpendicular to the beach. Globally standardised measures are recorded from 33 quadrats (0.25m2) along the transects, including seagrass percent cover, species composition, canopy height and other benthic organisms. For each quadrat, the per cent cover is estimated with standardized per cent cover photographs and the per cent contribution of individual species to total cover (species composition). Seeds are measured in 30 50mm cores; at MMP sites, reproductive status is assessed in 15 100mm cores from within the site. The 5.5 ha site is also mapped. The MMP also reports on data collected by the Reef Joint Field Management Program (QPWS) for subtidal seagrass, which uses a similar method to the TropWATER subtidal block seagrass monitoring program (drift camera drops) and Seagrass-Watch for intertidal seagrass. Environmental pressures are also measured at most MMP sites (light, temperature, sediment). The MMP seagrass report card is based on abundance and a resilience index (incorporating species, reproductive effort, and seagrass condition (Collier et al. 2021a).

Drones are used to a limited extent in several programs but are not routinely used in report cards or for reporting on trends. However, they offer promise for fine-scale mapping, such as restoration and measuring fragmentation (James et al. 2020, Yang et al. 2020, Karang et al. 2024).

3. SEAGRASS RESTORATION IN THE GBR

The Kunming-Montreal Global Goals for 2050 COP15 aim to have restoration activities completed or underway in at least 30% of degraded terrestrial, inland waters, coastal, and marine ecosystems. This goal emphasizes the urgent need for concerted action to preserve and rehabilitate these crucial environments. Prevention is often better than cure and the protection of healthy seagrass meadows continues to be a priority, however, a recent study examining the levels and achievable targets for the protection of seagrass showed that protection alone would only provide a 1% gain in seagrass by 2050, versus a 35% gain where protection was combined with restoration (Buelow et al. 2022).

The push for seagrass restoration has gained significant traction recently due to several key reasons. People are increasingly recognising its importance in storing blue carbon, providing habitats for fish, offering offsets for biodiversity loss linked to development projects, and safeguarding endangered species like turtles and dugongs. Additionally, there's a growing

sense of urgency to recover from and address the impacts of various stressors. While we used to be concerned mainly about localized issues such as anchor damage, nutrient pollution, and land reclamation, the bigger threat now is the widespread loss of entire seagrass meadows due to climate change-induced factors like severe storms and rising temperatures. This highlights the critical need for effective restoration efforts that tackle both the direct and indirect threats facing seagrass ecosystems.

Decisions for restoration are usually made based on the past occurrence of a specific seagrass species at a particular location, which relies on robust historical data. In tropical and subtropical systems found in the GBR, where many seagrass meadows are transient, and the distribution is highly dynamic, identifying an area where seagrass has been permanently lost is difficult without long-term data. In areas where the natural environment has been significantly modified, some seagrass areas may be lost permanently (e.g. through land claim) or have become unsuitable for growth. Equally, areas may exist where seagrass has not previously been recorded, but habitats may be suitable.

3.1. Seagrass restoration approaches

Restoring seagrass habitats is essential to mitigate seagrass losses and promote vital ecosystem services, including habitat for threatened and endangered species (e.g., sea turtles, dugongs), coastal protection from storms and erosion, and improved water quality in coastal estuaries through the sequestration of nutrients and trapping of sediments. Various seagrass restoration techniques have been developed and trialed worldwide on a small scale (limited to a few hectares) and have varying degrees of success. It is important to note that the success of seagrass restoration is dependent upon the location and environmental conditions of the restoration site, existing environmental stressors, target seagrass species, and restoration techniques (van Katwijk et al. 2009, Cunha et al. 2012). Methods have previously focused on transplanting mature shoots from a donor meadow to an area of interest for restoration. This approach has been largely successful (reviewed in van Katwijk et al. 2016), and its advantages consist of increased survival with larger size transplants, maintained associated infauna communities, and the ability to hold, store, and grow seagrass in nurseries (Table 1). However, transplantation can be expensive to upscale, cause damage to roots and rhizomes of harvested plants, and damage donor meadows by removing large amounts of plant material. Thus, seedling and seed-based restoration techniques are emerging to increase scalability with lower costs and reduce harm to donor meadows, with the added benefit of more easily maintaining genetic diversity. However, success has been highly variable, and there are bottlenecks related to seed dormancy and germination, as well as difficulties collecting enough seed material for large-scale restoration (Table 1).

Table 1 The advantages and disadvantages of seagrass restoration methods and examples of how seagrass nurseries can be beneficial to restoration projects using vegetative plant and/or seed material are presented. The percentage of studies included in the review that used each seagrass restoration method is given.

Method	Advantage	Disadvantage	Nurseries
Transplanting plugs/cores (25%)	Maintain associated fauna. Survival increases with size but so does cost.	Damage to donor meadows. Expensive to collect, store and plant out.	Holding / storage Grow-out / hardening. Avoid/reduce donor damage
Seedlings (3%)	Bypassing germination issues.	Require aquaculture facilities; vulnerable to damage	Grow from seed
Bare root sprigs (23%)	Ease of collection and temporary storage. Removal of any potential parasites, disease or bioturbators.	Damage to roots and rhizomes, lose potential mutualistic relationships, change rhizosphere biochemistry	Storage/holding e.g. drift cast. Grow sprigs
Turf/mats (13%)	Easier to handle larger sized units.	Lose potential mutualistic relationships, change rhizosphere biochemistry	Holding, grow-out. Avoid/reduce donor damage
Enhancement / facilitation (30%)	Low cost, no damage to donor meadows.	May disrupt natural hydrodynamics, dependency.	Research
Seeds (6%)	Reduced damage to donor meadow. Easier to manage genetic diversity.	Seed herbivory, dormancy, germination bottlenecks, collection difficulties	Production, native spathe fruit holding

31

There is an estimated 5.5% loss of seagrasses across Australia since the 1930s (Statton et al., 2018). The Great Barrier Reef (GBR) contains one of the world's largest seagrass ecosystems with 88,331 km^2 of potential seagrass habitat (Carter et al. 2021), yet seagrass meadows within the GBR are also declining in extent (Coles et al. 2015). In a recent analysis of desired state for different community types and the long-term trends in biomass (1995-2018), most estuary and coastal community types had failed to reach desired state in the last few years of the data set (Carter et al 2021). Although there has been increased intervention to restore seagrass habitats in recent decades, there is currently no comprehensive review of restoration activities focused on seagrass species found within the GBR. To summarise seagrass restoration efforts on species found within the GBR, occurring both within and outside of Australia, and to highlight restoration methodologies implemented within the GBR, we systematically reviewed the literature and describe how restoration efforts are designed and conducted.

We conducted a search to capture past and current studies on seagrass restoration efforts for species found within the Great Barrier Reef (GBR). We performed a literature search on 14 February 2024, using the *ISI Web of Knowledge* (www.webofknowledge.com) and *Scopus* (www.scopus.com) databases, and the following search term: (seagrass* OR eelgrass* OR "turtle grass" OR "manatee grass" OR "shoal grass" OR "sea grass" OR "SAV" OR "submerged aquatic vegetation" OR "*Cymodocea*" OR *"Enhalus"* OR *"Halophila"* OR *"Halodule"* OR *"Syringodium"* OR *"Thalassia"* OR *"Thalassodendron"* OR *"Zostera"*) AND (restor* OR rehabilitat*). We had no restriction on publication date and found 2,784 articles after excluding duplicates. We used the PRISMA protocol to determine relevance of each article, first by examining the title, and then the abstract of articles whose titles were relevant. After gathering a comprehensive list of potentially relevant articles, we assessed all remaining articles at the whole-paper level. We only included papers that detail restoration efforts on seagrass species found within the GBR, located within and outside of Australia. However, we acknowledge that our search only captures peer reviewed published literature and does not include ongoing, unpublished restoration efforts occurring within the GBR. To fill this gap, we provide information on ongoing, well-known, and documented restoration projects within the GBR that have yet to be published.

A total of 64 studies across 35 papers were included in this review, in addition to three ongoing restoration projects in the GBR not yet published (Table 2). Most restoration studies occurred in Australia (50%), followed by Indonesia (28%), India (18%), and New Zealand (4%). Of the 15 seagrass species found within the GBR, 12 species were considered in restoration projects. *Nanozostera muelleri* was the most common species used in restoration efforts (45%). The restoration technique used most often for *Nanozostera muelleri* was transplanting plugs (31% of all *Zostera* studies). No studies considered restoration of *Halophila minor*, *Thalassodendron ciliatum, or Halophila capricorni.* Transplanting mature seagrass (i.e., sprigs, shoots, sods, turfs, and plugs) was the most common restoration method across all studies (94%), followed by seeds (6%) and seedlings (3%; Table 2) Note that some studies used multiple methods and assessed multiple species in their restoration efforts, and therefore the total percent of methods and species across studies can be greater than 100. An ARC Linkage grant on *Future proofing and restoring Australia's tropical seagrasses* (Rasheed et al) is researching reproduction and restoration techniques for as many of the tropical species as possible (except *N. muelleri* and *H. ovalis*) but with an initial focus on *H. uninervis* and *T. hemprichii*.

	Nanozostera muelleri	*Thalassia hemprichii*	*Syringodium isoetifolium*	*Halophila decipiens*	*Halophila tricostata*	*Halophila ovalis*	*Halophila spinulosa*	*Halodule uninervis*	*Halodule pinifolia*	*Enhalus acoroides*	*Cymodocea rotundata*	*Oceana serrulata*	Australia	New Zealand	India	Indonesia
Sprigs	5	1	4	0	0	0	0	0	0	2	0	3	3	2	9	1
Sods	4	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0
Turfs	4	1	0	1	1	0	0	0	1	0	0	0	7	0	1	0
Plugs	9	1	1	0	0	2	1	0	0	0	0	1	12	0	3	0
Shoots	4	3	2	1	1	2	0	2	0	5	2	0	7	0	0	15
Seedlings	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2
Seeds	4	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
Not specified	4	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
Australia	26	1	0	1	1	2	1	0	0	0	0	0	-	-	-	-
New Zealand	3	0	0	0	0	0	0	0	0	0	0	0	-	-	-	-
India	0	2	4	0	0	0	0	0	1	1	0	3	-	-	-	-
Indonesia	0	2	2	0	0	2	0	2	0	8	2	0	-	-	-	-
Large-scale efforts (≥ 1 ha)	3	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
Small-scale efforts (<1 ha)	26	5	6	1	1	4	1	2	1	9	2	3	22	1	4	8

Across all restoration efforts included in this study, 10 studies were conducted within the GBR (16%; Table 2). *Nanozostera muelleri* was the most common species studied (70%), followed by *Thalassia hemprichii* (1%), *Halophila decipiens* (1%), and *Halophila tricostata* (1%; Table 2). The most common seagrass restoration methods implemented in the GBR were transplanting turfs (50%) and individual shoots (50%). Methods using seeds (30%), plugs (20%), and sprigs (10%) were less common (Table 3**Error! Reference source not found.**). Only three restoration trials are considered large-scale (≥ 1 ha), and are currently ongoing (results are not yet published) in Gladstone Harbour, Mourilyan Harbour, and Pioneer Bay (Table 3). All three trials are with *N. muelleri*, using seeds and springs for restoration. Despite being the most widespread of the strap-leaved seagrasses, there have been no restoration studies on *H. uninervis* in the GBR to, date and only two studies were found in the literature search on restoring *H. uninervis*.

Our approach for the systematic literature search only captured peer reviewed studies because of the assumption that undergoing a peer-review process is preferred prior to using data to develop hypotheses or include in broader studies. We acknowledge that a limitation of this review, therefore, is that grey literature (e.g., government reports) might not have been captured in the search. However, peer-review is regarded as a gold standard for quality control and a standard for reviews because it provides systematic criteria for literature searches.

Table 3 Seagrass restoration efforts conducted within the Great Barrier Reef World Heritage Area in Queensland, Australia. Note that some studies assessed multiple restoration methods, so the sum of studies across individual methods may be greater than the total number of studies listed per species.

Species	Number of studies	Small-scale trial (< 1 ha)	Large-scale trial (≥ 1 ha)
Nanozostera muelleri	**7**	**4**	**3**
Turfs	2	2	0
Plugs	2	2	0
Shoots	2	2	0
Sprigs	1	0	1
Seeds	3	0	3
Thalassia hemprichii	**1**	**1**	**0**
Turfs	1	1	0
Shoots	1	1	0
Halophila decipiens	**1**	**1**	**0**
Turfs	1	1	0
Shoots	1	1	0
Halophila tricostata	**1**	**1**	**0**
Turfs	1	1	0
Shoots	1	1	0
Total number of studies	**10**	**7**	**3**

3.2. Seagrass nurseries

Successful large-scale seagrass restoration requires large quantities of donor material for successful outcomes. Aquaculture systems as a restoration tool (e.g., seagrass nurseries) can increase seagrass seed and plant yields for use in restoration efforts while minimising impacts to donor meadows and maintaining genetic diversity in restored meadows (van Katwijk et al. 2021). Seagrass nurseries can ultimately increase the scale at which seagrass meadows can be restored. Nurseries can be used to produce seed material, grow seedlings, and hold native spathe material collected from donor meadows. However, they have applications across the range of seagrass restoration techniques and species (Table 1). For example, naturally detached rhizome fragments of *Posidonia australis* collected through a citizen science project were stored in aquaria tanks in New South Wales before transplanting into mooring scars (Ferretto et al. 2021). In a study in Gladstone, growing out of wild-collected cores in seagrass nurseries for three months positively influenced transplant survival.

Terrestrial native seed production areas (SPAs) are critical for land-based restoration (Zinnen et al. 2021). Similarly, seed production for seagrass restoration has been identified as a vital component for restoring seagrass at scale, though not all species are suitable (van Katwijk et al. 2021). Highlighting target species ideal for domestication considers maximum seed production potential, harvestability, and life cycle period (van Katwijk et al. 2021). There are four seagrass species found within the GBR that have a high potential for domestication and rewilding (i.e., self-sustainable restoration), including *Halophila decipiens*, *Halophila tricostata*, *Nanoostera muelleri*, and *Halodule uninervis* (van Katwijk et al. 2021; Figure 5). Where possible, these species should be targeted in large-scale restoration efforts and mariculture activities to further enhance the scalability of restoration, with a focus on *Nanoostera muelleri* and *Halodule uninervis*.
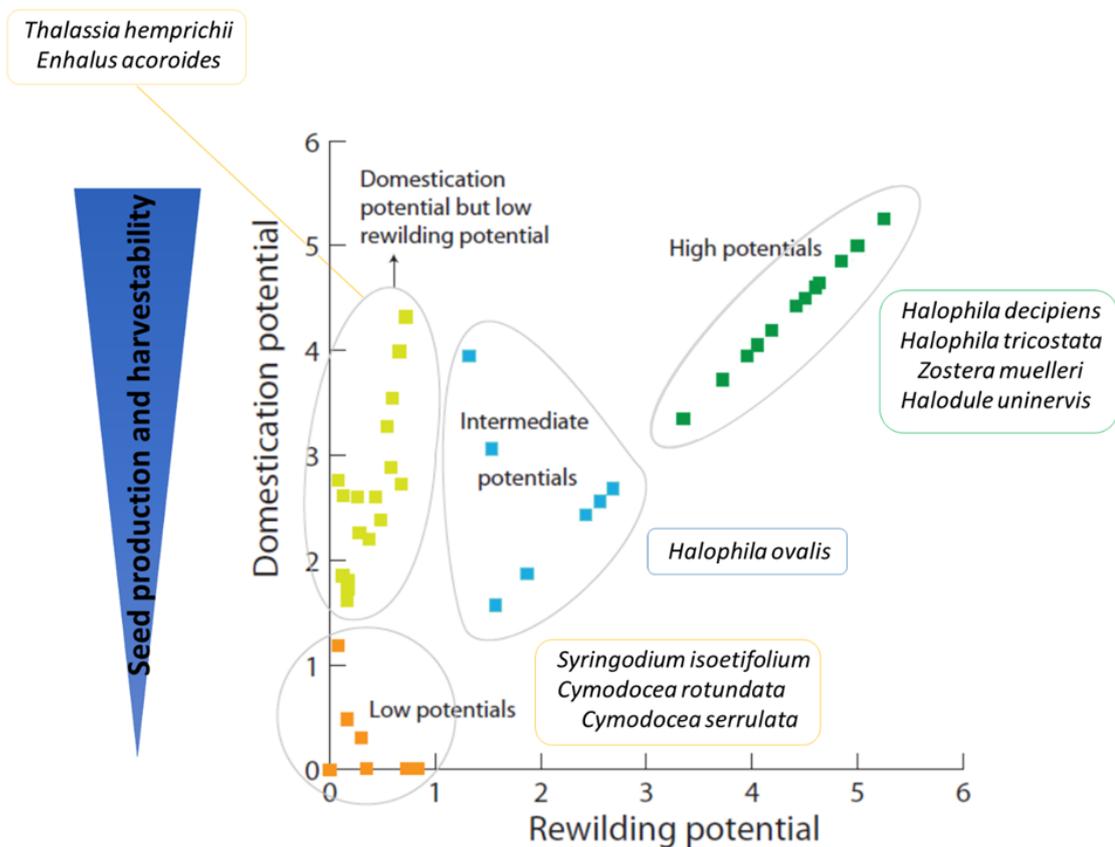
Figure 5 Potential for domestication and rewilding of seagrass species, determined by maximum seed production, harvestability, and life cycle. Example species are given within each low, intermediate, and high potential grouping. Four species found within the Great Barrier Reef are identified as having high potentials for rewilding and domestication (i.e., species that have high seed production and harvestability), including Halophila decipiens, Halophila tricostata, Nanozostera muelleri, and Halodule uninvervis *(modified from van Katwijk et al. 2021).*

Opportunities for use of existing infrastructure for seagrass nurseries

Existing infrastructure that can be used to establish seagrass nurseries along the Queensland coastline should be considered when identifying priority areas for large-scale seagrass restoration in the GBR region. There are currently three seagrass nurseries in Gladstone, Konomie (North Keppel) Island, and Airlie Beach, and one nursery is currently under construction in Cairns. To identify existing infrastructure along the GBR region that could be utilised for seagrass nursery operations, we conducted a search of existing seagrass nurseries, marine and aquaculture research centres, aquaria, sea turtle rehabilitation centres, hatcheries, fish and prawn farms, and terrestrial plant nurseries from Cape York to Urangan, Queensland. Google Earth satellite and aerial imagery was used to identify locations of the aforementioned facilities, which were then confirmed using Google Maps. A separate search was conducted to identify all universities with research facilities, and aquaria, along the GBR coastline, which were then located on Google Earth. We were limited by available Google Earth imagery that ranged from 2013 to 2022 and, therefore, the location and current state of some of the facilities (e.g., fish and prawn farms) might not be current. Additionally, we only considered facilities found within 10 km of the coastline.

We identified 92 locations with existing infrastructure that could be used for, or converted to, seagrass nurseries (Figure 6). We classified each location across six levels of opportunity (1 = highest, 6 = lowest), based on the type of infrastructure and existing resources (e.g. seawater supply), the ease of incorporating a seagrass nursery (based on practical aspects alone), and proximity to the coastline (Table 4). We identified 16 sites classified as level 1 and 2 opportunities (Table 5).
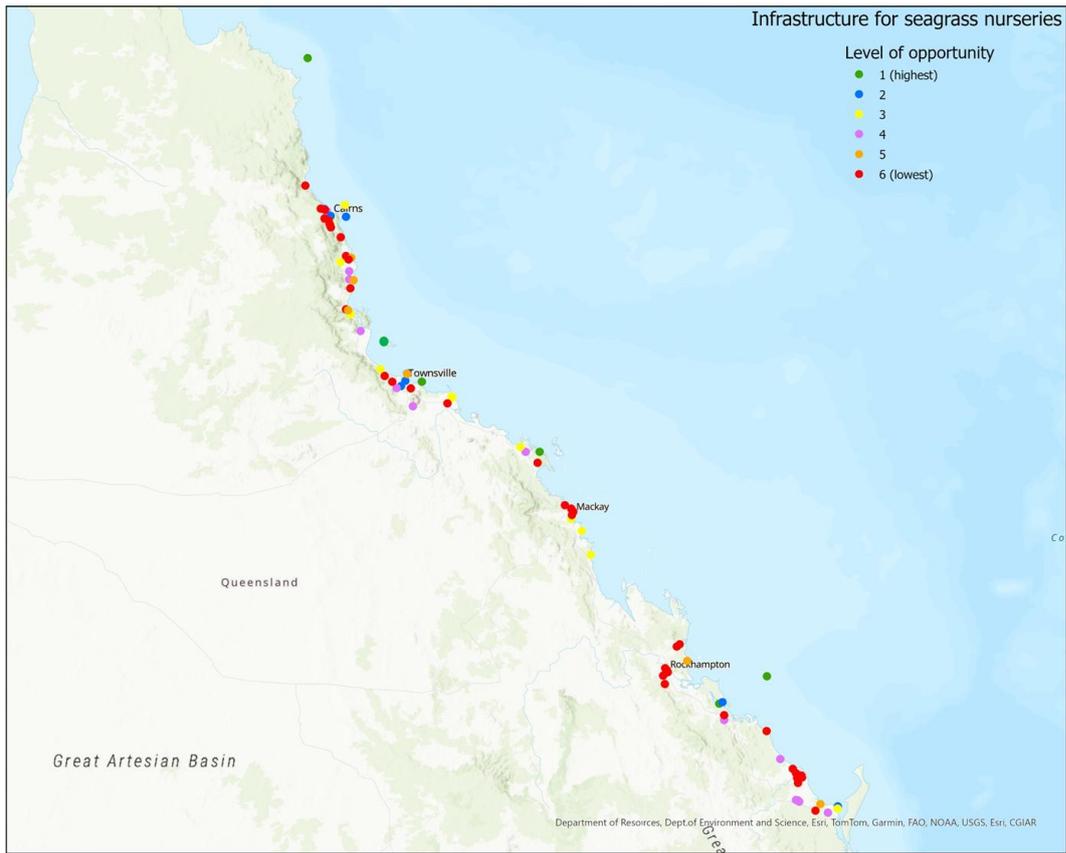
Figure 6 Map of existing infrastructure along the coastline of the Great Barrier Reef region that provides opportunities for creating seagrass nurseries in priority locations for large-scale seagrass restoration. Site are classified across opportunity levels (1 = highest, 6 = lowest) based on ease of converting the facility to a seagrass nursery and proximity to the coastline.

Table 4 Classification of existing infrastructure along the coastline of the GBR region that could be utilised for or converted to seagrass nurseries to support large-scale restoration efforts. Level of opportunity ranges from 1 (highest) to 6 (lowest) based on ease of converting the site to a seagrass nursery and its proximity to the coast.

Level of opportunity	Description
1	Existing seagrass nursery, marine research institute, located < 1 km from the coast (coastal)
2	Existing marine or aquaculture research and/or laboratory facility, marine aquarium, sea turtle rehabilitation centre, located > 1 km from the coast (inland)
3	Fish or prawn farms, hatcheries, and other aquaculture facilities, located < 1 km from the coast (coastal)
4	Fish or prawn farms, hatcheries, and other aquaculture facilities, located > 1 km from the coast (inland)
5	Existing terrestrial plant nurseries, located < 1 km from the coast (coastal)
6	Existing terrestrial plant nurseries, located > 1 km from the coast (inland)

Table 5 Existing infrastructure highlighted as high opportunity (levels 1 and 2) for use as seagrass nurseries in the GBR region. Sites comprise current seagrass nurseries, marine and aquaculture research facilities, aquaria and/or marine education centres, and sea turtle rehabilitation centres.

Existing infrastructure	Location	Latitude	Longitude	Priority level	Notes
Lizard Island Research Station	Lizard Island	-14.678516	145.448392	1	marine research station, island
Australian Institute of Marine Science	Townsville	-19.267822	147.055693	1	marine research station, coastal
UQ Heron Island Research Station	Gladstone	-23.444249	151.911153	1	marine research station, island
Coastal Marine Ecosystems Research Centre, Gladstone SeaGrow	Gladstone	-23.831481	151.239754	1	marine research station, seagrass nursery, coastal
Coral Sea Marina seagrass nursery	Airlie Beach	-20.264136	148.713378	1	seagrass nursery, coastal
Konomie Island SeaGrow	North Keppel Island	-20.264136	148.713378	1	seagrass nursery, island
Orpheus Island Research Station	Townsville (offshore)	-18.564313	146.476524	1	aquarium and education centre, research station
Marine and Aquaculture Research Facilities Unit (MARFU), James Cook University	Townsville	-19.327842	146.760936	2	aquaculture research institute, inland
Reef Research Aquarium Laboratories	Townsville	-19.329046	146.760962	2	aquaculture research institute, inland
JCU eduQuarium	Smithfield	-16.816631	145.687382	2	aquarium and education centre, research station, inland
Cairns Aquarium	Cairns	-16.918249	145.773781	2	aquarium, coastal
Aquasearch Aquarium	Magnetic Island	-19.152076	146.847308	2	aquarium and research laboratory, island
Great Barrier Reef Aquarium	Townsville	-19.257339	146.823048	2	aquarium, coastal
Reef World Aquarium	Urangan	-25.288118	152.908405	2	aquarium, coastal
Fitzroy Island Turtle Rehabilitation Centre	Fitzroy Island	-16.927700	145.990562	2	turtle rehabilitation centre, coastal
Quoin Island Turtle Rehabilitation Centre	Gladstone	-23.811286	151.286204	2	turtle rehabilitation centre, coastal

3.3. Permitting considerations

Seagrass restoration initiatives within the Great Barrier Reef (GBR) region requires careful planning and compliance with regulations and permitting processes, which are site specific depending on whether the location is within the Great Barrier Reef Marine Park, State Marine Park, or Fish Habitat Area (FHA). These regulations encompass various aspects, including provisions outlined in the Fisheries Act 1994 in Queensland, designed to manage and safeguard fisheries resources, including seagrass beds (Bell-James et al. 2023). For instance, applications for Marine Plant disturbance must comply with Accepted Development procedures under Section 51 of the Fisheries Act 1994, which includes any collection of seagrass propagation material for restoration.

Permitting requirements for seagrass restoration projects can entail obtaining several approvals, such as development approvals, permissions to operate in fish habitat zones, authorizations for marine vegetation removal, Marine Parks permits, and approvals from the Resource Allocation Authority (Bell-James et al. 2023). A multitude of agencies are involved in overseeing these processes, including local government bodies, the Department of Resources, the Department of Agriculture and Fisheries (DAF), Queensland Parks and Wildlife Service (QPWS), the Department of Environment, Science and Innovation (DESI), and the Great Barrier Reef Marine Park Authority (GBRMPA) (Bell-James et al., 2023). However, complexities arise due to the required permits and the potential for conflicting guidance from different agencies involved in the process.

Shumway et al. (2021) identified that increased transparency and better integration into coastal policy as crucial areas for enhancing coastal restoration efforts in Australia. They recommended streamlining and improving the adoption of coastal and marine restoration by addressing several key issues. Firstly, Australia lacks a national coastal management legislation or policy framework, leading to fragmented implementation predominantly at the state and territory levels. This decentralised approach hampers the coordination and consistency necessary for large-scale restoration endeavours. Moreover, the permitting process in Queensland is intricate, varying based on location, activity type, and the department overseeing the application process. Streamlining the process and assigning marine restoration policy and legislative responsibilities to a single department could enhance efficiency and reduce complexity.

The involvement of multiple government departments, including fisheries, environment, and planning, in Queensland's marine restoration policy complicates matters further, resulting in conflicting advice and shared responsibilities. Integrating large-scale coastal restoration projects into conservation and coastal planning activities could facilitate a more cohesive approach. Despite the recognised importance of coastal restoration, significant barriers persist, particularly concerning permitting criteria and approval processes.

Maritime Safety Queensland (MSQ) oversees maritime safety regulations and may require approvals or permits for restoration activities that could impact navigation or pose risks to maritime traffic. Projects near coastal areas may also necessitate approvals from local councils to ensure compliance with zoning regulations, land use planning, and other environmental considerations. Furthermore, projects located within port areas may require approvals from port authorities to address potential impacts on port operations, shipping channels, and infrastructure. Collaborating with these agencies ensures that seagrass restoration efforts are conducted in a manner that prioritises safety, minimises risks to maritime navigation, and adheres to relevant regulations and guidelines.

Furthermore, stakeholders engaging in seagrass restoration projects must prioritise involvement with Traditional Owners and other relevant parties to address cultural and traditional concerns, ensuring adherence to the principles of Free, Prior, and Informed Consent. This engagement is essential, upfront, for fostering collaboration, respecting traditional knowledge, and promoting sustainable restoration practices that align with cultural values and heritage.

As part of the National Environmental Science Program (NESP) Marine and Coastal Hub, Saunders et al. (2022) developed a Roadmap for Coordinated Landscape-scale Coastal and Marine Ecosystem Restoration. The roadmap highlighted the complexity, lack of clarity, and variation across local and state governments in the permitting process, which was often described by the survey's respondents as overly difficult, lengthy, and expensive. Permitting criteria, the lack of an overarching national framework and approval processes were identified as major barriers to scaling restoration, with a national framework being designed for grey infrastructure projects and poorly suited to restoration projects.

3.4. Habitat suitability modelling

Habitat suitability models can be used to indicate where seagrass habitat could occur particularly in data poor areas that have not been thoroughly surveyed and are consulted as a step in the restoration roadmap. Various environmental and biological variables influence seagrass distribution, with species specific thresholds requiring separate habitat modelling for each species. For example, depth influences light attenuation and current and wave near-bed velocities. Seabed slope impacts on rhizome elongation, sediment stability and meadow size. The minimum limit in current velocity relates to oxygen availability. Maximum current velocities in seagrasses are a result of mechanical disturbance, with sediment re-suspension and erosion rates being greater than the seagrasses' ability to bind sediment and baffle currents. Seagrass has a high light requirement ranging from 10 to 37% of SI (surface irradiance). A two-week rolling average of 6 mol photons m^2d^1 has been identified as the requirement for *Zostera muelleri* (considered to be a highly light sensitive species)(Chartrand et al. 2016).

Recent seagrass data consolidation (Carter et al 2021) and greatly improved biophysical environmental data layers (both sampled and modelled, e.g. eReefs) provided an opportunity to classify seagrass habitat in more detail than previously possible and, for the first time, to describe seagrass community types throughout the GBRWHA (Carter et al 2021). There is now available a compilation of 35 years of seagrass surveys, and GBRWHA-wide spatial models of environmental conditions.

Using these data potential seagrass community extent was quantified using six random forest models that include environmental data and seagrass sampling history. 88,331 km^2 of potential seagrass habitat in intertidal and subtidal areas: 1,111 km^2 in estuaries, 16,276 km^2 in coastal areas, and 70,934 km^2 in reef areas were identified. Thirty-six seagrass community types were defined by species assemblages within these habitat types using multivariate regression tree models. The structure, location and distribution of the seagrass communities was the result of complex environmental interactions. These environmental conditions include depth, tidal exposure, latitude, current speed, benthic light, proportion of mud in the sediment, water type, water temperature, salinity, and wind speed.

Other more localised habitat suitability models currently exist for the Whitsundays (Jackson et al., 2020), Gladstone (Jackson et al., submitted), The Keppel Islands (Aiken et al. unpublished), Lizard Island (Saunders et al., 2014; Callaghan et al., 2015) and Cleveland Bay

(Petus et al., 2014). Table 6 provides examples of existing habitat suitability models for the GBR.

Table 6 Summary of seagrass habitat suitability models for the GBR.

Location	Species	Year	Environmental Variables	Resolution (m)	Citation
Lizard Island	*Thalassia hemprichii, Halodule uninervis and Halophila ovalis*	2014	Wave parameters (wave height, peak period and benthic wave orbital velocity)	5	Saunders et al, 2014; Callaghan et al, 2015
Cleveland Bay	*Halodule uninervis, Halophila spinulosa, Zostera muelleri, Cymodocea serrulata, Halophila ovalis and Halophila decipiens*	2014	type of turbid water	250	Petus et al 2014
Whitsunday Islands	*Thalassia hemprichii, Halodule uninervis, Halophila ovalis and Zostera muelleri)*	2020	Bathymetry, slope, near bed velocity, temperature, salinity, turbidity, EpiPAR, DIP, DIN.	200	Jackson et al 2020
GBRWHA and adjacent estuaries	*Cymodocea rotundata, Cymodocea serrulata, Enhalus acoroides, Halophila capricorni, Halophila decipiens, Halophila ovalis, Halophila spinulosa, Halophila tricostata, Halodule uninervis, Syringodium isoetifolium, Thalassia hemprichii, and Zostera muelleri*	2021	Bathymetry, tidal exposure, latitude, current speed, benthic light, proportion of mud, water type, water temperature, salinity, and wind speed	==RESOLUTION==	Carter et al 2021
Port Curtis and Rodds Bay (Gladstone Harbour)	*Zostera muelleri*	2020	Bathymetry, slope, near bed velocity	100	Jackson et al 2020

3.5. Methods for assessing risk

Spatial risk assessments are an important GIS decision-support tools in prioritizing seagrass restoration by identifying areas where restoration intervention is likely to be most effective. They can assist in evaluating the risk to seagrass by combining spatial data on species distribution and anthropogenic impacts to identify sites of overlap, and determine the consequences or the effects of an adverse event; and the likelihood or probability of the event occurring (Grech et al. 2011a).

Existing reviews of the risk of disturbance for seagrass in the GBR highlight various threats and their impacts on seagrass ecosystems. Studies emphasize the significance of river runoff, flood plumes, maintenance dredging, and cumulative disturbances on seagrass meadows. River plumes are identified as a major source of land-sourced contaminants affecting seagrass health. Collier and Waycott (2009) reviewed key processes explaining the distribution, variability and limitations to growth in seagrass meadows of the Great Barrier Reef to recognise ecosystems under stress and when management actions may be required. Coles et al. (2011) combined geospatial data with qualitative measures of the vulnerability of seagrass habitats from multiple threats and evaluated the risk to seagrass at a local and regional scale. Grech et al. (2011a) examined the risk to coastal marine habitats from cumulative threats as an alternative approach by identifying sites that are exposed to multiple anthropogenic threats at broad scales. They combined qualitative measures of vulnerability with geospatial data to evaluate the risk to coastal seagrasses at the scale of the Great Barrier Reef.

However, a limitation in current risk assessment methodologies is the lack of recent, broad-scale analysis for seagrass disturbance, with the most comprehensive analysis being over a decade old (Grech et al., 2011a). Moreover, existing risk assessments often do not fully encompass the risks associated with climate change, such as increasing sea temperatures, ocean acidification, and more frequent extreme weather events like cyclones. Incorporating these factors into future risk assessments will be essential for developing effective management strategies to safeguard seagrass ecosystems in the face of ongoing environmental challenges.

To update risk assessments for seagrass disturbance in the GBR, various data sets and sources could be utilised. The Scientific Consensus Statement (Waterhouse et al. 2017) provides valuable insights and recommendations for enhancing the understanding of seagrass ecosystems in the region. Some data sets that can be leveraged to update risk assessments include information on coastline erosion from Digital Earth Australia (DEA), coastal adaptation data from Coast Adapt (https://coastadapt.com.au), regional Coastal Hazard Adaptation Strategies (CHAS) and climate change projections, including sea level rise and changes in rainfall patterns. Additionally, data on land use, tidal exposure, and eReefs data such as temperature, wind speeds, and current speeds could contribute to a comprehensive risk assessment framework.

4. PRIORITISATION OF INTERVENTION SITES

The Great Barrier Reef, World Heritage Area, spans over 348,000 square kilometres, with a potential seagrass habitat area surpassing coral. Monitoring such a large region is expectedly limited to select sites, and while these sites are representative of larger patterns, significant areas remain unmapped and unmonitored. Identifying and prioritising restoration efforts poses challenges, and waiting for complete data is not viable given the urgency of preserving sensitive habitats. Thus, we propose a pragmatic, large-scale approach to prioritise seagrass

habitat restoration in the GBR, emphasising vulnerabilities due to disturbance risk and data gaps. We gathered the best available information, acknowledging potential outdatedness, to develop a roadmap for seagrass meadow restoration. It is important to note caveats and limitations throughout the text.

The decision tree in Figure 7 illustrates the first steps in the selection of locations based on the availability of data on the resolution of that data. Locations were first split into those where monitoring data was available, even if this was just one-off mapping and those where no monitoring data was available, even presence-absence data. We first needed to look at those locations where, despite a lack of monitoring data, broad-scale habitat suitability models based on Carter et al. 2021 (Figure 3, Appendix 1) suggest that the habitat is suitable for seagrass species. We propose that those areas where the habitat is not suitable for seagrass, based on the modelling, and no monitoring or distribution data exist, are not a priority for restoration or mapping. Locations where there is no monitoring data, but habitat suitability is high (here we used a probability threshold of 0.6 probability) should be further assessed to examine the risk of disturbance. Allocation with no data high probability of suitable habitat and where the risk of disturbance is high should be flagged as a priority for mapping and monitoring seagrass. Where the risk of disturbance is low even if there is a high probability of suitable habitat it is proposed that these locations are not a priority for restoration or mapping (Figure 3). Such an approach is proposed based on limited resources and does not propose that these locations are never mapped.

For locations where monitoring data was available, we looked at the resolution of that data, separating locations based on the frequency of data collection, which would allow an assessment of broad trends and the spatial resolution of the data to see whether individual meadows for intervention could be identified. For locations with low temporal resolution of data which we defined as less than five years of data within the last 10 years we propose querying this data to assess if there was a risk of disturbance (Figure 7), see section3.5. Where the frequency of monitoring data was high (more than five years of data in the last 10 years) we examined the trend by observing the data set and report narrative for the locations to identify if the seagrass was declining, increasing, or stable.

In reviewing data from sites with high-resolution temporal data for declining trends, eleven locations (ten within and one just outside of the GBR) were identified (see Table 7). Loss and degradation of seagrass is found across the GBR, and these locations by no means represent the only sites of concern in terms of restoration. Rather these eleven locations are areas where the monitoring data is available at a good enough resolution to make a strong case for targeting these sites for potential restoration activities in the immediate future. Funding opportunities for Blue Carbon and seagrass restoration usually require evidence of decline. For example, the recent round of Australian Government grants for Blue Carbon habitat restoration included a specific criterion on evidence that there was a need for restoration at the site. Biodiversity Offsets require data showing that an offset intervention would be providing a net gain in cover at a degraded site, and permits for habitat restoration require a knowledge base of previous condition and trend analysis to understand if habitats are likely to recover naturally, or if restoration is required, what is the target condition for restoration.

Traditional Owners, including Indigenous communities, have lived in and managed the Great Barrier Reef (GBR) region for thousands of years, possessing a deep cultural and spiritual connection to the land and sea. Their historical and traditional knowledge of the GBR ecosystem, including seagrass meadows, provides a unique perspective on what constitutes a healthy and thriving marine environment. When it comes to seagrass restoration, it is important to recognise that Traditional Owners may have a different baseline for restoration

compared to Western scientific or regulatory perspectives. Their baseline may be influenced by:

- » Historical Knowledge: Traditional Owners often have long-term knowledge of the natural variability of the environment, including changes in seagrass health over generations. Their understanding of a healthy ecosystem may extend beyond contemporary scientific benchmarks.
- » Cultural Significance: Seagrass meadows and other marine environments may hold special cultural, spiritual, or subsistence value for Traditional Owners. Their perception of restoration success might include not just ecological health but also the preservation of cultural heritage and traditional practices.
- » Holistic Approach: Traditional Owners often view ecosystems holistically, considering interconnectedness with other species, habitats, and cultural elements. This perspective can provide a broader and more nuanced view of what restoration should aim to achieve.
- » Collaborative Management: Traditional Owners may have their own practices and methods for managing seagrass meadows and other marine environments, based on centuries of experience. Collaborating with them can lead to more effective and culturally sensitive restoration projects.

Given these differing baselines and perspectives, it is essential to actively engage with Traditional Owners in the planning and implementation of seagrass restoration projects. This collaboration can involve:

- » Co-designing Projects: Involving Traditional Owners in the design of restoration projects to ensure that their knowledge, values, and priorities are integrated.
- » Mutual Learning: Facilitating the exchange of knowledge between Traditional Owners and marine scientists to combine traditional practices with contemporary restoration techniques.
- » Cultural Protocols: Respecting cultural protocols and practices, including those related to access, harvesting, and management of marine resources.
- » Shared Decision-Making: Allowing Traditional Owners to have an active role in decision-making processes and governance structures for restoration projects.

By acknowledging and incorporating the perspectives of Traditional Owners, seagrass restoration projects in the GBR can achieve more meaningful and sustainable outcomes that respect the cultural and ecological heritage of the region.
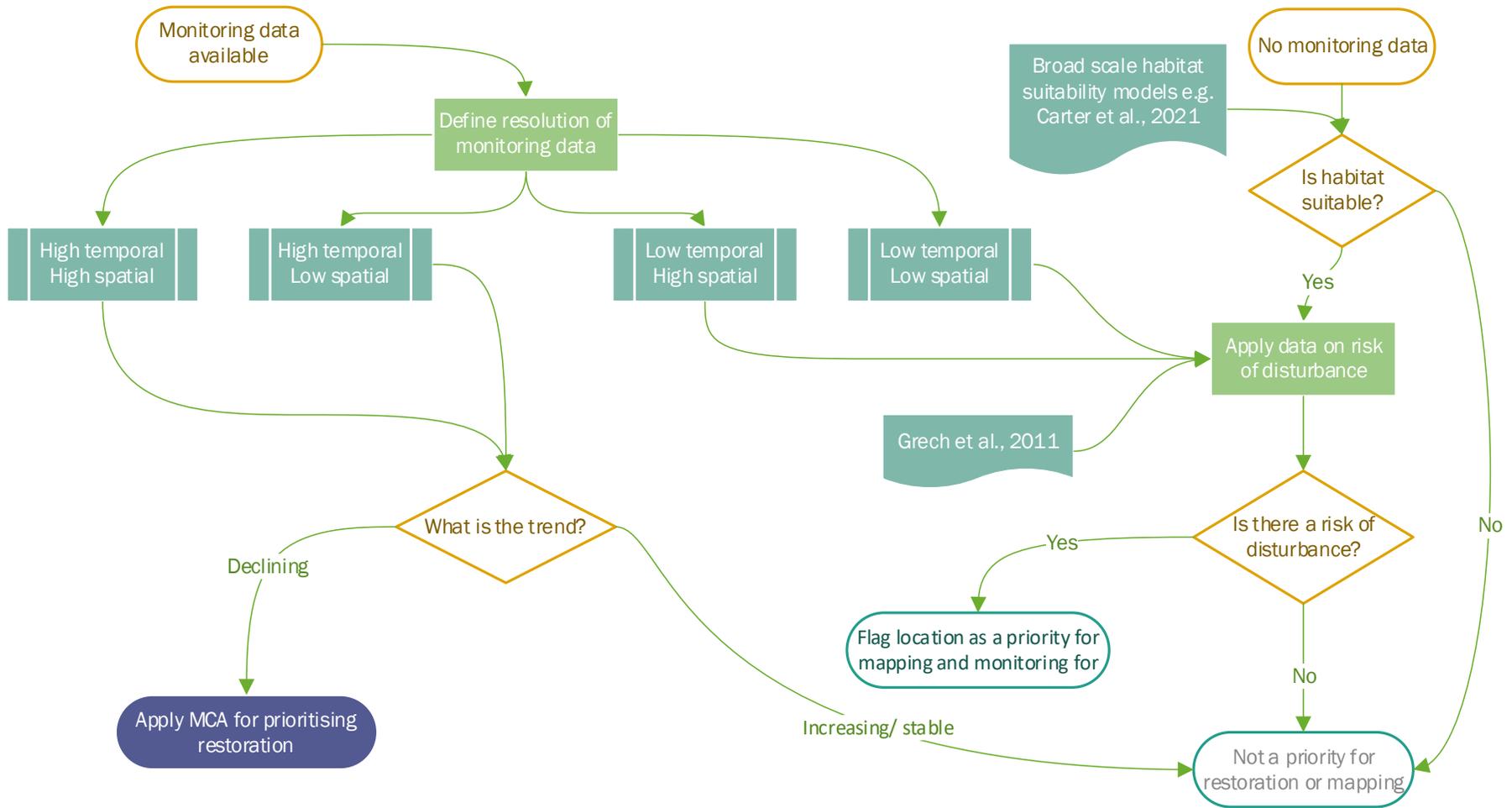
Figure 7   Decision tree for broad scale selection of locations for multiple criteria analysis.

The following text appears within the figure:

- Monitoring data available
- No monitoring data
- Define resolution of monitoring data
- Broad scale habitat suitability models e.g. Carter et al., 2021
- Is habitat suitable?
- High temporal High spatial
- High temporal Low spatial
- Low temporal High spatial
- Low temporal Low spatial
- Apply data on risk of disturbance
- Yes
- Grech et al., 2011
- What is the trend?
- Is there a risk of disturbance?
- No
- Declining
- Yes
- Flag location as a priority for mapping and monitoring for
- No
- Apply MCA for prioritising restoration
- Increasing/ stable
- Not a priority for restoration or mapping

Table 7 Summary of condition and trend for monitoring sites with high temporal resolution (MMP, QPSMP)

NRM region	Summary commentary	Recent decline (~5 years) 2021-22-23			Long-term trends*# Sites of concern		
		Estuary	**Coast**	**Reef**	**Estuary**	**Coast**	**Reef**
Cape York	Overall MMP abundance ranking of moderate in 2021-22. Only one site (Flinders Group subtidal) that had declined in 2021-22 but the data history isn't long enough to know whether this is part of inter-annual variation (McKenzie et al. 2023a). Overall abundance ranking of moderate in 2022-23. Two sites (Flinders Group subtidal and Bathurst Bay subtidal, which are nearby) were low in 2022-23 but the data history isn't long enough to know whether this is 'typical' inter-annual variation (McKenzie et al., 2024).(McKenzie et al. In Prep)Resilience is also low at Piper Reef and Shelburne Bay to the north. Piper Reef (FR2) has shown significant long-term decline (2012-2022), however the reason for the decline is unclear and the adjacent site (FR1) is stable. One site at Archer point (AP1) had shown long-term decline from 2003-2017 but monitoring ceased and the long-term trend cannot be assessed.						Piper Reef (FR2)
Wet Topics	There are no MMP sites in the northern Wet Tropics that were of concern in 2021-22 or 2022-23 (Low Isles subtidal declined in 2023 but is a variable site) (McKenzie et al. 2023a). Resilience scores were good to very good in 2022-23 except at Low Isles, which were very poor as usual. Site GI3 showed a small decline from 2008 to 2022 using a Kendal-r test, however this does not flag as a site of concern. A small *Nanozostera muelleri* dominated meadow in Trinity Inlet (Meadow 20) was rated satisfactory for area and poor for biomass in 2022 ((Reason et al. 2023a). All others in good or very good condition. In the southern Wet Tropics MMP sites, abundances have been recovering at Dunk Island intertidal and subtidal since the extreme weather events of 2008-2011, but have not recovered at Lugger Bay. This appears to be due to scouring and lowering of the bank combined with turbid water – can't get enough light to establish?				Lugger Bay (LB1* LB2*) Mourilyan Harbour#		

NRM region	Summary commentary	Recent decline (~5 years) 2021-22-23			Long-term trends*# Sites of concern		
		Estuary	Coast	Reef	Estuary	Coast	Reef
	Seagrass in Mourilyan Harbour was classified as Very Poor in 2022 with each meadow being either poor or very poor despite some improvements in biomass (i.e. area remains low) (Reason et al. 2023b). One of the meadows (Lily) was absent for the third year in a row.						
Burdekin	Seagrass abundances in the Burdekin region are highly variable depending largely on extreme weather events such as floods and sustained periods of wind/turbidity. Abundances at Burdekin MMP sites are variable with patterns of loss and recovery. In 2021-22 abundance was rated moderate overall. It was below the maximum levels it can reach. Coastal sites had higher abundances on average and were closest to historical maxima, followed by reef intertidal and reef subtidal sites which were well below levels and recovering from losses during the 2019 floods. It was similar in 2022-23, though there had been a small amount of recovery at the reef subtidal site. The reef intertidal and subtidal sites at Magnetic Island have not been recovering as quickly as they did following the 2008-2011 floods, but given their history of recovery, they are not particularly concerning. Nearly all seagrass meadows in the Ports Long-term Seagrass Monitoring Program declined in area and/or biomass between October 2021 and October 2022. However, 9 of the 12 meadows were in satisfactory or better condition while only 3 were in poor condition including two at Magnetic Island (Cockle Bay intertidal and Geoffrey Bay which have been below average for the last 4 years) and one at Shelley Beach. Total area of seagrass in the LTMP declined from 2008-2011, but recovered and has remained above average for seven years including 2022. In 2022, the overall condition of Abbot Point seagrasses remained good for the third consecutive year (Reason et al. 2023c). There had been a trend of			Meadow 6# (*N. muelleri*) area Cockle Bay and Meadow 5# biomass (*H. uninervis*) Meadow 3# *H. uninervis* biomass in Geoffrey Bay			Cockle Bay, Magnetic Island (MI2)*

NRM region	Summary commentary	Recent decline (~5 years) 2021-22-23			Long-term trends*# Sites of concern		
		Estuary	Coast	Reef	Estuary	Coast	Reef
	improving seagrass condition since 2017 when there were impacts of Cyclone Debbie.						
Mackay-Whitsunday	Abundances in the Mackay-Whitsunday NRM region in 2021-22 were scored poor on average. Generally, coastal and reef sites were lower than historical maxima but were in moderate condition, except for HM1. Abundance at the estuarine sites at Sarina Inlet is highly variable and was low in 2021-22 and the coastal subtidal site at Newry Bay was low but is variable and there is insufficient historical data to assess. There was significant (<0.05) long-term decline at CH4, but the data set is short and the subtidal habitats in the region are variable and there is insufficient evidence to determine if this is of concern. In 2022-23 the coastal and reef sites were in a similar state, but the estuarine and coastal subtidal sites have recovered showing positive signs of recovery. The biomass and area of seagrass meadows in the southern Mackay-Whitsunday region (including Clairview) were rated as good overall in 2021 in the fifth year of surveying the region (Rasheed et al. 2022). There were no meadows that have recently declined, and the long-term trend (2017-2021) was for recovery following Cyclone Debbie.					PI2*	HM1* and HM2*
Fitzroy	In 2021-22 the abundance score for the inshore seagrass MMP in the Fitzroy was very poor. There have been large declines in abundance after reaching peak abundance in 2018 at Shoalwater Bay. The cause of the declines is not clear. There have also been declines since 2020 at the large Pelican Banks in Gladstone Harbour after a small increase between 2018 and 2020 and this continues a long-term declining trend in abundance at these sites. The reef sites at Great Keppel Island declined from 2018-19 to 2021-22 but also have historically low abundance but.	Gladstone Harbour (GH1 GH2) Pelican Banks, meadow 43	Shoalwater Bay (RC1 WH1)		Pelican Banks, Gladstone Harbour# GH1*		GK1*

NRM region	Summary commentary	Recent decline (~5 years) 2021-22-23			Long-term trends*# Sites of concern		
		Estuary	Coast	Reef	Estuary	Coast	Reef
	The Ports monitoring program also identified that Pelican Banks was again in a poor condition in 2022 after having returned briefly to satisfactory condition in 2021, matching a trend of decline in meadows outside of the western Basin. It is the largest meadow in the Ports monitoring program (>650ha). Environmental conditions were not thought to be the cause of decline, but rather potentially grazing intensity especially after floods/decline of seagrass in Hervey Bay. The inner harbour meadow 58 was in very poor condition due to large declines in biomass. This meadow was lost in 2010 and transformed from Zostera-dominated to *H. uninervis* and *H. ovalis* dominated, which has lower biomass. Decreases in 2022 were attributed to rainfall and river discharge. However, there are longer-term declines as well. Seagrass in the Western Basin and Narrows remained in generally good condition as did those at South Trees Inlet and Quoin Island.				Inner Harbour meadow 58#		
Burnett-Mary	Abundance at MMP sites in the Burnett-Mary region was rated as very poor in 2021-22 after extreme rainfall events and this was unchanged in 2022-23. The estuarine sites at Rodds Bay and Urangan have been historically highly variable. At Urangan, peak abundances were observed in 2002-03 with small recovery in 2010-11, followed by decline and moderate recovery in 2015-16 but declined again in 2016-17 and continued on a declining trajectory in 2022-23. There was a higher proportion of colonizing species present in 2022-23 instead of foundational species, which indicates recovery potential but high vulnerability to further disturbances. Due the variability at this site, trend analysis does not show long-term decline, but abundance over the last 15 years is lower than what it was in the early 2000s. Seagrass abundance at coastal sites at Burrum Heads in 2022-23 was also the lowest since 2000-01. All three Rodds Bay meadows were in poor condition, which serve as reference meadows in the Port Curtis monitoring program. This was predominantly due to a decline in biomass since 2019, while meadow area has not declined by as much for the largest of the meadows (meadow 96).	Rodds Bay Urangan (UG1 and UG2)				RD2*	

NRM region	Summary commentary	Recent decline (~5 years) 2021-22-23			Long-term trends*# Sites of concern		
		Estuary	**Coast**	**Reef**	**Estuary**	**Coast**	**Reef**
	The cause of decline is thought to be climate drivers, such as flooding. Biomass has been through two large cycles of biomass increase and decline at Rodds Bay and is in a low after recent decline but a long-term trend in the Ports monitoring meadows is not evident.						

5. MULTI-CRITERIA ANALYSIS

While the initial focus in prioritising and planning seagrass restoration should begin with understanding where seagrass has been lost or is in decline, many other factors should be considered when considering how to expand restoration efforts and identify new sites. We use a multi-criteria analysis to evaluate sites, weigh and prioritise them for restoration, and pinpoint where investment is needed to achieve successful outcomes. This analysis is applied to the eleven locations mentioned above, which are in decline and in poor condition but could be applied to other areas where Traditional Ecological Knowledge (TEK)or local observations suggest the need for restoration.

A rubric is presented (Table 10) to promote consistent evaluation of the sites against each criterion, with levels from 0-5, whereby 5 indicates a stronger weighting.

The scoring is not intended here to be used to rank sites for restoration in order of priority for restoration interventions, but rather as an approach to highlight the strengths and weaknesses (or knowledge gaps) of restoring seagrass at a specific location. Here we apply the MCA to the eleven locations identified in the review of trend data from high-resolution monitoring, however the MCA can be used as a tool for other locations to identify investment and information needs to strategically develop restoration programmes.

The criteria and rubric were established by the entire team. However, only one team member scored each of the high temporal sites that showed declining trends against the multi-criteria rubric, which was then assessed by two senior members of the team. Alternatively, each team member could individually score each site of interest against the multi-criteria rubric, and either collectively determine the final scores or take the average across each individual team member. Another approach could be to apply a more quantitative method of scoring the sites against the multi-criteria.

5.1. Description of Assessment Criteria

Seagrass status, trends and data resolution

See above.

Seagrass resilience

The Marine Monitoring Program includes a resilience indicator. It is based on the premise that resilience includes a resistance and recovery element. Seagrass species vary in their dependence on these traits. 'Colonising' species generally have low levels of resistance traits and 'persistent' species have high levels of these traits. Resistance is incorporated into the metric through species composition and meadow condition.

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

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

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

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

The resilience indicator is calculated for sites where reproductive effort is measured (MMP sites, but not for Seagrass-Watch). It is also a site-level indicator relevant to the scale of the MMP sites. There is a need to develop a spatial resilience index that can be overlaid with other spatial information for prioritising seagrass restoration based on loss, risk, and resilience. Resilience cores between 0-30 indicate low resilience, where species may be less resistant to pressures or show low potential for natural recovery, these are given a high score in the MCA to reflect the great need for restoration.

Connectivity and Distance to healthy donor meadows

Seagrass meadows in the Great Barrier Reef Australia show genetic connectivity at regional scales, with unique genetic clusters spreading over hundreds of kilometres, indicating long-distance dispersal limitations (McMahon et al. 2018). Grech et al. (2018) used biophysical modelling and network analysis to measure functional connectivity of seagrass in the central GBRWHA and found that dense seagrass networks suggested seagrasses are resilient to the random loss of meadows, but also that certain meadows are important sources of propagules and are valuable nodes in the network.

Connectivity is an important factor in determining where to restore seagrass because it helps identify locations with the highest chance of long-term persistence. By understanding the relationships between propagule sources and sinks, restoration efforts can be focused on areas where they will bolster broader metapopulation resilience and persistence. Connectivity also highlights areas where natural recovery may be limited due to isolation from other meadows, even if the habitat is suitable. Additionally, it shows sites with strong natural recovery potential, where restoration efforts and costs should not be expended.

Modelling dispersal patterns in a region is a recommended step prior to specific restoration site selection. Specific hydrodynamic modelling has been undertaken in specific regions, for example, Gladstone Harbour (Jackson et al. 2021c), The Whitsunday Islands (Jackson et al. 2021a) and The Keppel Islands (Aiken et al., un published). However, many areas do not have regional dispersal models, therefore in scoring this criterion we looked at the isolation of meadows as a proxy for natural recovery potential and scored meadows with good connectivity lower than more isolated meadows. Specifically, we scored meadows as:

1. Strong evidence (hydrodynamic modelling and genetics) that the meadow is a sink for propagules from other meadows.
2. Good connectivity likely with other seagrass meadows within 10 km;
3. Some connectivity likely with other meadows within 50 km;
4. Isolated meadow no other seagrass meadow within 10 km; and
5. Very isolated meadow, no other seagrass within 50km.

Proximity to other meadows is also an important consideration in terms of donor sites. In accordance with State Development Assessment Provisions guideline State code 11: Removal, destruction or damage of marine plants, marine plant material, such as seeds or seedlings, should be gathered only from the local vicinity, typically within 100 km of the

proposed restoration site (Couchman and Beumer 2007). However, transferring marine plants within their natural distribution range is permissible under certain conditions:

- » The removal of individuals does not unreasonably endanger the source population.
- » The receiving area offers suitable and ample habitat for the species' survival.
- » The translocated species is not expected to cause unjustifiable harm, such as spreading disease or parasites, in the new area.
- » Measures to address the factors contributing to the species' decline in the receiving area have been identified, implemented, and are unlikely to recur.
- » Genetic integrity remains intact in the receiving area.

Therefore, we also scored sites based on the distance to healthy donor meadows. Sites with donor meadows <10 km scored highly (5) due to the ease at which restoration material could be sourced. Sites less than 100 km, and therefore in keeping with guidelines, were scored moderately (3) and those with donor meadows > 100 km and requiring the DAF conditions above to be met (often requiring more comprehensive research) were given a low score (1).

Exogenic pressures

Exogenic environmental pressures are external factors that impact ecosystems from outside their natural environment. In the context of seagrass meadows, these pressures can significantly influence their health and resilience. Examples include nutrient or fine sediment inputs from a catchment, heat stress and more frequent (and intense) storms related to climate change. These are important to assess as they likely inform the type of meadows you expect at a site; high levels of exogenic disturbance will often result in transitory meadows, again with implications for ongoing interventions to enhance recovery. Three levels were applied:

1. No exogenic pressures;
2. Medium frequency of flooding /cyclones, heat stress, nutrient enrichment etc; and
3. High frequency of flooding/ cyclones, heat stress, nutrient enrichment etc.

Endogenic pressures

Endogenic manageable pressures (c. Elliott, 2011) can be and should be managed before restoration is attempted. For example, local sources of nutrients and fine sediments or disturbance by boat anchoring or propellors. We therefore applied criteria scores based on:

1. No endogenic pressures;
2. Local manageable pressures with no management in place; and
3. Local manageable pressures with management in place.

Knowledge base for restoration of that species

Based on the review of literature in Section 3.1 we considered the available knowledge on restoring the dominant seagrass species at the location. With this criterion it is important to consider succession in species especially in degraded meadows. Species composition may change over time at a site, for example in some inshore coastal meadows *N. muelleri* may dominate during periods of low disturbance when the biomass and area are good. After a disturbance event, less persistent species, such as the Halophila, may dominate.

This criterion highlights whether more research is first required to be undertaken before any major plans for infrastructure or demonstration sites are set up. Therefore, the weighting was applied as follows:

1. No restoration research on this genus or species;

2. Successful small scale field trials of restoration for this genus;
3. Successful large-scale trials of restoration for this genus;
4. Successful small scale field trials of restoration for this species; and
5. Successful large scale field trials of restoration for this species in the GBR

Knowledge base for restoration of the site

Whilst research may be available for the restoration of a particular species, research has shown that restoration approaches are extremely site specific (van Katwijk et al. 2016). Therefore, we considered the amount of existing knowledge of both the ecology of the species at the site and restoration research that had already occurred at the site. Sites where successful large scale field trials of restoration for this species had occurred (no examples in the GBR) would represent an immediate opportunity for in vesting in scaled up seagrass restoration. Sites were therefore weighted as:

1. No applicable knowledge for restoration at these sites;
2. Some understanding of the ecology of this species at different sites;
3. Some understanding of the ecology of this species in similar sites;
4. Understanding of environmental conditions at the site; or
5. Understanding of species dynamics and environmental conditions at this site.

Species traits and meadow type

As described in Section 2.4 life-history traits of seagrass allows for a functional classification of species as colonising, opportunistic or persistent (Kilminster et al. 2015b). Persistent species form enduring meadows, while opportunistic and colonizing species can establish either enduring or transitory meadows. Meadows near their physiological limits or under human impact are more likely to be transitory. Knowing the meadow type helps guide effective management and monitoring strategies. Whilst contributing to assessments of resilience, this information also provides an indication of the restoration approaches (seed versus fragment methods, use of nurseries) and targets (in terms of the time taken to restore).

In the species trait criterion, higher priority is given to meadows where the dominant or target restoration species are persistent, followed by opportunistic species, and then colonising species. This prioritisation reflects the potentially high natural recovery rate of colonising species.

For the meadow type criterion, persistent meadows are given only a slightly higher priority for restoration than transitory meadows due to their somewhat greater potential for natural recovery. Both meadow types are important for restoration, but while restoring persistent meadows may be a one-time effort, restoring transitory meadows might necessitate regular interventions to support recovery after disturbances.

End users and sustainable funding

Ensuring the long-term sustainability of restoration involves careful planning and economic considerations spanning various timeframes, from short to long-term. A key point to consider is identifying drivers of restoration (e.g. biodiversity offsets, national and international targets that are embedded in legislation, blue carbon or nature credit schemes) and end-users (e.g. environment protection agencies; port or coastal managers, marine park authorities and even natural engineering and restoration consultancies). These are also the potential markets for seagrass nursery production. If a nursery to support restoration is being considered the

nursery set-up might be a large upfront cost but there is also an ongoing regular amount of money required. Sites were therefore assessed based on the following criteria:

0. No identifiable funders or end users;
1. No identifiable funders but strong community Traditional Owner aspirations;
2. Initial short term/ start-up funding available;
3. General mid-term funding available;
4. Site-specific long-term funder/end user identified; or
5. Site-specific long-term funder/end-user already engaged (e.g. seagrass habitat creation/restoration identified for offset requirements, or another funded.

Ecosystem services

Considering ecosystem services is crucial for setting targets for seagrass restoration because it helps to quantify the full range of benefits that healthy seagrass ecosystems provide to both the environment and human communities. Ecosystem services assessment helps prioritise areas for restoration based on their potential to provide specific services. For example, areas that offer significant carbon sequestration potential or shoreline protection benefits may be prioritized over others.

By considering ecosystem services, restoration targets can be set that aim to restore not only the structural aspects of seagrass ecosystems but also their functional roles in providing ecosystem services. This ensures that restoration efforts are more comprehensive and holistic.

Highlighting the ecosystem services provided by seagrass ecosystems can also help engage stakeholders and garner support for restoration efforts. When people understand the tangible benefits that healthy seagrass ecosystems provide, they are more likely to support conservation and restoration initiatives.

Sites were differentiated in this criterion as sites where:

1. there was no information available on ecosystem services for the same species and similar environment;
3. ecosystem services for that species and environment have been studied at other locations; or
5. sites where data exist demonstrating the value of the seagrass site in terms of a key ecosystem service.

Accessibility

Site accessibility is essential for the effective planning, implementation, and long-term success of seagrass restoration projects. It facilitates logistical operations, including monitoring and maintenance efforts; enables rapid response to threats, enables local community engagement; and promotes scalability and replicability of restoration efforts.

Accessible sites are easier to reach, making logistics and operations more efficient and cost-effective. This includes transporting equipment, personnel, and materials needed for restoration activities such as planting or seeding. Accessible sites also facilitate regular monitoring and maintenance activities essential for adequately assessing restoration success and allow for timely responses to changing environmental conditions or emerging threats. Costs for research transport are also reduced.

Accessible sites enable easier engagement with local communities, stakeholders, and volunteers. This involvement is crucial for gaining support, raising awareness, and fostering stewardship towards seagrass restoration efforts.

Therefore, accessible sites allow for scalability and replicability of restoration efforts. Successful projects can serve as models for similar initiatives in other locations, contributing to broader conservation and restoration goals. We therefore scored locations as:

1. Accessible but not close a town;
2. Isolated location with poor access;
3. Close to a town/volunteer base but sites are difficult to access (e.g. require boat transport);
4. Close to a town/volunteer base and sites are accessible.
5. Close to a town/volunteer base and donor site is easily accessible >10 km from research base/ facility but <10km to a major town of >10000 people; or
6. Within 10km of facility or research base and site easily accessible for volunteers and research practitioners and/or Close to a town/volunteer base and donor/restoration site is easily accessible.

Delivery partners

Strong partnerships are critical to seagrass restoration success. Delivery partners may have access to resources, expertise, or infrastructure that can enhance the restoration project. Collaborating with partners allows for the sharing of equipment, funding, technical knowledge, and labour, which can reduce costs and improve project efficiency. Partner organisations often bring specialised expertise and experience to the table, e.g. researchers with experience working in the local ecosystem, port managers navigating regulatory requirements, or practitioners implementing similar projects in the past; or the Traditional Ecological Knowledge of Traditional Owners.

Partners can also help engage stakeholders and build support for the restoration project within the community. They may have relationships with the local community, government agencies, nonprofit organisations, or businesses that can facilitate outreach efforts and build support (e.g. Natural Resource Management organisation). Collaborating with delivery partners could also minimise risks associated with the restoration project. Partners may be able to identify potential challenges or obstacles early on and work together to develop strategies to address them. Additionally, partnering with reputable organisations can enhance the project's credibility and legitimacy.

1. No partnerships;
2. Recent partnerships;
3. Some relevant established partnerships; or
4. Established partnerships between researchers, managers, Traditional Owners, other stakeholders (e.g. OzFish, fishing groups).

Training partners

Training is an essential component of scaling up restoration efforts as it builds capacity, standardises practices, promotes innovation, engages stakeholders and ensures sustainability.

For example, vocational training programs build the capacity of restoration practitioners by equipping them with the knowledge, skills, and techniques necessary to implement

restoration projects effectively. This ensures that restoration activities are conducted competently and efficiently, leading to better outcomes. For example, CQUniversity are developing a seagrass restoration stream of the Certificate III in Conservation and Ecosystem Management which focuses on the establishment of seagrass restoration with a focus on seagrass nursery management.

Providing training to local communities, stakeholders, and volunteers in restoration efforts fosters longer-term engagement. By providing education and hands-on experience, volunteers can be empowered to actively participate in and contribute to restoration activities, encouraging a sense of ownership and stewardship.

As an indicator of the accessibility of training for partners at a site we scored sites based on:

1. Training partners would require overnight stay;
2. Training partners within a day trip; or
3. Training partners within 20km.

Research partners

Seagrass restoration is still a developing field and therefore another partner critical to successful restoration activities are research partners. Having research partners on a novel restoration project brings several valuable benefits. They can help design research protocols, conduct experiments, analyse data, and interpret findings, ensuring that restoration efforts are based on sound scientific principles. Research partners often bring innovative ideas and technologies to the table, which can enhance the effectiveness and efficiency of restoration strategies. Their expertise in cutting-edge research methods, such as genetic analysis or remote sensing, can lead to novel approaches for addressing restoration challenges. Research partners play a key role in long-term monitoring and evaluation of restoration outcomes. By collecting and analysing data over time, they can assess the ecological, social, and economic impacts of the project, track changes in ecosystem health, and inform adaptive management strategies.

Research partners can also help ensure the quality and rigor of the restoration project by conducting scientific assessments and evaluations. Their involvement can help verify the success of restoration efforts, identify areas for improvement, and refine best practices for future projects. The involvement of research partners can enhance the credibility and legitimacy of the restoration project, particularly when seeking funding or engaging with stakeholders. Their affiliation with academic institutions or research organizations may also open up additional funding opportunities and resources.

We scored sites in terms of research partnerships based on:

0. Unknown;
1. No research on seagrass carried out within 100km of the site;
2. No research carried out on the site's seagrass;
3. At least one research group working on seagrass in region;
4. Multiple researchers working on seagrass in the region or research centre/facility > 100km; or
5. Multiple researchers working on seagrass in the region and research centre/facility within 100km.

Infrastructure base

The description for this criterion is provided in section 0.

5.2. Applying the assessment criteria - case studies in the GBR

As example case studies, we applied the MCA, scoring on a consensus basis, on the scores of four of the report authors, to the eleven locations identified in the review of trend data from high-resolution monitoring. Results can be seen in Table 6. The descriptions demonstrate the application of the approach and the use of the information in terms of the roadmap for scaling restoration, which also inform the key recommendations in Section 7.

Piper Reef

Piper Reef shows long-term trends of seagrass decline and meadow condition is currently classed as poor, with annual monitoring conducted since 2012. Note that the decline in seagrass coverage is slight, but significant based on a Mann-Kendall test. The site remains consistent and not a site of major concern as it is located within a large reef lagoon and well connected to other seagrass meadows within a 10 km radius for propagules. This site is dominated by the persistent species, *Thalassia hemprichii,* but also includes *H. ovalis* and *Cymodocea* species, and has a high seagrass resilience index. As this site is annually monitored, there is over 10 years of data that led to our current understanding of species dynamics and environmental conditions at the site, and data demonstrating the key ecosystem services provided by the seagrass habitats. Piper Reef is also exposed to both exogenous pressures (e.g., three cyclones in the last 10 years) and endogenous pressures (e.g., minor land use activities). However, this region is monitored and managed by Piper Island National Park (CYPAL) and Kuuku Ya'u Traditional Owners. Furthermore, the Kuuku Ya'u Traditional Owners are currently working on seagrass monitoring within the area.

Piper Reef was highlighted as a site of interest for seagrass restoration against the multi-criteria assessment due to trends of decline and exposure to multiple pressures, the meadow's high resilience, a dominant meadow composition of a persistent species, and knowledge of the site and seagrass species found at the site. However, Piper Reef is in an isolated area in Cape York and must be accessed via boat, making the site poorly accessible. Training and research partners would require overnight stay, as JCU in Cairns is the closest research facility and is located approximately 585 km away from the site. There is also no existing infrastructure within 100 km that is suitable for starting a seagrass nursery in the region, nor is there a healthy donor meadow within 10 km (the closest monitored meadow that is classed as "fair" is Lloyd Bay, Lockhart River approximately 60 km away). If seagrass continues to decline at this site and restoration is prioritised, efforts should be made to establish relationships with local Traditional Owners and other potential research partners interested in monitoring and restoring seagrass meadows in the area.

Additionally, there have only been small-scale (< 1 ha) restoration trials on *T. hemprichii* (n = 5), *H. ovalis* (n = 4), and *Cymodocea* (n = 5) species, and only three studies were conducted within Australia and within the GBR. Therefore, additional research should be conducted to identify appropriate methods for restoration, particularly of *T. hemprichii* and *Cymodocea* species, and begin pilot restoration trials at the site of interest.

Lugger Bay

Lugger Bay also shows long-term trends of seagrass decline, and meadow condition is currently classed as poor based on triennial data collected since 2005. This site scores high as

a site of interest against our MCA, as meadow resilience is low, reproductive effort is poor, and seed banks are not present. There is also high disturbance in Lugger Bay, with four tropical cyclones observed since 2009 and the presence of local pressures including agricultural runoff and erosion that lead to high turbidity at the site. Lugger Bay seagrass meadows are also monospecific, composed of the opportunistic species, *Halodule univervis*. As this site has been annually monitored for 20 years, there is also foundational knowledge of species dynamics and environmental conditions at this site. Additionally, there is at least one research group already monitoring seagrass in the region (JCU), and training partners are located within a day trip (JCU in Cairns, located approximately 120 km away). There are also relevant partnerships already established in the region, as JCU is currently working with OzFish and Mandaburra and Goondoi Traditional Owners on seagrass restoration within Mourilyan Harbour (approximately 40 km away). Existing infrastructure is also located within 40 km of the site, both coastal prawn farms and terrestrial nurseries, which could be used to establish seagrass nurseries to support local restoration efforts. If Lugger Bay is selected as a site of interest for seagrass restoration, we recommend identifying potential end users and funder within the area and establishing relationships with local Traditional Owners. Additionally, there are only two small-scale restoration studies on *H. univervis,* both conducted in Indonesia. Therefore, further research is needed on *H. uninervis* flowering and effective restoration methods for this species, followed by small-scale pilot restoration trials conducted at the site.

Mourilyan Harbour

Mourilyan Harbour scores high as a site of interest for seagrass restoration against our multi-criteria analysis tool. Seagrass meadows at Mourilyan Harbour are currently classed as very poor and are experiencing long-term trends of decline. Seagrass meadow resilience has been estimated as low (not a reported resilience index), as it is dominated by colonising *Halophila* species, but flowering a fruiting have recently been observed within the harbour. Meadows are also transitory, with one meadow absent for the third year in a row and biomass across monitoring sites remaining below baseline conditions.

The harbour has been monitored annually since 2000, providing data contributing to our current understanding of pressures and the important ecosystem services provided by the seagrass meadows at this site. Mourilyan Harbour has experienced recent major climactic events from 2009-2011, La Nina events in 2022, and recent wet weather and river flows that have contributed to overall seagrass declines. Port activity, coastal development, and land run-off are current local pressures within the Harbour. However, there is an ongoing strategic long-term assessment and monitoring program for seagrasses within the harbour, which provides information to ensure effective seagrass habitat management. Mourilyan Harbour is also of interest because restoration trials are ongoing, and delivery and research partners have already been established at this site. JCU is aiming to restore *Nanozostera muelleri* meadows within the harbour through ongoing trials with OzFish and Mandubarra and Gimuy Sea Rangers. Initial small-scale trials appear successful, and efforts are now shifting toward large-scale restoration trials. Furthermore, training partners are located within a day trip and there is existing infrastructure that can be used to establish seagrass nurseries to support restoration efforts, including fish farms and aquaculture facilities (located within 20 km) and the Cairns Aquarium (within 100 km). JCU is also building a seagrass nursery in Cairns, which would be located within 100 km, although a nursery at the location would be more practical and cost effective. Mourilyan Harbour is selected as a site of interest for seagrass restoration, we recommend establishing relationships with researchers, Traditional Owners, and other stakeholders currently working on seagrass restoration within the harbour. Additional

research should also be conducted on effective methods for large-scale *Nanozostera* restoration at this site, with the intention of beginning large-scale restoration trials.

Cockle Bay, Magnetic Island

Cockle Bay in Magnetic Island is another site found to have long-term trends of seagrass decline and is classed as poor or very poor in each of the last five years. Seagrass meadow resilience was the lowest recorded in 2022-2023, following previously high resilience indices over the previous five years. Species composition has recently changed to >99% colonising species at the site, with a complete loss of *C. serrulata* and large declines of *T. hemprichii* and *H. uninervis*. Furthermore, no reproductive structures have been identified in any of the opportunistic species over the last five years. Meadows in Cockle Bay are also transitory, fluctuating over time and experiencing periods of <10% total seagrass cover.

Monitoring has been ongoing in Cockle Bay since 2005, contributing to our current understanding of species dynamics and environmental conditions at the site, including exogenous and endogenous pressures. There were two cyclones that affected this site in the last 20 years, and flood events in 2008-2011 and 2019 that caused seagrass declines in the bay. Coastal development, ground-water seepage, land run-off, and boat and pedestrian traffic are local pressures affecting the site. However, this area is monitored and managed by GBRMPA and the Department of Environment and Heritage who are actively addressing pressures that negatively impact the seagrass meadows. Additionally, JCU in Townsville are potential training and research partners for seagrass restoration efforts (located less than 20 km away) and are currently conducting research and monitoring seagrass meadows in the area. There are also several existing infrastructures that could be used to establish a seagrass nursery to support restoration efforts in the area, including the Aquasearch Aquarium on Magnetic Island, as well as AIMS and MARFU research centres located within 20 km from Cockle Bay. If Cockle Bay is selected as a site of interest for seagrass restoration, we recommend establishing relationships with Mamu and Wulgurukaba Traditional Owners in the area to gauge interest in starting seagrass restoration efforts in Cockle Bay. Additionally, only one *T. hemprichii* restoration trial has been conducted in Australia and the GBR and three trials in India and Indonesia, while all efforts on *H. uninervis* (n = 1) and *C. serrulata* (n = 3) occurred in India and Indonesia. Therefore, we recommend additional research be conducted to identify appropriate methods for restoration and enhance our understanding of flowering across all three opportunistic species and begin small-scale pilot restoration trials at the site.

Pigeon Island

Pigeon Island also scores high as a site of interest for seagrass restoration against our multi-criteria analysis tool. Although classified as fair condition in the last five years, most recent reports class this meadow as poor to fair, with recent meadow declines in the last five years. Seagrass meadow resilience is high, with annual flowering of *N. muelleri* recorded and meadows dominated by the opportunistic species, *H. uninervis*. This meadow is also transitory, indicating seasonal trends of >20% cover in summer and fall, but <20% cover in winter and spring. Pigeon Island also has some connectivity to other seagrass meadows within 50 km (e.g., Hamilton Island, Tongue Bay). Long-term monitoring at this site (> 20 years) also contributes to our current knowledge of key ecosystem services provided by the seagrass meadows at Pigeon Island, including dugong and turtle feeding grounds, and high detritus, grazing matter, and faunal prey. Additionally, medium frequency of exogenic pressures is identified at this site, with two cyclone events since 2010. Endogenic pressures without management practices in place include high sedimentation rates, high epiphytic algal

cover, and sewage and stormwater runoff contributing to accumulation of fine muds with high organic content.

Pigeon Island is also a site of interest because seagrass restoration trials are ongoing at this site, and delivery and research partners have already been identified for this site. CQUniversity is aiming to enhance resilience and restore cover of *N. muelleri* meadows at this site, in collaboration with Ngaro Traditional Owners, GBRF, and Reef Catchments. Furthermore, there are three ongoing large-scale trials occurring within the GBR on *N. muelleri*, as well as small-scale trials across Australia (n = 20) and New Zealand (n = 3). Small-scale trials have also been conducted on the other two species present at this site, *H. uninervis* and *H. ovalis*, in Australia (n = 2; *H. ovalis*) and Indonesia (n = 2 for each species). Pigeon Island also scores highly against the matrix because there is a seagrass nursery located within 2 km of the site in Airlie Beach, QLD, which can support ongoing restoration activities, and healthy donor meadows are located within a 100 km radius. Training partners are already located in the area, and other potential infrastructure that could be used for nursery operations include prawn farms, hatcheries, aquaculture facilities, and terrestrial nurseries, all located within 30 km of the site. Further large-scale restoration trials with *N. muelleri* should continue at Pigeon Island to determine the success of restoration at this site, and further research on *H. univervis* flowering and restoration methods is needed, with the intention of beginning small-scale pilot restoration studies of this species at Pigeon Island.

Hamilton Island

Hamilton Island meadows are classed as very poor condition, with biannual monitoring indicating long-term trends of decline that are consistent since monitoring at this site was established in 2007. Seagrass meadow resilience is also low, with cover consistently below 6% since 2012, and no reproductive structures of any foundational species observed. The meadows are opportunistic, dominated either by *H. uninervis* with little *H. ovalis*, or by *N. muelleri* with *H. uninervis* and *H. ovalis*. Hamilton Island meadows are also transitory, with cover fluctuating over long timescales but consistently below 10% coverage. Hamilton Island also has some connectivity with other seagrass meadows within 50 km (e.g., Tongue Bay, Cannonvale Beach, Hydeaway Bay). Long-term monitoring has led to an understanding of species dynamics and environmental conditions at this site, as well as identification of key ecosystem services. Meadows provide shelter for fish and prawns, grounds for sea turtle foraging. There is also a medium frequency of exogenic pressures, with two cyclones occurring since 2010. The seagrass meadows on Hamilton Island are also located near a resort area, but motorised vehicles are prohibited and there are relatively low impacts from boating activities.

Hamilton Island is also a site of interest for restoration because delivery, research, and training partners have already been stablished within the area. CQUniversity is conducting restoration trials in the Whitsundays (approximately 25 km away) in partnership with GBRF, Reef Catchments, and Ngaro Traditional Owners. JCU and Seagrass Watch also conduct seagrass monitoring throughout the Whitsundays. Furthermore, there is an existing seagrass nursery in Airlie Beach to support restoration efforts, located within 25 km. Other potential infrastructure that could be converted for use as a seagrass nursery are also located within 100 km of the site, including prawn farms, hatcheries, aquaculture facilities, and terrestrial nurseries. However, note that this site is only accessible via boat transport. Small-sale restoration trials have also been conducted for all three seagrass species found at this site across Australia, New Zealand, and Indonesia. There are also ongoing large-scale restoration trials occurring in the GBR with *N. muelleri*, including a trial at Cannonvale Beach (within 25 km). For consideration of restoration at this site, we recommend further research be

conducted on *H.uninervis* flowering, effective methods for restoration, and small-scale trials at Hamilton Island. Additionally, we recommend beginning large-scale trials of *N. muelleri* at this site.

Gladstone Harbour, Pelican Banks

Seagrass meadows within Gladstone Harbour have been classed as poor or very poor in the last five years (e.g., Pelican Banks, meadow #43), with long-term trends of decline in biomass. Note that percent cover increased considerably in October 2023, indicated some improvement in meadow condition since 2015-2016. However, Inner Harbour meadow #58 shows consistent long-term declines in biomass since 2009. Gladstone Harbour meadows have a high seagrass resilience index, with meadows dominated primarily by the opportunistic species, *N. muelleri*, and recording of annual flowering across meadows. Meadows are persistent, with areas dominated by high coverage of *N. muelleri*. However, some meadows have shifted to *H. uninvervis* dominated with increased presence of *H. ovalis*, with some meadows now composed of only colonising species. However, some meadows are becoming fragmented with fluctuating seagrass coverage. Gladstone Harbour is also well connected to nearby seagrass meadows (within 10 to 20 km). Biannual monitoring has occurred within Gladstone Harbour since 2005, contributing to our knowledge of species dynamics and environmental conditions at this site. Seagrass meadows within the harbour provide feeding grounds for dugongs and sea turtles, and studies have assessed blue carbon storage potential and fisheries production across meadows. There is medium frequency of exogenic pressures, with one cyclone occurring within the harbour since 2015, and high rainfall and river discharge causing turbid conditions in 2022. Endogenic pressures include land run-off and industrial and port development. However, management is in place to regulate dredging operations, with programs such as the Healthy Harbour Partnership and Marine Monitoring Program informing management within the harbour.

Gladstone Harbour is a site of interest for seagrass restoration because there are already well-established end users and funders, and delivery, training, and research partners. CQUniversity and JCU are already monitoring seagrass meadows within the harbour, Gladstone Ports Corporation (GPC) and GBRF are funding seagrass research. This site is also very accessible via public ferry transport. The Coastal Marine Ecosystems Research Centre (CMERC) is located within the Gladstone Marina, which has research facilities, resources, and an existing seagrass nursery to support seagrass restoration efforts. Another seagrass nursery is located on Konomie Island within 100 km. Healthy donor meadows are also located in the harbour (within 10 km). Ongoing large-scale trials of *N. muelleri* restoration are also occurring at Pelican Banks, in collaboration with GBRF, Coles, Gidarjil Development Corporation, and Gladstone Ports Corporation (GPC). Two additional large-scale restoration trials of *N. muelleri* are occurring within the GBR. Small-scale restoration trials have also occurred for the three dominant seagrass species found within the harbour, conducted across Australia, New Zealand, and Indonesia. We recommend continuing trials to investigate effective methods of large-scale *N. muelleri* at this site, and further research on *H. uninervis* flowering and methods of restoration, with the goal of beginning small-scale pilot studies for restoring *H. uninervis* within Gladstone Harbour.

Shoalwater Bay

Shoalwater Bay seagrass meadows were classed as very poor to moderate in the last five years and very poor in the last two years, with recent declines at one site (RC1) over the last five years. Meadows have a high seagrass resilience index dominated primarily by opportunistic species. However, total seagrass cover was below the threshold for resilience in

2022-2023, and reproductive structures have not been observed at this site in the last three years. Meadows are dominated by opportunistic *N. muelleri* and *H. uninervis*, but there is an increased proportion of the colonising species, *H. ovalis*, since 2011. Despite fluctuations in seagrass coverage within Shoalwater Bay, meadows are classed as persistent with consistent seagrass coverage over time. Shoalwater Bay is well connected to other seagrass meadows within the bay (within 10 km), as well as meadows within 50 km (e.g., Clairview). Annual monitoring at this site since 2005 also led to an understanding of species dynamics and environmental conditions at this site, and key ecosystem services provided, including provision of dugong and sea turtle foraging grounds and support of inshore fishing industries. Shoalwater Bay is also at medium risk of exogenic pressures, with one cyclone occurring since 2015. Endogenic pressures include freshwater and sediment run-off from land, and extensive scarring and sediment deposition that caused large-scale declines of seagrass in 2016. However, annual monitoring indicates signs of recovery.

Shoalwater Bay is close to a town and volunteer base (e.g., CQUniversity in Gladstone), but access to sites is limited due to Department of Defence restrictions. However, this site is of interest for restoration because training partners are located within a day trip (within 160 km), there is ongoing research and monitoring at this site and neighbouring locations, and some relevant partnerships have already been established in the area. This is the Sea Country of the Darumbal People. CQUniversity Rockhampton is on Darumbal Country and has CQU have long standing collaborations with the Darumbal People. Neighboring Traditional Owners Woppaburra have a partnership with CMERC and Konomie Island Environmental Education Centre on seagrass restoration on Konomie Island (within 80 km). CQUniversity also has a working relationship with the Port Curtis Coral Coast (PCCC) and Woppaburra Traditional Owners who are interested in seagrass restoration efforts. Furthermore, a seagrass nursery is located within 100 km on Konomie Island, which can support restoration efforts. Small-scale restoration trials have been conducted on the three dominant species found at this site across Australia, New Zealand, and Indonesia. Ongoing large-scale restoration trials on *N. muelleri* are also occurring within the GBR, including within Gladstone Harbour (approximately 160 km away). For consideration for restoration in Shoalwater Bay, we recommend discussing accessibility with the Department of Defence to determine feasibility of conducting restoration trials and long-term monitoring at this site. We also recommend engaging with Traditional Owners (e.g., PCCC) to identify their aspirations for ongoing seagrass restoration and monitoring in the region. Additionally, further research should be conducted on effective methods of restoration for *N. muelleri* and *H.uninervis* and enhancing understanding of flowering in *H.uninervis*, followed by small-scale pilot studies to restore both species at this site.

Great Keppel Island

Great Keppel Island seagrass meadows were classed as very poor in each of the last five years, and long-term trends of decline were highlighted at one site (GK1). Seagrass meadow resilience is low, with low seagrass coverage (<10%) recorded consistently since annual monitoring began in 2007, and evidence of very low reproductive effort. Meadows are dominated by the opportunistic *H. uninervis*, with some *N. muelleri* and *H. ovalis*. There is also connectivity with other seagrass meadows within 10 km (e.g., Middle Reef, Konomie Island). Long-term monitoring at Great Keppel Island contributes to our understanding of species dynamics and environmental conditions at this site, as well as the key ecosystem services provided by the seagrass meadows. For example, seagrass meadows are important for spawning and recruitment of coral grouper, coral trout, and stripey snapper at this site. There has also been research on sediment nutrient concentrations and nutrient concentrations

in seagrass tissues on Keppel Island. Additionally, there is medium frequency of exogenic pressures, with 1 cyclone occurring since 2015. Land run-off and local sources of nutrient and sediment inputs are also issues of concern at Great Keppel Island.

Great Keppel Island also scores high as a site of interest for restoration against our multi-criteria analysis tool because there are end users, delivery, research, and training partners already identified in the area. CQUniversity is working on Konomie Island and already has a working relationship with the Woppaburra Traditional Owners who have active projects mapping and restoring seagrass in the Keppel Islands. In terms of research partners, JCU also conducts monitoring and research in the area, and CMERC, CQUniversity is collaborating with Woppaburra and the Konomie Island Environmental Education Centre on seagrass restoration on Konomie Island and in nearby Gladstone Harbour (within 80 km) with the Gidarjil Development Corporation. Furthermore, two seagrass nurseries are located within 100 km (Konomie Island and Gladstone), and can support restoration efforts on Great Keppel Island. Healthy donor meadows are also located within 10 km. Furthermore, small-scale restoration trials have occurred across Australia, New Zealand, and Indonesia, focussing on the three common seagrass species found on Great Keppel Island. Large-scale trials of *N. muelleri* are also ongoing within the GBR (including Gladstone Harbour located within 80 km), with aspirations to begin trials on Konomie Island in the future. If Great Keppel Island is a site of interest for restoration, we recommend research be conducted on *H. uninervis* flowering and methods for restoration, as well as small-scale pilot studies to begin restoring *N. muelleri* and *H. uninervis* at this site.

Rodds Bay

Rodds Bay seagrass meadows were classed as very poor in the last two years, with recent declines in biomass and area (meadows 94, 96, 104), but high variability hinders the identification of long-term trends of decline. Seagrass meadow resilience is generally high across sites, dominated primarily by the opportunistic *N. mulleri;* however, resilience is declining as *H. ovalis* presence increases and seagrass cover remains consistently low (<20%). Meadows are transitory, with large fluctuations in seagrass presence and absence recorded, and low seagrass coverage (<10%) observed since 2020. Flowering is regularly observed in Rodds Bay. Additionally, Rodds Bay is well connected to other seagrass meadows within 10 km (e.g., Hummock Hill Island, Wild Cattle Island). Dugong and sea turtle grazing occur within Rodds Bay, and there is an understanding of species dynamics and environmental conditions at this site. No cyclones have been recorded in Rodds Bay in the last 20 years, but land run-off is a major concern at this site.

Rodds Bay is a site of interest for seagrass restoration because some relevant delivery partners have already been established in the area, training partners are located within a day trip (i.e., CQUniversity in Gladstone), and both CQUniversity and JCU are already conducting research and monitoring on seagrass in the region. However, note that accessibility of this site is dependent on boat transport. CQUniversity is also conducting restoration trials in Gladstone Harbour (within 40 km) in collaboration with GBRF, Coles, Gidarjil, and GPC, and has a relationship with the PCCC who is interested in seagrass restoration and monitoring in the region. Furthermore, there is an existing seagrass nursery located in Gladstone (within 40 km) to support restoration efforts; however, there are no healthy donor meadows located within 10 km, but there are potential donor meadows located in Gladstone Harbour (within 100 km). Small-scale restoration trials for *N. muelleri* and *H. uninervis* have also occurred in Australia, New Zealand, and Indonesia. Additionally, there are three ongoing large-scale trials of *N. muelleri* restoration within the GBR, including Gladstone Harbour. If Rodds Bay is a site of interest for seagrass restoration, we recommend

engaging with local Traditional Owners to identify key concerns and aspirations for seagrass restoration in the area. Also, further research is needed to enhance understanding of flowering and effective methods of restoration of *H.uninervis*. Small-scale trials of restoration of both *N. muelleri* and *H.uninervis* should also begin within Rodds Bay.

Urangan

Urangan is located outside of the GBR, but this region consists of one of the most extensive seagrass beds on the east coast of Queensland and meadows are well connected to northern meadows located within the GBR. Therefore, we include Urangan as a case study in our report. Urangan meadows were classed as very poor in each of the last five years and there have been recent declines in the last five years. Seagrass meadow resilience is low (reported as 0 in 2022-2023). Meadows are dominated by the colonising species, *H. ovalis*, as of 2022 and have consistently low seagrass coverage (<5%) reported since 2023. Urangan meadows are also transitory, with cyclical periods of recovery and decline, and little recovery observed until 2021. Additionally, flowering has been observed since 2017. There is, however, good connectivity with other seagrass meadows within 10 km (e.g., Hervey Bay meadows, Booral). Seagrass meadows in Urangan provide several key services, including dugong and sea turtle feeding grounds, and records of high abundance of gastropods and polychaetes, indicating high concentrations of mud and organic detrital matter in the sediments. However, Urangan has a medium risk of exogenic pressures, with two major flooding events occurring in 2022. Endogenic pressures include urban development, stormwater and land run-off, worm digging, and marina development.

There are not well-established delivery or research partners in Urangan, and training partners would require an overnight stay. JCU conducts seagrass monitoring in this region, and CQUniversity in Gladstone is one of the closest research institutes working on seagrass restoration (approximately 230 km away). There are no healthy donor meadows located within 100 km, with the nearest potential donor meadows in the Sunshine Coast (150 km away) and Moreton Bay (200 km away). There are also no existing seagrass nurseries within 100 km of this site, but other infrastructure that could be used to set up nurseries to support restoration efforts are located within 20 km (e.g., Reef World Aquarium, prawn and fish farms, terrestrial plant nurseries). Small-scale restoration trials, however, have occurred for *N. muelleri, H. uninervis*, and *H.ovalis* in Australia, New Zealand, and Indonesia. There is also ongoing large-scale restoration trials of *N. muelleri* occurring across three locations in the GBR. To consider seagrass restoration in Urangan, we recommend investigating potential infrastructure that can be used to set up a seagrass nursery in the region. Additionally, we recommend engaging with local Traditional Owners to build relationships and discuss aspirations for seagrass monitoring and restoration at this site. Further research should also be conducted to enhance our understanding of *H.uninervis* flowering and identify effective methods of restoration. Small-scale trials of *H.uninervis* and *N. muelleri* should also be conducted at the site.

Table 8 Multi-criteria analysis (MCA) for monitoring sites with high temporal resolution and indicate declining trends in seagrass meadows used as case studies to demonstrate the MCA method (MMP, QPSMP). Sites were assessed across 21 criteria to help identify the level of priority for restoration (5 is weighted high).

NRM	Site	Seagrass status	Seagrass trends	Number years sampled	First year sampled	Last year sampled	Seagrass resilience index	Connectivity	Exogenic pressures	Endogenic pressures	Knowledge base for restoration of the species	Species traits	Meadow type	Knowledge base for restoration at that site	End users and funders	Ecosystem services	Accessibility	Delivery partners	Training partners	Research partners	Infrastructure base	Distance to healthy donor meadows
Cape York	Piper Reef	4	5	4	3	5	3	2	5	5	4	5	4	4	4	5	0	4	3	3	1	3
Wet Tropics	Lugger Bay	4	5	4	3	5	5	2	5	3	4	3	4	4	2	3	3	4	4	3	4	3
Wet Tropics	Mourilyan Harbour	5	5	5	5	5	5	3	5	5	4	1	2	5	4	5	1	5	4	5	4	3
Burdekin	Cockle Bay	4	5	4	3	5	5	2	3	5	4	1	2	4	2	5	2	2	5	5	4	5
Mackay-Whitsunday	Pigeon Island	3	3	5	3	5	3	3	3	3	4	3	2	5	5	5	5	5	5	5	5	3
Mackay-Whitsunday	Hamilton Island	5	5	4	3	5	5	3	3	5	4	3	2	4	5	5	2	5	4	5	5	3
Fitzroy	Gladstone Harbour	4	5	4	3	5	3	2	3	5	4	3	4	4	5	5	5	5	5	5	5	5
Fitzroy	Shoalwater Bay	5	3	3	3	5	3	2	3	3	4	3	4	4	2	5	2	4	4	5	5	3
Fitzroy	Great Keppel Island	5	5	4	3	5	5	2	3	3	4	3	4	4	4	5	5	5	4	5	5	5
Burnett-Mary	Rodds Bay	5	3	4	3	5	3	2	3	3	4	3	2	4	2	5	2	4	4	5	5	3
Burnett-Mary	Urangan	5	3	5	5	5	5	2	3	3	4	1	2	4	2	5	1	4	3	3	4	1

6. SUMMARY OF KEY FINDINGS FROM THE ASSESSMENT FRAMEWORK.

Effective conservation of seagrass ecosystems will require novel and strategic investments. Immediate plans and on-ground actions to improve seagrass resilience can be achieved by using existing tools, however, in a rapidly changing world, strategies will need continual improvement by trialling new approaches, by being innovative and by embracing emerging technologies.

Partnerships and people are key to this success. Seagrass ecosystems are generally perceived by the wider public to only support iconic species of conservation concern (e.g. dugong, turtle, seahorse) or provide nursery areas of fish and crustaceans of commercial interest. With the increasing impacts of a changing climate, the acknowledgement of the importance of seagrass carbon storage to climate change mitigation is slowly gaining traction. However, a greater appreciation of the ecological role and the value of ecosystem contributions to human wellbeing is required.

Building scientific literacy and awareness encourages confidence and involvement of wider public in decisions that affect them. Formal and informal educational programmes coupled with proactive science–media partnerships are required.

Engagement in organized citizen science programs (e.g. SeagrassSpotter and The Great Reef Census) can instil a sense of resource pride, and pairing citizen scientists with formally trained scientists in participatory science programs, such as Seagrass-Watch, provides opportunities to collect critical data on seagrass condition and trend (Dalby et al. 2021). Participating in evidence-base gathering eliminates barriers and shifts community thinking so that the wider public are aware of the problems facing seagrass resources to create an understanding of how seagrass damage can impact the economic, cultural and ecological values of our marine resources. The benefit is greater environmental stewardship. This in turn, empowers people to contribute more widely to public policy formulation and debate on environmental issues.

This report highlights that despite the anecdotal and low-resolution data indicating seagrass declines, there is still a concerning lack of data providing clear evidence of declines to a level that could inform and support seagrass restoration at scale. There is also a dearth of information on the restoration techniques for *Halophila minor*, *Thalassodendron ciliatum, or Halophila capricorni* and very few restoration studies on one of the most abundant strap-leaved seagrass *Halodule uninervis*.

 Other research gaps for seagrass function and resilience in the GBR include:

- » Knowledge on site specific delivery of goods and benefits of Reef seagrasses including food webs, biodiversity, water quality improvement, cultural values;
- » Key species and habitats, such as the role of apex predators in maintaining seagrass resilience;
- » Carbon pools and fluxes contributing to the Net Ecosystem Carbon Balance including deepwater habitats and dynamics;
- » Resilience enhancement options (e.g. genetic rescue, where individuals from genetically diverse populations are introduced to genetically depauperate populations to enhance diversity, fitness and adaptive potential and 'assisted migration' of species);
- » Critical processes (e.g. reproduction, growth, connectivity, species succession) and timelines for natural seagrass recovery;

- » Scalability of different restoration approaches;
- » The conditions that lead to high-density seed banks in some areas, and low or no seed banks in others;
- » The role of benthic substrate and biogeochemical processes in facilitating recovery and in restoration success.

Specific knowledge gaps relevant to seagrass restoration include:

- » Improve understanding of the role inter-connected ecosystems outside the Marine Park have in supporting Reef resilience.
- » Resilience is characterised by process-based metrics. These need to be quantified and the functional groupings of species established based on these so that we can simplify and improve protection and management strategies of seagrass habitat.
- » There are many gaps including tolerance range for some species (e.g. *Enhalus*, *Thalassia*, *Syringodium*) and genototypes, and how fringe communities (e.g. edge of range), changes in growth substrate (e.g. changes in sediment type, and bio-geochemical processes), and cumulative pressures.
- » Connectivity between metapopulations in the network will be critical to ensure they function as an interconnected network, not stand alone refugia. Existing models of connectivity (seagrass dispersal and settlement) are limited to a single region (e.g. central Reef) (Grech et al. 2016) or subregion (e.g. Whitsunday Islands and Gladstone Harbour) (Jackson et al. 2021a, Jackson et al. 2021c), and will need to be completed for the remaining regions and scaled up to Reef-wide. The time-scales over which recruitment occurs over such distances is not known within the Reef and will need investigating.
- » Progress has been made in understanding how pressures affect seagrass habitat of the Reef. But there are many gaps including tolerance for some species (e.g. *Enhalus*, *Thalassia*, *Syringodium).*

7. RECOMMENDATIONS

Based on the gaps and information collated by this study we propose the following top five recommendations:

1. Use this report as a tool to discuss aspirations for restoration and mapping with Traditional Owner groups

The research team respects First Nation People's rights, decision-making and priorities and identify the need for co-design and co-production of a framework for scaling restoration. Within the scope of this project, we undertook a review of instances of Traditional Owner involvement in seagrass management projects, mentions of seagrass in Traditional Owner organization or Traditional Use of Marine Resources Agreements (TUMRA) strategic plans, and applications for seagrass management and training programmes (e.g. involvement in Seagrass-Watch). We recognise that it would be disingenuous to make presumptions about the aspirations or pathways of involvement of Traditional Owners. A genuine and thorough consultation of groups across the GBR, recognising participation with financial compensation, is beyond the scope (budget and timing) of the current project. It will be recommended as the next first step based on the information provided. Acknowledging any restoration activities would require free, prior, and informed consent. Indigenous Engagement Guidelines are being developed under NESP Project 3.2 as a partnership between Charles Darwin University,

NAILSMA and ICIN (https://www.nespmarinecoastal.edu.au/publication/project-3-20-information-sheet/).

Other opportunities here include supporting capacity building in seagrass restoration training (for example CERT III in Conservation and Ecosystem Management (Seagrass Restoration Stream) at CQUniversity) and entrepreneurship for sustainable business models for First Nation led seagrass nurseries and restoration industries.

2. Increase research and restoration trials on *Halodule uninervis* and *Thallasia hemprichii*

To-date the majority of research and restoration trials in the GBR have focused on *Nanozostera muelleri.* Ongoing research on *N. muelleri* continues to be important, however the current project found that of those monitored sites showing trends, many are also dominated by *Halodule uninervis,* yet research on restoring this species in the GBR is limited. As a species tolerant of high temperature this species may shift its distribution southward and replace *Nanozostera muelleri* in the future with climate change predictions.

It is also important to build on initial GBR research on the restoration more persistent species such as *Thallassia* but also initiate research on rarer species such as *Thallasadendron*, which may become Matter of National Ecological Significance.

3. Target restoration research and trials in locations with declining trends, based on high temporal resolution data for intervention.

For near future investment (restoration pilots, research, building capacity, infrastructure, funding opportunities), we recommend focussing on the locations identified in this report in the first instance, as pilots for research on those species at those sites. We recommend the use of the multicriteria analysis results to identify gaps in capacity to prioritise.

4. Target locations with high habitat suitability but no data and high risk, for the establishment of mapping, monitoring and restoration trials.

Given that increasing the availability of long-term mapping is not a data gap that can be addressed in the short term, and seagrass restoration often cannot wait, one option is to combine information on habitat suitability modelling, disturbance risk, and connectivity to identify potential sites for focussing restoration trials. Habitat modelling at a GBR scale has recently been carried out. However, an improved GBR wide risk assessment, which incorporates climate change impacts would need to be carried out to facilitate this.

5. Developing a clear pathway and guidance for the planning and appropriate permitting of seagrass restoration activities.

Despite the recognised importance of seagrass restoration, significant barriers persist, particularly concerning permitting criteria and approval processes. Seagrass restoration projects involve several permitting requirements, which can vary depending on the location and specific

project. A multitude of agencies are involved in overseeing these processes, including local government bodies, the Department of Resources, the Department of Agriculture and Fisheries (DAF), Queensland Parks and Wildlife Service (QPWS), the Department of Environment, Science and Innovation (DESI), and the Great Barrier Reef Marine Park Authority (GBRMPA) (Bell-James et al., 2023). However, complexities arise due to the required permits and the potential for conflicting guidance from different agencies involved in the process. Shumway et al. (2021) identified that streamlining the process and assigning marine restoration policy and legislative responsibilities to a single department could enhance efficiency and reduce complexity. Advocating and lobbying for these changes would significantly increase opportunities for restoring valuable seagrass meadows. Meanwhile working with these agencies to produce a guide to the permitting processes for seagrass restoration in the GBR would be a valuable tool for researchers and practitioners.

8. REFERENCES

Adams, M. P., R. K. Hovey, M. R. Hipsey, L. C. Bruce, M. Ghisalberti, R. J. Lowe, R. K. Gruber, L. Ruiz-Montoya, P. S. Maxwell, D. P. Callaghan, G. A. Kendrick, and K. R. O'Brien. 2016a. Feedback between sediment and light for seagrass: Where is it important? Limnology and Oceanography **61**:1937-1955.

Adams, M. P., R. K. Hovey, M. R. Hipsey, L. C. Bruce, M. Ghisalberti, R. J. Lowe, R. K. Gruber, L. Ruiz-Montoya, P. S. Maxwell, and D. P. Callaghan. 2016b. Feedback between sediment and light for seagrass: Where is it important? Limnology and Oceanography **61**:1937-1955.

Bell-James, J., R. Foster, and N. Shumway. 2023. The permitting process for marine and coastal restoration: A barrier to achieving global restoration targets? Conservation Science and Practice **5**:e13050.

Brodie, J., and J. Waterhouse. 2018. Great Barrier Reef (Australia): A Multi-ecosystem Wetland with a Multiple Use Management Regime. Pages 447-460 *in* C. M. Finlayson, G. R. Milton, R. C. Prentice, and N. C. Davidson, editors. The Wetland Book: II: Distribution, Description, and Conservation. Springer Netherlands, Dordrecht.

Brown, C. J., W. Taylor, C. C. C. Wabnitz, and R. M. Connolly. 2020. Dependency of Queensland and the Great Barrier Reef's tropical fisheries on reef-associated fish. Scientific reports **10**:17801.

Buelow, C. A., R. M. Connolly, M. P. Turschwell, M. F. Adame, G. N. Ahmadia, D. A. Andradi-Brown, P. Bunting, S. W. Canty, J. C. Dunic, and D. A. Friess. 2022. Ambitious global targets for mangrove and seagrass recovery. Current Biology **32**:1641-1649. e1643.

Carruthers, T., W. C. Dennison, B. Longstaff, M. Waycott, E. Abal, L. McKenzie, and W. Long. 2002. Seagrass habitats of northeast Australia: models of key processes and controls. Bulletin of Marine Science **71**:1153-1169.

Carter, A. B., C. Collier, E. Lawrence, M. A. Rasheed, B. J. Robson, and R. Coles. 2021. A spatial analysis of seagrass habitat and community diversity in the Great Barrier Reef World Heritage Area. Scientific Reports **11**:22344.

Carter, A. B., S. A. McKenna, M. A. Rasheed, L. J. McKenzie, and R. G. Coles. 2016. Seagrass mapping synthesis: A resource for coastal management in the Great Barrier Reef World Heritage Area. Report to the National Environmental Science Programme., Reef and Rainforest Research Centre Limited, Cairns.

Chartrand, K. M., C. V. Bryant, A. B. Carter, P. J. Ralph, and M. A. Rasheed. 2016. Light thresholds to prevent dredging impacts on the great barrier reef seagrass, *Zostera muelleri* ssp. *capricorni*. Frontiers in Marine Science **3**.

Coles, R., A. Grech, L. McKenzie, and M. Rasheed. 2011. Evaluating risk to seagrasses in the tropical Indo-Pacific region. CERF 2011. Pages 6-10 *in* 21st Biennial Conference of the Coastal and Estuarine Research Federation Conference Abstracts. Societies, Estuaries & Coasts: Adapting to Change.

Coles, R., L. McKenzie, G. De'ath, A. Roelofs, and W. Lee Long. 2009a. Spatial distribution of deepwater seagrass in the inter-reef lagoon of the Great Barrier Reef World Heritage Area. Pages 57-68 Marine Ecology Progress Series.

Coles, R., L. McKenzie, G. De'ath, A. Roelofs, and W. L. Long. 2009b. Spatial distribution of deepwater seagrass in the inter-reef lagoon of the Great Barrier Reef World Heritage Area. Marine Ecology Progress Series **392**:57-68.

Coles, R., L. J. McKenzie, G. De'ath, A. Roelofs, and W. J. Lee Long. 2009c. Spatial distribution of deepwater seagrass in the inter-reef lagoon of the Great Barrier Reef World Heritage Area. Marine Ecology Progress Series **392**:57-68.

Coles, R. G., M. A. Rasheed, L. J. McKenzie, A. Grech, P. H. York, M. Sheaves, S. McKenna, and C. Bryant. 2015. The Great Barrier Reef World Heritage Area seagrasses: Managing this iconic Australian ecosystem resource for the future. Estuarine, Coastal and Shelf Science **153**:A1-A12.

Collier, C. J., L. Langlois, Y. Ow, C. Johansson, M. Giammusso, M. P. Adams, K. R. O'Brien, and S. Uthicke. 2018. Losing a winner: thermal stress and local pressures outweigh the positive effects of ocean acidification for tropical seagrasses. New Phytologist **219**:1005-1017.

Collier, C. J., L. Langlois, M. Waycott, and L. McKenzie. 2021a. Resilience in practice: development of a seagrass resilience metric for the GBR inshore seagrass marine monitoring program.

Collier, C. J., L. Langlois, M. Waycott, and L. J. McKenzie. 2021b. Resilience in practice: Development of a seagrass resilience metric for the Great Barrier Reef Marine Monitoring Program. Great Barrier Reef Marine Park Authority, Townsville.

Collier, C. J., L. M. Langlois, K. M. McMahon, J. Udy, M. Rasheed, E. Lawrence, A. Carter, M. W. Fraser, and L. Mckenzie. 2021c. What lies beneath: predicting seagrass below-ground biomass from above-ground
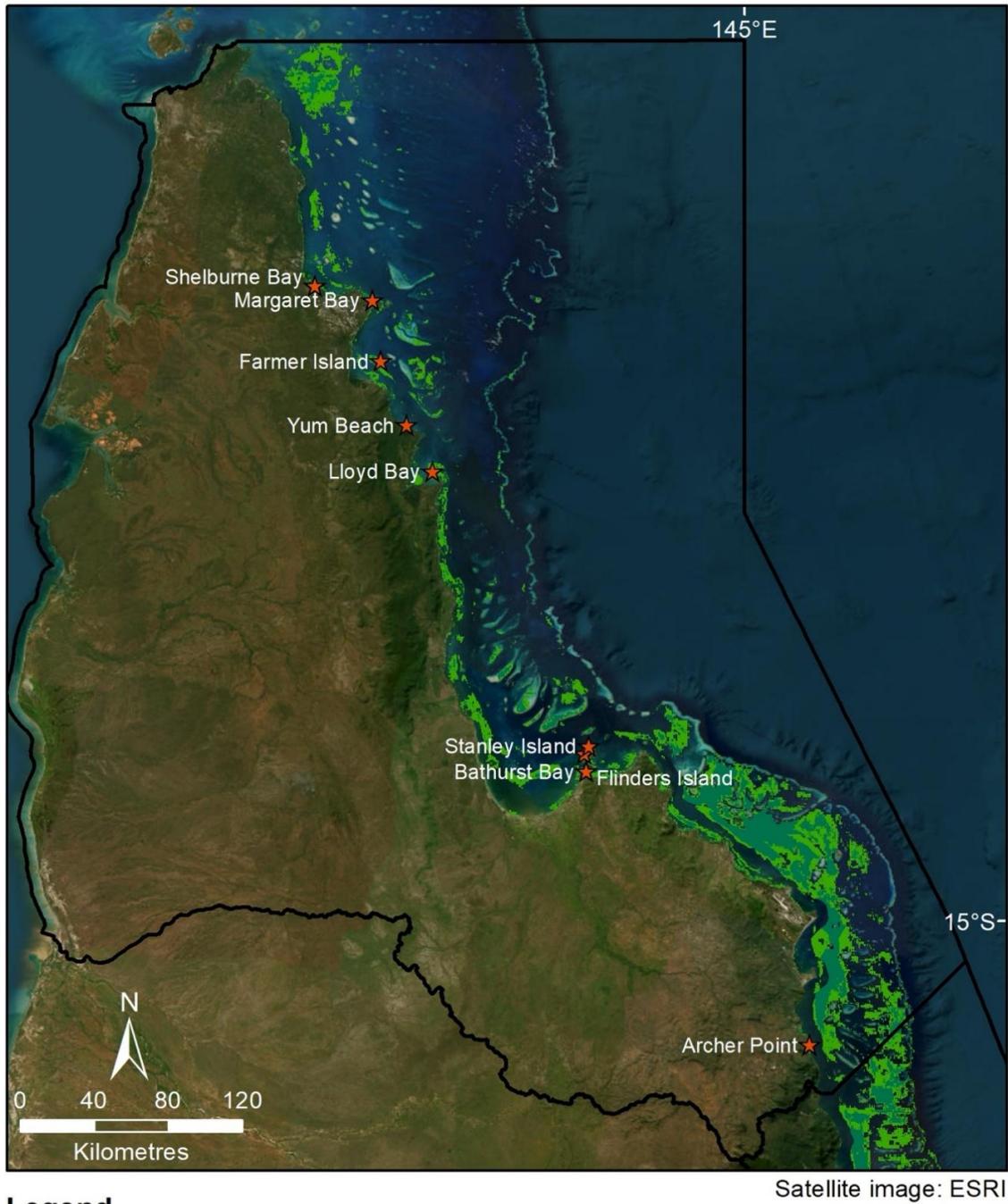
biomass, environmental conditions and seagrass community composition. Ecological Indicators **121**:107156.

Collier, C. J., S. Uthicke, and M. Waycott. 2011. Thermal tolerance of two seagrass species at contrasting light levels: implications for future distribution in the Great Barrier Reef. Limnology and Oceanography **56**:2200-2210.

Collier, C. J., J. van Dijk, M. Adams, K. O'Brien, M. Waycott, L. J. McKenzie, S. Uthicke, C. Johansson, Y. O. Xiang, L. Langlois, S. R. Phinn, and C. M. Roelfsema. 2016. Seagrass growth and diversity: attributes of a resilient GBR, in Annual Report to the Great Barrier Reef Foundation. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook University, Cairns.

Couchman, D., and J. Beumer. 2007. Management and protection of marine plants and other tidal fish habitats. Queensland Department of Primary Industries and Fisheries, Fish Habitat Management Operational Policy FHMOP 001.

Dalby, O., I. Sinha, R. K. F. Unsworth, L. J. McKenzie, B. L. Jones, and L. C. Cullen-Unsworth. 2021. Citizen Science Driven Big Data Collection Requires Improved and Inclusive Societal Engagement. Frontiers in Marine Science **8**.

Duarte de Paula Costa, M., C. E. Lovelock, N. J. Waltham, M. Young, M. F. Adame, C. V. Bryant, D. Butler, D. Green, M. A. Rasheed, C. Salinas, O. Serrano, P. H. York, A. A. Whitt, and P. I. Macreadie. 2021. Current and future carbon stocks in coastal wetlands within the Great Barrier Reef catchments. Global Change Biology **27**:3257-3271.

Dunic, J. C., C. J. Brown, R. M. Connolly, M. P. Turschwell, and I. M. Côté. 2021. Long-term declines and recovery of meadow area across the world's seagrass bioregions. Global Change Biology **27**:4096-4109.

Ferretto, G., T. M. Glasby, A. G. Poore, C. T. Callaghan, G. P. Housefield, M. Langley, E. A. Sinclair, J. Statton, G. A. Kendrick, and A. Vergés. 2021. Naturally-detached fragments of the endangered seagrass Posidonia australis collected by citizen scientists can be used to successfully restore fragmented meadows. Biological Conservation **262**:109308.

Grech, A., R. Coles, and H. Marsh. 2011a. A broad-scale assessment of the risk to coastal seagrasses from cumulative threats. Marine Policy **35**:560-567.

Grech, A., R. G. Coles, and H. March. 2011b. A broad-scale assessment of the risk to coastal seagrasses from cumulative threats. Marine Policy **35**:560-567.

Grech, A., E. Hanert, L. McKenzie, M. Rasheed, C. Thomas, S. Tol, M. Wang, M. Waycott, J. Wolter, and R. Coles. 2018. Predicting the cumulative effect of multiple disturbances on seagrass connectivity. Global Change Biology. Wiley/Blackwell (10.1111).

Grech, A., J. Wolter, R. Coles, L. McKenzie, M. Rasheed, C. Thomas, M. Waycott, and E. Hanert. 2016. Spatial patterns of seagrass dispersal and settlement. Diversity and Distributions **22**:1150-1162.

Gullström, M., M. Bodin, P. G. Nilsson, and M. C. Öhman. 2008. Seagrass structural complexity and landscape configuration as determinants of tropical fish assemblage composition. Marine Ecology Progress Series **363**:241-255.

Halpern, B. S., M. Frazier, J. Afflerbach, J. S. Lowndes, F. Micheli, C. O'Hara, C. Scarborough, and K. A. Selkoe. 2019. Recent pace of change in human impact on the world's ocean. Scientific reports **9**:11609.

Hayes, M. A., E. C. McClure, P. H. York, K. I. Jinks, M. A. Rasheed, M. Sheaves, and R. M. Connolly. 2020. The Differential Importance of Deep and Shallow Seagrass to Nekton Assemblages of the Great Barrier Reef. Diversity **12**.

Holmer, M. 2019. Productivity and biogeochemical cycling in seagrass ecosystems. Pages 443-477 Coastal wetlands. Elsevier.

Infantes, E., S. Hoeks, M. P. Adams, T. van der Heide, M. M. van Katwijk, and T. J. Bouma. 2022. Seagrass roots strongly reduce cliff erosion rates in sandy sediments. Marine Ecology Progress Series **700**:1-12.

Jackson, E. L., C. Aiken, R. Mulloy, L. Harrison, and L. J. McKenzie. 2021a. Resilience-based mapping to support seagrass restoration and management in the Whitsundays. Reporting Period Jul–Dec 2020. Whitsunday Reef Islands Initiative - Draft report. CMERC, CQUniversity, Gladstone.

Jackson, E. L., T. M. Smith, P. H. York, J. Nielsen, A. D. Irving, and C. D. Sherman. 2021b. An assessment of the seascape genetic structure and hydrodynamic connectivity for subtropical seagrass restoration. Restoration Ecology **29**:e13269.

Jackson, E. L., T. M. Smith, P. H. York, J. Nielsen, A. D. Irving, and C. D. H. Sherman. 2021c. An assessment of the seascape genetic structure and hydrodynamic connectivity for subtropical seagrass restoration. Restoration Ecology **29**:e13269.

James, D., A. Collin, T. Houet, A. Mury, H. Gloria, and N. Le Poulain. 2020. Towards better mapping of seagrass meadows using UAV multispectral and topographic data. Journal of Coastal Research **95**:1117-1121.

Jinks, K. I., C. J. Brown, M. A. Rasheed, A. L. Scott, M. Sheaves, P. H. York, and R. M. Connolly. 2019. Habitat complexity influences the structure of food webs in Great Barrier Reef seagrass meadows. Ecosphere **10**:e02928.

Johnson, J. E., D. J. Welch, P. Marshall, J. Day, N. Marshall, C. Steinberg, J. Benthuysen, C. Sun, J. Brodie, H. Marsh, M. Hamann, and C. A. Simpfendorfer. 2018. Characterising the values and connectivity of the northeast Australia seascape: Great Barrier Reef, Torres Strait, Coral Sea and Great Sandy Strait. Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns.

Karang, I. W. G. A., N. L. P. R. Pravitha, I. W. Nuarsa, and P. Wicaksono. 2024. High-Resolution Seagrass Species Mapping and Propeller Scars Detection in Tanjung Benoa, Bali through UAV Imagery. Journal of Ecological Engineering **25**:161-174.

Kelleway, J. J., O. Serrano, J. A. Baldock, R. Burgess, T. Cannard, P. S. Lavery, C. E. Lovelock, P. I. Macreadie, P. Masqué, M. Newnham, N. Saintilan, and A. D. L. Steven. 2020. A national approach to greenhouse gas abatement through blue carbon management. Global Environmental Change **63**:102083.

Kilminster, K., K. McMahon, M. Waycott, G. A. Kendrick, P. Scanes, L. McKenzie, K. R. O'Brien, M. Lyons, A. Ferguson, and P. Maxwell. 2015a. Unravelling complexity in seagrass systems for management: Australia as a microcosm. Science of the Total Environment **534**:97-109.

Kilminster, K., K. McMahon, M. Waycott, G. A. Kendrick, P. Scanes, L. McKenzie, K. R. O'Brien, M. Lyons, A. Ferguson, P. Maxwell, T. Glasby, and J. Udy. 2015b. Unravelling complexity in seagrass systems for management: Australia as a microcosm. Science of The Total Environment **534**:97-109.

King, O. C., R. A. Smith, M. S. J. Warne, J. P. van de Merwe, R. M. Connolly, and C. J. Brown. 2021. Combined impacts of photosystem II-inhibiting herbicides and light availability on seagrass and marine microalgae. Marine Ecology Progress Series **668**:215-230.

Lambert, V., Z. T. Bainbridge, C. Collier, S. E. Lewis, M. P. Adams, A. Carter, M. I. Saunders, J. Brodie, R. D. R. Turner, M. A. Rasheed, and K. R. O'Brien. 2021. Connecting targets for catchment sediment loads to ecological outcomes for seagrass using multiple lines of evidence. Marine Pollution Bulletin **169**:112494.

Lavery, P. S., M.-Á. Mateo, O. Serrano, and M. Rozaimi. 2013. Variability in the Carbon Storage of Seagrass Habitats and Its Implications for Global Estimates of Blue Carbon Ecosystem Service. PloS one **8**:e73748.

Lefcheck, J. S., B. B. Hughes, A. J. Johnson, B. W. Pfirrmann, D. B. Rasher, A. R. Smyth, B. L. Williams, M. W. Beck, and R. J. Orth. 2019. Are coastal habitats important nurseries? A meta-analysis. Conservation letters **12**:e12645.

McGlathery, K. J., K. Sundback, and I. C. Anderson. 2007. Eutrophication in shallow coastal bays and lagoons: the role of plants in the coastal filter. Marine Ecology Progress Series **348**:1-18.

McKenzie, L. J., C. J. Collier, L. A. Langlois, H. Brein, and R. L. Yoshida. In Prep. Marine Monitoring Program: Annual Report for Inshore Seagrass Monitoring 2022-23. Great Barrier Reef Marine Park Authority, Townsville.

McKenzie, L. J., C. J. Collier, L. A. Langlois, and R. L. Yoshida. 2023a. Marine Monitoring Program: Annual Report for inshore seagrass monitoring 2020-2021. Great Barrier Reef Marine Park Authority, Townsville.

McKenzie, L. J., C. J. Collier, L. A. Langlois, and R. L. Yoshida. 2023b. Marine Monitoring Program: Annual Report for Inshore Seagrass Monitoring 2021–22. Report for the Great Barrier Reef Marine Park Authority. Great Barrier Reef Marine Park Authority, Townsville.

McKenzie, L. J., C. J. Collier, L. A. Langlois, R. L. Yoshida, J. Uusitalo, and M. Waycott. 2021a. Marine Monitoring Program: Annual Report for inshore seagrass monitoring 2019-2020. Great Barrier Reef Marine Park Authority.

McKenzie, L. J., C. J. Collier, L. A. Langlois, R. L. Yoshida, J. Uusitalo, and M. Waycott. 2022a. Marine Monitoring Program: Annual Report for inshore seagrass monitoring 2020-2021. Great Barrier Reef Marine Park Authority.

McKenzie, L. J., C. J. Collier, L. A. Langlois, R. L. Yoshida, and M. Waycott. 2022b. Marine Monitoring Program: Annual Report for Inshore Seagrass Monitoring 2020–21. Report for the Great Barrier Reef Marine Park Authority. 2208-4037, Great Barrier Reef Marine Park Authority, Townsville.

McKenzie, L. J., L. M. Nordlund, B. L. Jones, L. C. Cullen-Unsworth, C. Roelfsema, and R. K. Unsworth. 2020. The global distribution of seagrass meadows. Environmental Research Letters **15**:074041.

McKenzie, L. J., C. A. Roder, and R. L. Yoshida. 2016. Seagrass and associated benthic community data derived from field surveys at Low Isles, Great Barrier Reef, conducted July-August, 1997. PANGAEA.

McKenzie, L. J., R. L. Yoshida, J. W. Aini, S. Andréfouet, P. L. Colin, L. C. Cullen-Unsworth, A. T. Hughes, C. E. Payri, M. Rota, C. Shaw, R. T. Tsuda, V. C. Vuki, and R. K. F. Unsworth. 2021b. Seagrass ecosystem contributions to people's quality of life in the Pacific Island Countries and Territories. Marine Pollution Bulletin **167**:112307.

McKenzie, L. J., R. L. Yoshida, and R. K. F. Unsworth. 2014. Disturbance influences the invasion of a seagrass into an existing meadow. Marine Pollution Bulletin **86**:186-196.

McMahon, K., E. A. Sinclair, C. D. Sherman, K.-J. van Dijk, U. E. Hernawan, J. Verduin, and M. Waycott. 2018. Genetic connectivity in tropical and temperate Australian seagrass species. Seagrasses of Australia: Structure, ecology and conservation:155-194.

McMahon, K., K.-j. van Dijk, L. Ruiz-Montoya, G. A. Kendrick, S. L. Krauss, M. Waycott, J. Verduin, R. Lowe, J. Statton, E. Brown, and C. Duarte. 2014. The movement ecology of seagrasses. Proceedings of the Royal Society B: Biological Sciences **281**.

Nordlund, L. M., , E. W. Koch, E. B. Barbier, and J. C. Creed. 2016. Seagrass Ecosystem Services and Their Variability across Genera and Geographical Regions. Page e0163091 PloS one. Public Library of Science.

O'Brien, K. R., M. P. Adams, A. J. P. Ferguson, J. Villarreal-Samper, P. S. Maxwell, M. E. Baird, and C. J. Collier. 2018a. Seagrass resistance to light deprivation: implications for resilience.*in* A. W. D. Larkum, R. P.J., and G. Kendrick, editors. Seagrasses of Australia. Springer International Publishing AG, part of Springer Nature 2018.

O'Brien, K. R., M. Waycott, P. Maxwell, G. A. Kendrick, J. W. Udy, A. J. P. Ferguson, K. Kilminster, P. Scanes, L. J. McKenzie, K. McMahon, M. P. Adams, J. Samper-Villarreal, C. Collier, M. Lyons, P. J. Mumby, L. Radke, M. J. A. Christianen, and W. C. Dennison. 2018b. Seagrass ecosystem trajectory depends on the relative timescales of resistance, recovery and disturbance. Pages 166-176 Marine Pollution Bulletin.

Plaisted, H. K., A. B. Novak, S. Weigel, A. S. Klein, and F. T. Short. 2020. Eelgrass genetic diversity influences resilience to stresses associated with eutrophication. Estuaries and Coasts **43**:1425-1438.

Rasheed, M. A., C. van De Wetering, and A. B. Carter. 2022. Mackay-Whitsunday-Isaac Seagrass Monitoring 2017-2021. Centre for Tropical Water & Aquatic Ecosystem Research Cairns.

Reason, C., P. H. York, and M. Rasheed. 2023a. Seagrass Habitat of Cairns Harbour and Trinity Inlet: Annual Monitoring Report 2022. Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) James Cook University Cairns.

Reason, C., P. H. York, and M. Rasheed. 2023b. Seagrass Habitat of Mourilyan Harbour: Annual Monitoring Report 2022. Centre for Tropical Water & Aquatic Ecosystem Research, JCU Publication

Reason, C. L., S. A. McKenna, and M. A. Rasheed. 2023c. Port of Abbot Point Long-Term Seagrass Monitoring Program - 2022. Centre for Tropical Water & Aquatic Ecosystem Research, Cairns.

Reynolds, L. K., K. DuBois, J. M. Abbott, S. L. Williams, and J. J. Stachowicz. 2016. Response of a habitat-forming marine plant to a simulated warming event is delayed, genotype specific, and varies with phenology. PloS one **11**:e0154532.

Saunders, M. I., E. Bayraktarov, C. M. Roelfsema, J. X. Leona, J. Samper-Villarreal, S. R. Phinn, C. E. Lovelock, and P. J. Mumby. 2015. Spatial and temporal variability of seagrass at Lizard Island, Great Barrier Reef. Botanica Marina **58**:35–49.

Saunders, M. I., N. J. Waltham, T. Cannard, M. Sheppard, M. Fischer, A. Twomey, M. Bishop, K. Boody, D. Callaghan, and B. Fulton. 2022. A roadmap for coordinated landscape-scale coastal and marine ecosystem restoration. Cairns, Australia.

Shumway, N., J. Bell-James, J. A. Fitzsimons, R. Foster, C. Gillies, and C. E. Lovelock. 2021. Policy solutions to facilitate restoration in coastal marine environments. Marine Policy **134**:104789.

Smith, A. J. 1987. An ethnobiological study of the usage of marine resources by two Aboriginal communities on the east coast of Cape York Peninsula, Australia. James Cook University of North Queensland, Townsville.

Turschwell, M. P., R. M. Connolly, J. C. Dunic, M. Sievers, C. A. Buelow, R. M. Pearson, V. J. Tulloch, I. M. Côté, R. K. Unsworth, and C. J. Collier. 2021. Anthropogenic pressures and life history predict trajectories of seagrass meadow extent at a global scale. Proceedings of the National Academy of Sciences **118**:e2110802118.

UNESCO. 2020. UNESCO Marine World Heritage: Custodians of the globe's blue carbon assets. Paris, France.

Unsworth, R. K., L. C. Cullen-Unsworth, B. L. Jones, and R. J. Lilley. 2022. The planetary role of seagrass conservation. Science **377**:609-613.

Unsworth, R. K. F., C. J. Collier, M. Waycott, L. J. McKenzie, and L. C. Cullen-Unsworth. 2015. A framework for the resilience of seagrass ecosystems. Pages 34-46 Marine Pollution Bulletin.

Van Dam, B. R., M. A. Zeller, C. Lopes, A. R. Smyth, M. E. Böttcher, C. L. Osburn, T. Zimmerman, D. Pröfrock, J. W. Fourqurean, and H. Thomas. 2021. Calcification-driven CO_2 emissions exceed "Blue Carbon" sequestration in a carbonate seagrass meadow. Science Advances **7**:eabj1372.

van Katwijk, M. M., A. Thorhaug, N. Marbà, R. J. Orth, C. M. Duarte, G. A. Kendrick, I. H. Althuizen, E. Balestri, G. Bernard, and M. L. Cambridge. 2016. Global analysis of seagrass restoration: the importance of large-scale planting. Journal of Applied Ecology **53**:567-578.

van Katwijk, M. M., B. I. van Tussenbroek, S. V. Hanssen, A. J. Hendriks, and L. Hanssen. 2021. Rewilding the sea with domesticated seagrass. Bioscience **71**:1171-1178.

Waterhouse, J., J. Brodie, D. Tracey, R. Smith, M. VanderGragt, C. Collier, C. Petus, M. Baird, F. Kroon, and R. Mann. 2017. 2017 scientific consensus statement: Land use impacts on the great barrier reef water quality and ecosystem condition, chapter 3: The risk from anthropogenic pollutants to great barrier reef coastal and marine ecosystems.

Waycott, M., G. Procaccini, D. H. Les, and T. B. H. Reusch. 2006. Seagrass Evolution, Ecology and Conservation: A Genetic Perspective. Pages 25-50 SEAGRASSES: BIOLOGY, ECOLOGYAND CONSERVATION. Springer Netherlands, Dordrecht.

Weatherall, E. J., E. L. Jackson, R. A. Hendry, and M. L. Campbell. 2016. Quantifying the dispersal potential of seagrass vegetative fragments: A comparison of multiple subtropical species. Estuarine, Coastal and Shelf Science **169**:207-215.

Wu, P. P.-Y., K. McMahon, M. A. Rasheed, G. A. Kendrick, P. H. York, K. Chartrand, M. J. Caley, and K. Mengersen. 2017. Managing seagrass resilience under cumulative dredging affecting light: Predicting risk using dynamic Bayesian networks. Journal of Applied Ecology **55**:1339-1350.

Yang, B., T. L. Hawthorne, M. Hessing-Lewis, E. J. Duffy, L. Y. Reshitnyk, M. Feinman, and H. Searson. 2020. Developing an introductory UAV/drone mapping training program for seagrass monitoring and research. Drones **4**:70.

York, P. H., P. I. Macreadie, and M. A. Rasheed. 2018. Blue Carbon stocks of Great Barrier Reef deep-water seagrasses. Biology Letters **14**:20180529.

Zinnen, J., L. M. Broadhurst, P. Gibson-Roy, T. A. Jones, and J. W. Matthews. 2021. Seed production areas are crucial to conservation outcomes: benefits and risks of an emerging restoration tool. Biodiversity and Conservation **30**:1233-1256.
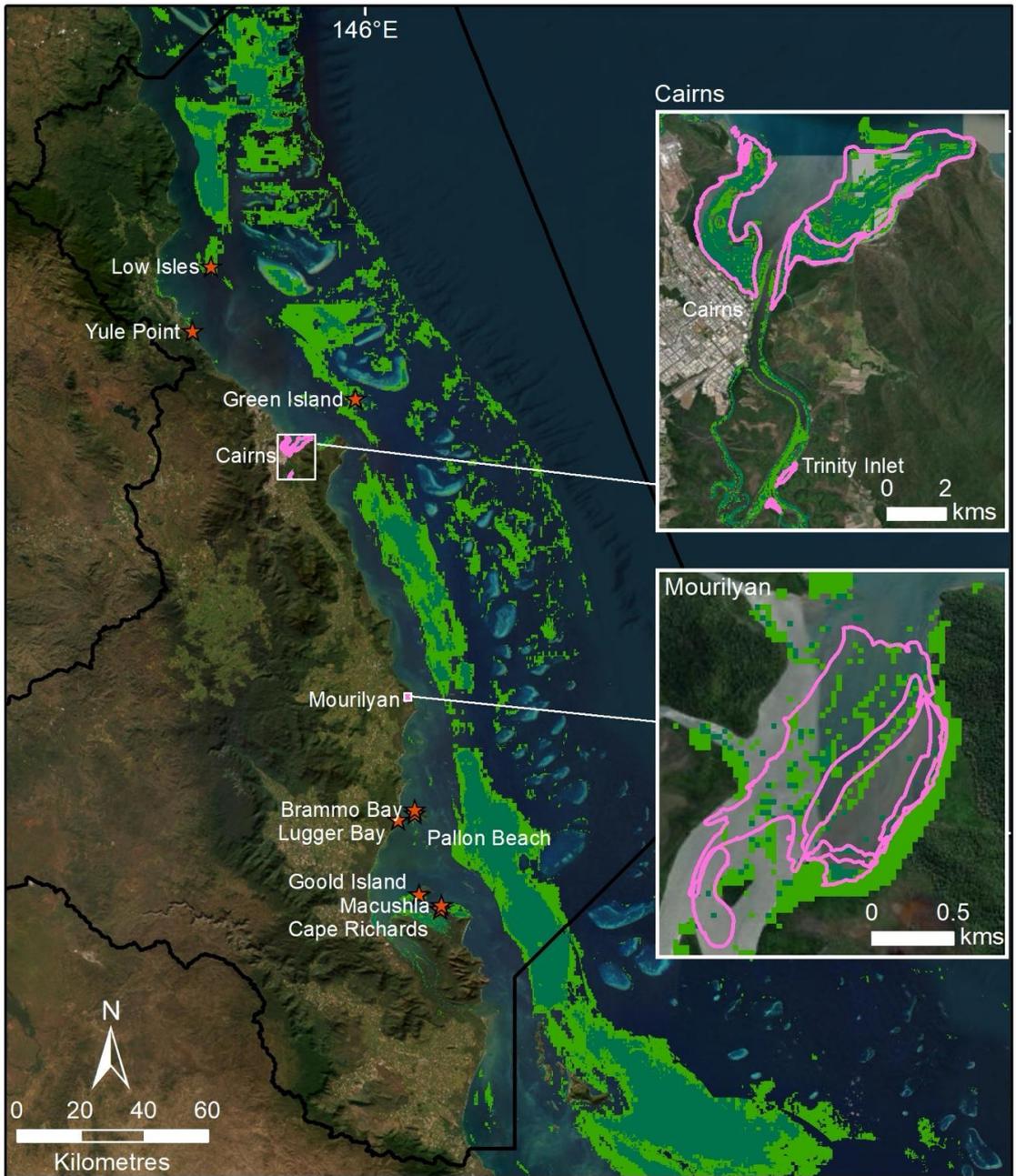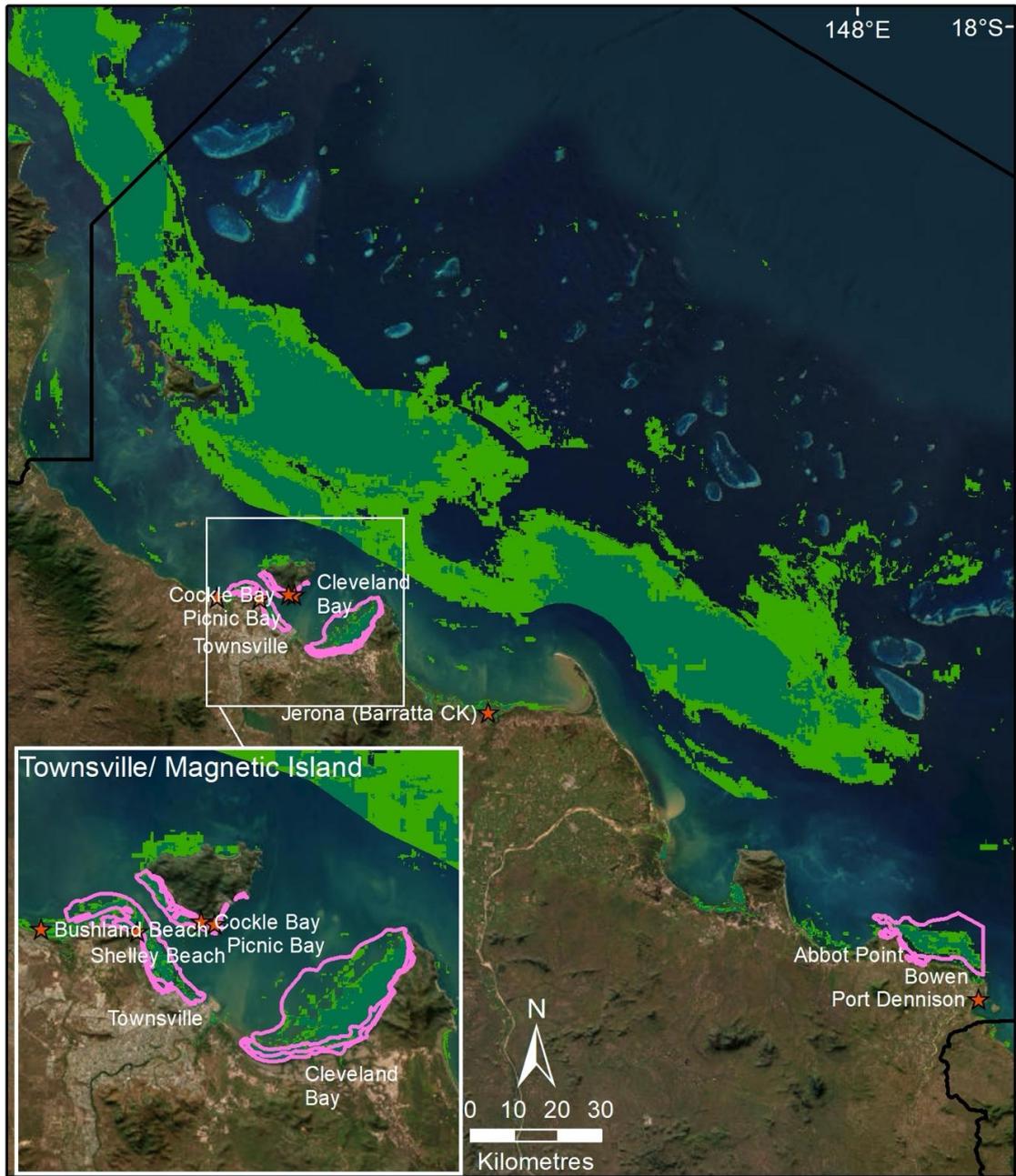
9. APPENDIX 1

Figure 8 Probability of seagrass (habitat suitability) from 0.6 to 0.8 (light green) and 0.8 to 1.0 (dark green) (Carter et al 2021), QPSMP monitoring area (none present in Cape York) and MMP locations (incorporating RJFMP and Seagrass-Watch sites) in the Cape York NRM.

Figure 9 Probability of seagrass (habitat suitability) from 0.6 to 0.8 (light green) and 0.8 to 1.0 (dark green) (Carter et al 2021), QPSMP monitoring area and MMP locations (incorporating RJFMP and Seagrass-Watch sites) in the Wet Tropics NRM.
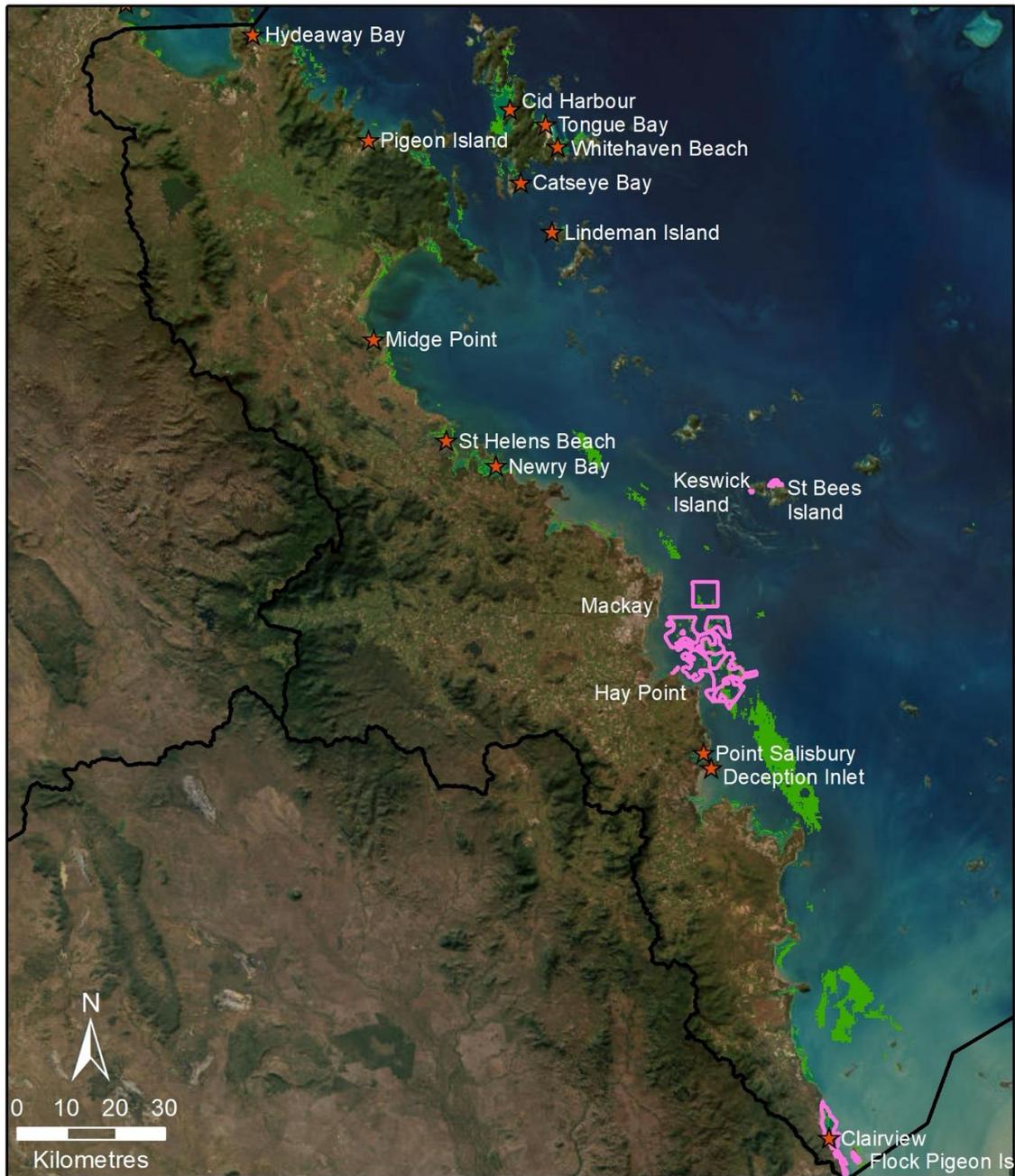
Figure 10 Probability of seagrass (habitat suitability) from 0.6 to 0.8 (light green) and 0.8 to 1.0 (dark green) (Carter et al 2021), QPSMP monitoring area and MMP locations (incorporating RJFMP and Seagrass-Watch sites) in the Burdekin NRM.
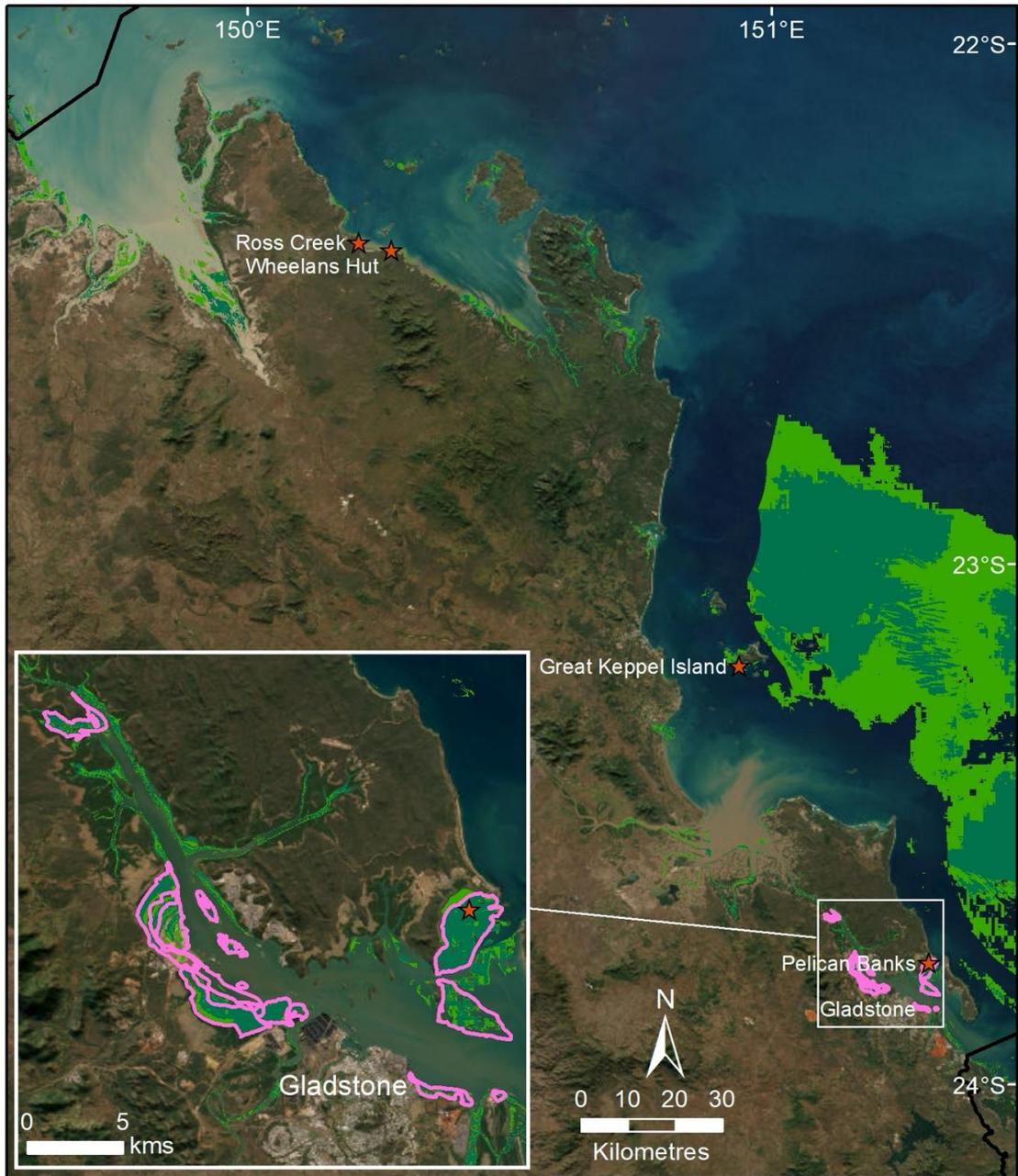
Figure 11 Probability of seagrass (habitat suitability) from 0.6 to 0.8 (light green) and 0.8 to 1.0 (dark green) (Carter et al 2021), QPSMP monitoring area and MMP locations (incorporating RJFMP and Seagrass-Watch sites) in the Mackay-Whitsunday NRM.
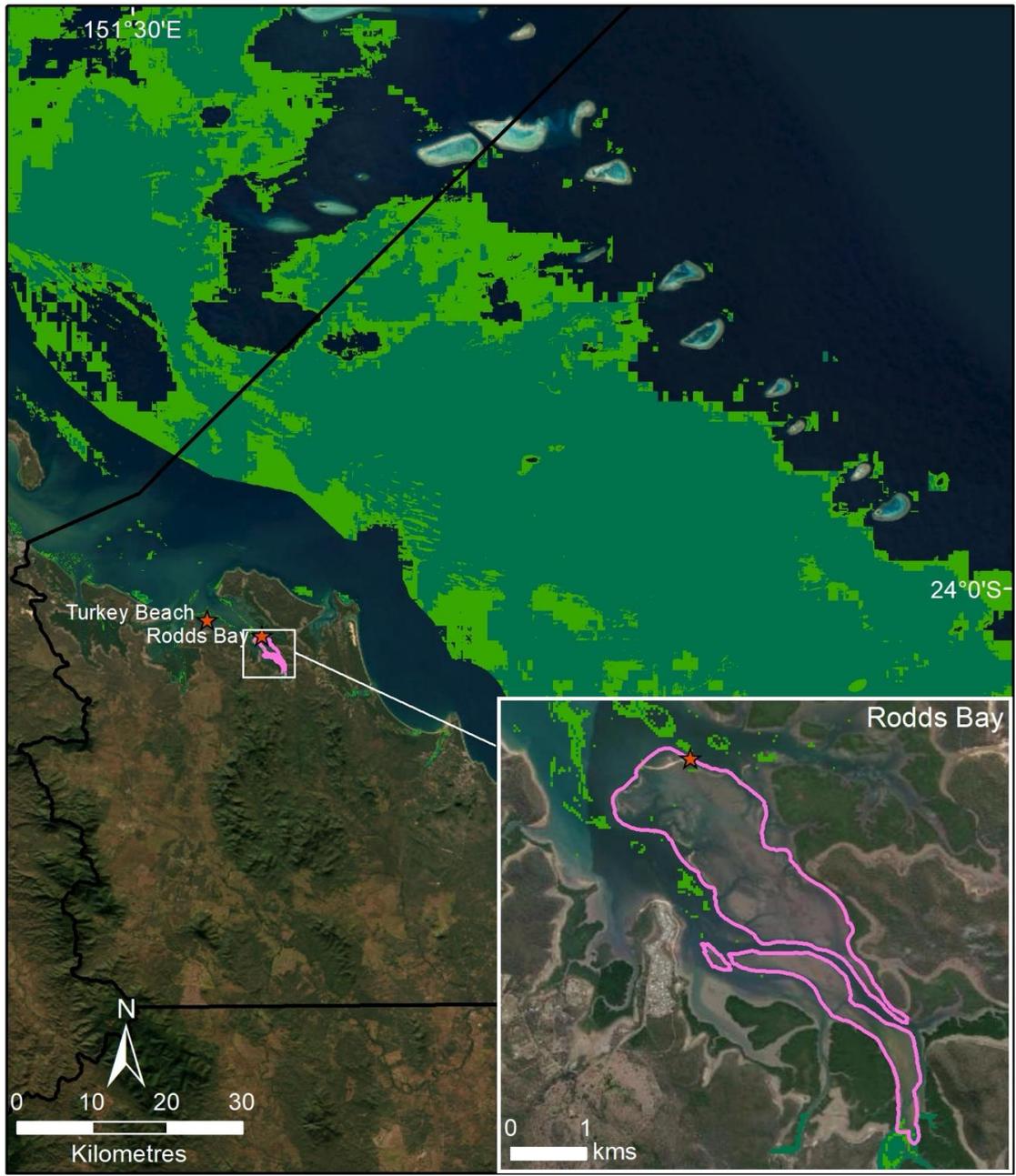
Figure 12 Probability of seagrass (habitat suitability) from 0.6 to 0.8 (light green) and 0.8 to 1.0 (dark green) (Carter et al 2021), QPSMP monitoring area and MMP locations (incorporating RJFMP and Seagrass-Watch sites) in the Fitzroy NRM.

Figure 13 Probability of seagrass (habitat suitability) from 0.6 to 0.8 (light green) and 0.8 to 1.0 (dark green) (Carter et al 2021), QPSMP monitoring area and MMP locations (incorporating RJFMP and Seagrass-Watch sites) in the Burnett-Mary NRM.

Table 9 Existing infrastructure highlighted as high priority (levels 1 and 2) for use as seagrass nurseries in the GBR region. Sites consist of current seagrass nurseries, marine and aquaculture research facilities, aquaria and/or marine education centres, and sea turtle rehabilitation centres.

Existing infrastructure	Location	Latitude	Longitude	Priority level	Notes
Lizard Island Research Station	Lizard Island	-14.67851625	145.4483928	1	marine research station, island
Australian Institute of Marine Science	Townsville	-19.2678223	147.0556932	1	marine research station, coastal
UQ Heron Island Research Station	Gladstone	-23.44424935	151.9111534	1	marine research station, island
Coastal Marine Ecosystems Research Centre, Gladstone SeaGrow	Gladstone	-23.83148142	151.2397548	1	marine research station, seagrass nursery, coastal
Coral Sea Marina seagrass nursery	Airlie Beach	-20.26413665	148.7133784	1	seagrass nursery, coastal
Konomie Island SeaGrow	North Keppel Island	-20.26413665	148.7133784	1	seagrass nursery, island
Marine and Aquaculture Research Facilities Unit (MARFU), James Cook University	Townsville	-19.32784256	146.7609367	2	aquaculture research institute, inland
Reef Research Aquarium Laboratories	Townsville	-19.32904652	146.7609623	2	aquaculture research institute, inland
JCU eduQuarium	Smithfield	-16.81663128	145.6873829	2	aquarium and education centre, research station, inland
Cairns Aquarium	Cairns	-16.91824998	145.7737818	2	aquarium, coastal
Aquasearch Aquarium	Magnetic Island	-19.15207663	146.8473083	2	aquarium and research laboratory, island
Great Barrier Reef Aquarium	Townsville	-19.25733905	146.823048	2	aquarium, coastal
Reef World Aquarium	Urangan	-25.28811838	152.9084051	2	aquarium, coastal
Fitzroy Island Turtle Rehabilitation Centre	Fitzroy Island	-16.92770009	145.990562	2	turtle rehabilitation centre, coastal
Quoin Island Turtle Rehabilitation Centre	Gladstone	-23.81128634	151.2862042	2	turtle rehabilitation centre, coastal

Table 10 Level descriptor rubric for the application of the multi-criteria analysis

Criteria	Score descriptors (scores 5 is weighted high)					
	5	4	3	2	1	0
Seagrass status (Inshore Marine Monitoring Program or Queensland Ports Seagrass Monitoring Program - most recent report results)	Classed as very poor in the last 5 years	Classed as poor in the last 5 years	Classed as satisfactory in the last 5 years	Classed as good in the last 5 years	Classed as very good in the last 5 years	No data available (never mapped or monitored) but high habitat suitability - mapping data gap
Seagrass trends	Long-term trends of decline		recent declines (over the last 5 years)		no data available	
Number of year sampled	>20	10 to 20	5 to 10	2 to 5	<2	None
First year sampled	>20		10 to 20 years ago		<10 years ago	
Last year sampled	In the last 3 years		3 to 10 years ago		>10 years ago	
Seagrass resilience index (Inshore Marine Monitoring Program)	0-30		30-70		70-100	
Connectivity	Very isolated meadow, no other seagrass within 50km	Isolated meadow no other seagrass meadow within 10 km	Some connectivity to other meadows within 50 km	Well connected to other seagrass meadows within 10 km	Strong evidence (hydrodynamic modelling and genetics) that the meadow is a sink for propagules from other meadows	
Exogenic pressures	High frequency of flooding/ cyclones, heat stress, nutrient enrichment etc.		Medium frequency of flooding /cyclones, heat stress, nutrient enrichment etc.		No exogenic pressures	
Endogenic pressures	Local manageable pressures with management in place		Local manageable pressures with no management in place		No endogenic pressures	
Knowledge base for restoration of that species	Successful large scale field trials of restoration for this species in the GBR	Successful small scale field trials of restoration for this species	Successful large-scale trials of restoration for this genus	Successful small scale field trials of restoration for this genus	No restoration research on this species	
Species traits - connectivity, resilience at this stage	Persistent		Opportunistic		Colonising	
Meadow type		Persistent		Transitory		Unknown
Knowledge base for restoration of that site	Successful trials at the site, established seagrass nursery protocols	Understanding of species dynamics and environmental conditions at this site	Understanding of environmental conditions at the site	Understanding of the species in similar sites	Understanding of the species at different sites	No applicable knowledge for restoration at these sites
"End users"/ funders	Site-specific long-term funder/end-user already engaged (e.g. seagrass habitat creation/restoration identified for offset requirements or another funded	Site-specific long-term funder/end user identified	General mid term funding available.	Initial short term/ start up funding may be available	No identifiable funders but strong community TO aspirations	No identifiable funders
Ecosystem services	Data exist demonstrating the value of the seagrass site in terms of a key ecosystem service		No data available on ecosystem services at the site		No data available on ecosystem services for this species and environment	
Accessibility	Within 10km of facility or research base and site easily accessible for volunteers and research practitioners. and/or Close to a town/volunteer base and donor/restoration site is easily accessible	Close to a town/volunteer base and donor site is easily accessible >10 km from research base/ facility but <10km to a major town of >10000 people	Close to a town/volunteer base and sites are accessible	Close to a town/volunteer base but sites are difficult to access (e.g. require boat transport)	Accessible but not close a town	Isolated location with poor access
Delivery partners	Established partnerships between researchers, managers, Traditional Owners, other stakeholders (e.g. OzFish, fishing groups)	Some relevant established partnerships	Recent partnerships	No partnerships		
Training partners	Training partners within 20km	Training partners within a day trip	Training partners would require over night stay	Training partners would require over night stay		
Research partners	Multiple researchers working on seagrass in the region and research centre/facility within 100km	Multiple researchers working on seagrass in the region or research centre/facility > 100km	At least one research group working on seagrass in region	No research carried out on the site's seagrass	No research on seagrass carried out within 100km of the site	Unknown
Infrastructure base	Existing seagrass nursery within 100km of site	Potential research aquaria infrastructure	Terrestrial nursery within 1 km coast	Terrestrial nursery within 10km of coast	No existing facility within 100km	
Distance to healthy donor meadows	<10km		<100km		>100km	