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Synthesis Report: Defining thresholds and indicators of primary producer response to dredging-related pressures: Report of Theme 5 prepared for the Dredging Science Node

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Defining thresholds and indicators of primary producer response to dredging-related pressures | Synthesis Report

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WAMSI Dredging Science Node

Theme 5 Report

Project 5.6

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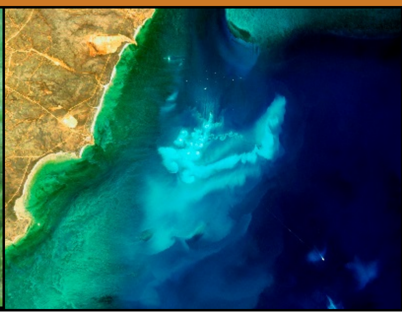
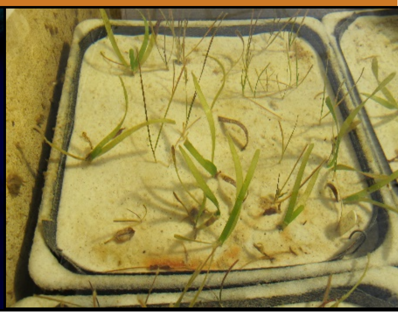

WAMSI Dredging Science Node

The WAMSI Dredging Science Node is a strategic research initiative that evolved in response to uncertainties in the environmental impact assessment and management of large-scale dredging operations and coastal infrastructure developments. Its goal is to enhance capacity within government and the private sector to predict and manage the environmental impacts of dredging in Western Australia, delivered through a combination of reviews, field studies, laboratory experimentation, relationship testing and development of standardised protocols and guidance for impact prediction, monitoring and management.

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The $20 million Dredging Science Node is delivering one of the largest single issue environmental research programs in Australia. This applied research is funded by **Woodside Energy, Chevron Australia, BHP Billiton and the WAMSI Partners** and designed to provide a significant and meaningful improvement in the certainty around the effects, and management, of dredging operations in Western Australia. Although focussed on port and coastal development in Western Australia, the outputs will also be broadly applicable across Australia and globally.

This remarkable **collaboration between industry, government and research** extends beyond the classical funder-provider model. End-users of science in regulator and conservation agencies, and consultant and industry groups are actively involved in the governance of the node, to ensure ongoing focus on applicable science and converting the outputs into fit-for-purpose and usable products. The governance structure includes clear delineation between end-user focussed scoping and the arms-length research activity to ensure it is independent, unbiased and defensible.

And critically, the trusted across-sector collaboration developed through the WAMSI model has allowed the sharing of hundreds of millions of dollars worth of environmental monitoring data, much of it collected by environmental consultants on behalf of industry. By providing access to this usually **confidential data,** the **Industry Partners** are substantially enhancing WAMSI researchers' ability to determine the real-world impacts of dredging projects, and how they can best be managed. Rio Tinto's voluntary data contribution is particularly noteworthy, as it is not one of the funding contributors to the Node.

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Front cover images (L-R)

Image 1: Trailing Suction Hopper Dredge *Gateway* in operation during the Fremantle Port Inner Harbour and Channel Deepening Project. (Source: OEPA)

Image 2: *Halophila ovalis* meadow in the Pilbara region of Western Australia. (Source: Kathryn McMahon)

Image 3: Dredge Plume at Barrow Island. Image produced with data from the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) taken on 29/08/2010.

Image 4: Pot with mixed seagrass species in the UWA Seagrass Facility at commencement of the Light-Frequency experiment. (Source: John Statton).

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1 Introduction

1.1 Seagrasses

Seagrasses form a small component of a diverse group of organisms termed 'benthic primary producers'. Benthic primary producers are organisms that grow on the sea-bed that obtain some or all of their energy needs from photosynthesis. This includes animals such as scleractinian corals and some sponges that host microscopic intercellular algae, coralline and turf algae, and the larger seaweeds such as the kelps and sargassum. Seagrasses are marine flowering plants, more closely related to land plants than seaweeds and algae. Seagrasses live mostly in soft sediments, and can be found from the shallow intertidal zone through to a depth of 60 m when waters are exceptionally clear allowing sufficient sunlight to reach the seafloor. Some species form persistent underwater meadows, while others form transitory meadows, and occur in low-density patches or as understorey species. Seagrasses typically require more light than algae to survive because of the respiratory demand of the underground roots and rhizomes. Seagrasses provide many important services. As primary producers, they contribute to the base of the marine foodweb and the habitats they form are important nursery areas for commercially-important prawns and provide shelter and foraging grounds for many species of fish. Seagrasses also play an important role in recycling nutrients, filtering water, sequestering carbon from the atmosphere and protecting the coastline from erosion. Because they are sensitive to change, they make useful indicators of environmental health. Furthermore, tropical seagrasses are essential food sources for dugong which is a marine mammal of particular conservation and Indigenous cultural interest.

Corals and sponges are the focus of dedicated research programs (see Theme 4 and Theme 6 synthesis reports, Jones et al. (2019), Wahab et al. (2019)). While macroalgae are also important primary producers, the Theme 5 research focussed on seagrasses because these were considered to be more sensitive to dredging-related pressures and less likely to be able to recover quickly from severe disturbance.

The WAMSI Dredging Science Node Theme 5 research program was undertaken to improve our understanding of the ecology and biology of seagrasses in the north west of Western Australia (NW WA), how they respond to dredging-induced pressures and how we can better predict and manage the impacts of dredging on them.

1.2 The importance of seagrasses in north west Western Australia

Western Australia is a global hotspot for seagrass biodiversity. There is a clear latitudinal gradient in seagrass species distribution along the Western Australian coast with a marked transition between temperate and tropical species occurring around Shark Bay. Shark Bay is arguably one of the world's largest seagrass based ecosystems (Walker 1989) and is dominated by temperate meadow forming seagrasses but also includes practically the full range of tropical species known in the State. The temperate species often form perennial meadows with high above ground biomass and are clearly visible in aerial and satellite imagery. Tropical species however do not typically form dense perennial meadows – they are typically ephemeral, have low above-ground biomass and occur in small patches or sparse meadows. The plants are often only a few centimetres tall and can be difficult to detect even with remote underwater video systems.

Recent work in the wet-tropics (Kimberley) has shown that deep water seagrasses are highly seasonal, with peak biomass in late spring, dying off over the summer wet season and then re-establishing from seed during the dry autumn and winter periods. From Shark Bay and southwards seagrasses have peak biomass in summer with declines during the winter months. The extent of any seasonality of seagrasses on the Pilbara coast is less well understood.

Although the biomass of tropical seagrasses on a unit area basis is relatively low, they are highly productive and provide a host of valuable ecological functions and ecosystem services. They provide the essential food requirements for one of the world's largest dugong populations and provide habitats critical to a wide variety of wildlife and economically important fisheries. A strong positive link has been established between seagrass biomass in Exmouth Gulf and the productivity of the prawning industry in Exmouth Gulf (Loneragon et al. 2013).

1.3 State of knowledge prior to the WAMSI Dredging Science Node

At the commencement of the Theme 5 research program we had a rudimentary understanding of the seagrasses present in NW WA. Earlier works (summarised in McMahon et al. 2015c) had recorded 11 species of seagrass occurring in the Pilbara and the Kimberley and the habitats in which they were likely to occur. The abundance of seagrasses was understood to be highly variable across NW WA, a vast area encompassing the sub-tropical Gascoyne, arid Pilbara and tropical Kimberley regions (approximately 10 degrees of latitude and 14 degrees of longitude). There was no clear picture of the annual and inter-annual dynamics of seagrasses in the regions. Studies in Exmouth Gulf indicated large inter-annual variability in the composition and abundance of seagrasses (e.g. Loneragon et al. 2013) while studies in the Kimberley suggested an annual pattern of abundance and reproduction in meadows dominated by opportunistic species (e.g. Hovey et al. 2015). On very limited information, the following generalisations emerged:

- Meadows were of two fundamental types, enduring or transitory;
- Transitory meadows could display an annual cycle in biomass and reproduction, with biomass loss in the wet season (summer) and recovery in the dry season (winter-spring) and reproduction in late winter and spring;
- Enduring meadows could show seasonality with maximum cover in the late dry to early wet season and minimum cover following the wet season and into the early dry season; and
- There can be strong inter-annual variability, in some case regular and predictable repeats of an annual cycle and in other cases less predictable changes in composition and abundance following major disturbances, such as cyclones.

Importantly, some unpublished literature, and particularly environmental impact assessment documents, presented a view that many meadows were highly transitory and so had mechanisms (presumably seed banks) to aid recovery, leading to the view that they would likely recover rapidly from dredging impacts and need not be considered within impact assessments. There was also a general view that in many dredging projects the background turbidity of sites affected by dredging was naturally high and variable, making it questionable whether dredging would significantly reduce the quantity or quality of light seagrasses experience.

Key information gaps lay in our understanding of spatial and temporal variability in seagrass abundance and composition (and the reasons for that variability), the timing and significance of reproduction, the relative importance of sexual and asexual modes of reproduction in the recovery of seagrasses following disturbance, the baseline environmental conditions at seagrass sites (e.g. turbidity, light intensity) and the nature and magnitude of dredging-induced changes to light climate in what were considered to be naturally highly turbid environments.

Our understanding of how the seagrasses might be affected by dredging was based on the global scientific literature. The main pressures exerted by dredging were considered to be the associated reductions in light availability and smothering when re-suspended sediments settle on the seabed (Erftemeijer & Lewis 2006). Most of the studies addressing the impact of dredging on seagrasses had focussed on these two pressures, though always in isolation; none had addressed the interactive effects. Key information gaps included: species-specific responses to reductions in light intensity; responses to burial under reduced light conditions; whether the nature (inorganic v organic) of the sediment resuspended during dredging affected the seagrass response; the effect of dredging-induced changes in the spectral quality of light on seagrass; and a lack of *in situ* data describing the light reduction and sediment deposition stress fields that are generated by dredging projects.

In Western Australia, and some other parts of Australia, the potential for dredging to impact seagrass habitat is managed through the EPA's (2016) framework. That framework requires proponents to predict the pressure fields that their dredging activities will produce and the biological responses to these pressure fields. For approved projects, proponents are generally required to implement environmental monitoring programs to inform management and to determine compliance with approval conditions. To meet these requirements, it is necessary to:

- Predict responses: this requires a sound understanding of the thresholds of tolerance of the various habitat-forming species to the pressures generated;
- Predict the persistence of those effects: requiring an understanding of the ability of the habitat to recover following particular severities and durations of pressure; and
- Monitor and manage impacts and validate predictions: requiring a management framework that includes robust monitoring protocols.

Despite the long-term and widespread nature of dredging, there is surprisingly little convincing information in the scientific literature that can be used to meet the information requirements of the EPA's framework for seagrasses. We have a general understanding of how seagrasses will respond to the environmental changes produced by dredging (Erftemeijer & Lewis 2006). This understanding is based on studies of a small number of species, yet as different species of seagrasses have different life-history strategies and potentials to resist and recover from disturbance, the magnitude, duration and frequency of stress they can cope with and recover from will vary among species (Kilminster et al. 2015, McMahon et al. 2017c). Furthermore, some of our understanding has been derived from studies of non-dredging related pressures and may not necessarily reflect the effects of dredging. For example, a lot of what we know about the responses of seagrasses to sediment burial has been derived from studies that mimicked burial by benthic animals, in which the depth and rate of sediment burial may not be representative of those occurring in dredging projects. At the commencement of the Theme 5 studies we had almost no locally-derived knowledge of how primary producers in NW WA respond to the environmental changes produced by dredging, making it difficult to predict and manage the impacts of dredging on these critical habitats with an acceptable level of certainty.

2 Research program

The Theme 5 research program was designed to address some of the critical knowledge gaps and to improve our capacity to predict and manage the impact of dredging on seagrasses.

2.1 Research projects

The program comprised five sub-projects:

- Project 5.1 reviewed the existing knowledge of seagrasses in NW WA, with particular focus on knowledge relevant to dredging pressures;
- Project 5.2 examined the genetic structure of seagrass populations in the NW WA and the level of connectivity among seagrass populations;
- Project 5.3 comprised a series of surveys designed to improve our understanding of the natural dynamics of seagrasses (spatial and temporal variation in composition, abundance and phenology) in non-dredging situations;
- Project 5.4 used a field experiment to determine the mechanisms and rates of recovery of seagrass following disturbance; and
- Project 5.5 used a series of mesocosm experiments to determine the tolerance thresholds of selected seagrasses to dredging related pressures, and to identify appropriate bio-indicators for use in seagrass monitoring programs. Because of the complexity of this project, it was split into 4 separate projects (5.5.1 – 5.5.4), each with a separate report.

Projects 5.1 to 5.4 were designed to improve our understanding of seagrasses in NW WA. This is important for allowing prediction of dredging impacts as it provides the context in which dredging-related pressures might act on seagrasses. Project 5.5 developed thresholds of tolerance and bio-indicators of seagrass condition for application in the EPA (2016) framework. The following sections of this synthesis describe the research priorities of Theme 5, and the rationale underpinning the approaches taken to address them, and then go on to summarise the findings of the research and its implications for the prediction and management of dredging impacts on seagrasses.

2.2 Research priorities

The Theme 5 sub-projects were designed to address three key knowledge gaps for seagrasses in NW WA: their natural dynamics; the impact of dredging-related pressures on them; and their ability to resist or recover from dredging-related impacts.

2.2.1 Natural Dynamics

Our understanding of the natural dynamics of seagrasses in the Pilbara region was improved through two projects. In Sub-project 5.3 (Vanderklift et al. 2017a), a series of seagrass surveys were undertaken in the Exmouth Gulf region, which was considered to be representative of the Pilbara region. The surveys were conducted over 18 months (August 2013 to March 2015) at three locations (South Muiron Island, Bundegi and Exmouth Gulf), which encompassed a range of natural turbidity. Environmental data, principally light data, were also collected at the locations during the entire survey period. Less intensive surveys were undertaken at other sites: Thevenard Island, Rosemary Island and Balla Balla. Data on seagrass abundance were also obtained for sites within Chevron's Wheatstone project.

In Sub-project 5.1 (McMahon et al. 2017b) field data from sites in the Pilbara were analysed to establish the importance of a number of environmental factors in controlling the amount of light reaching seagrass. This analysis was conducted for periods with and without dredging to determine whether the effects of dredging on light availability could be detected above background variation.

2.2.2 Species selection

Early in the Theme 5 studies a review was undertaken to identify which seagrass species that collectively cover the bio-geographic range in NW WA, were most appropriate for the focus of subsequent research into thresholds and indicators of response to dredging-related pressures (i.e. sub-project 5.5). An assessment was developed based on six criteria: biogeographic range; ecological relevance; current knowledge on thresholds and bioindicators; likely sensitivity and resilience to dredging-related stressors; likelihood of being able to grow the species in experimental mesocosms; and the extent to which research on those species would improvement our knowledge. Two species were identified as high priorities for research: *Halophila ovalis* and *Halodule uninervis*. Both are widely distributed throughout the region, across a wide variety of habitat type and are important forage for dugong. These two species are both colonising species, with similar life-histories, and likely similar sensitivities to disturbance and recovery potential. Consequently, a third species, *Cymodocea serrulata*, was also included in the program to represent persistent species, thereby broadening the applicability of the experimental findings. The review also identified that tropical seagrass meadows are commonly mixed-species assemblages. Therefore, it was recommended that the subsequent experimental studies use a combination of single-species and mixed-species experimental assemblages to improve our understanding of how tropical seagrasses respond to dredging related stressors.

2.2.3 Impact of dredging on seagrasses

In Sub-project 5.5, a series of mesocosm experiments tested the effect of light reduction and sediment burial on seagrasses (Statton et al. 2017 a-d; Strydom et al. 2017). These experiments imposed treatments thought to be representative of the stresses produced by dredging projects, though in many cases there was a lack of reliable field data to provide guidance on the stress fields actually produced around dredging sites. From these experiments we determined:

- cause-effect pathways of dredging impacts on seagrasses;
- potential bio-indicators of dredging-related pressures for use in dredging monitoring programs; and
- thresholds of tolerance to dredging-induced pressures, expressed as durations and intensities of light reduction or sediment burial that are likely to cause either sub-lethal or lethal effects on seagrasses.

These findings were synthesised into 'impact' criteria that are relevant to the EPA's guidance on predicting and managing the impacts of dredging (EPA 2016).

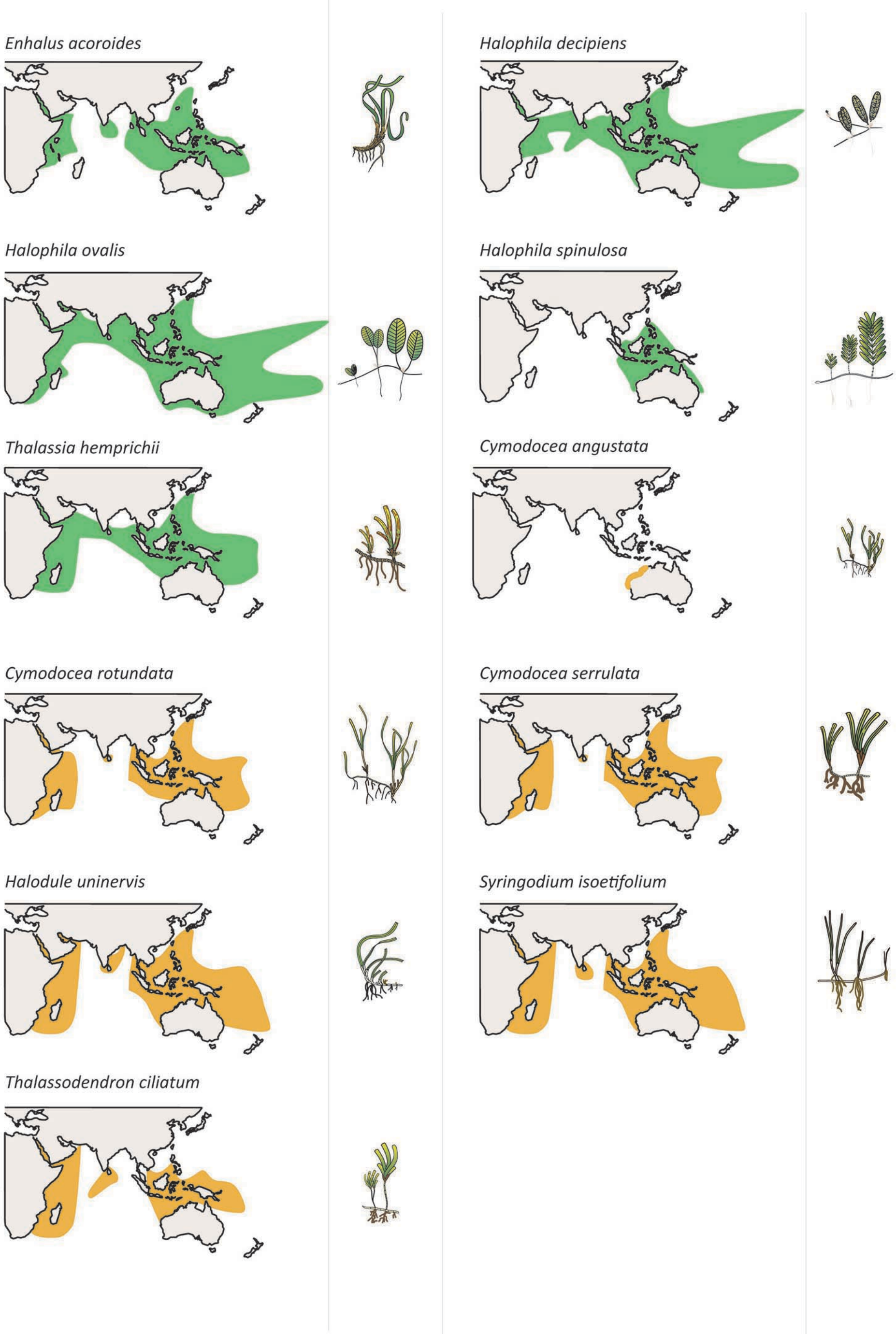

Figure 1. Biogeographic ranges of the seagrass species found in the NW of WA, including the three species selected for experimental studies: *Halophila ovalis*, *Halodule uninervis* and *Cymodocea serrulata*. Images adapted from Waycott et al. (2004) and Waycott et al. (2014). Distributions in green are for members of the Hydrocharitaceae; yellow is for Cymodoceaceae. *H. ovalis* includes *H. ovata* and *H. minor* and *H. uninervis* includes *H. pinifolia*.

2.2.4 Recovery from disturbance

Studies designed to test the potential for seagrass to recover from disturbance, and the mechanisms involved were undertaken in several sub-projects:

- Sub-project 5.2: the genetic diversity and genetic connectivity of seagrass populations were assessed throughout the Pilbara and the Kimberley region (see McMahon et al. 2017a). This information provided insights into the level of sexual reproduction within populations and the extent of exchange among them, both of which are related to the potential for recovery from disturbance;

- Sub-project 5.4: a field experiment was conducted to test for the presence of sexual and asexual mechanisms of seagrass recovery following disturbance (see Vanderklift et al. 2017b). The experimental design allowed recovery by rhizome extension from surrounding meadows to be distinguished from recovery through seedbanks or from seed/vegetative fragments drifting into the plots; and
- Sub-project 5.5: in sub-project 5.5.3 (Statton et al 2017c) seagrasses were subjected to light reduction stresses known to cause lethal effects. The recovery of the plants following removal of the stress was then monitored.

3 Overview and synthesis of findings

The findings of the studies described above, the current state of knowledge and its implications for predicting and managing the impacts of dredging under the EPA's (2016) framework, are summarised below.

3.1 Seagrasses dynamics – the context for dredging

The dynamics of seagrasses in a region provides the context in which any prediction of impacts or management of dredging need to be considered. These dynamics include the types of species that are expected to occur, when they will be present, when they are most abundant and when they reproduce. They also include information on the baseline environmental conditions at the site, which logically must be compatible with seagrass survival if seagrass is present, and which are the baseline to which any impacts of dredging need to be added. Theme 5 has clarified several aspects of the natural dynamics of seagrasses at sites in the Pilbara.

Eleven species of seagrass occur in NW WA (Figure 1), in a wide range of habitats and frequently forming multi-species meadows. The most common species of seagrass in the Pilbara region have colonizing or opportunistic life histories. They show considerable spatial and temporal variation in abundance and reproduction at the sites where they occur. The number of species recorded at each site varied from two to five. Seagrass abundance (measured as cover) and the way it changes throughout the year also varied among locations; some sites had highest cover in late summer and lowest in winter, while at others the cover remained low during all surveys. Different species of seagrass also displayed different patterns of temporal variation in abundances. At one location *H. ovalis* was dominant and followed a regular pattern of highest cover in March while at another location there was no evidence of a regular annual pattern in cover. Although predictable annual patterns in seagrass abundance were not typical, at those locations that did show a regular annual patterns in seagrass cover we saw summer maxima and winter minima.

At some sites there can be significant inter-annual variation in seagrass species composition and abundance. For example, at Exmouth Gulf preliminary surveys first indicated that little seagrass was present. For the following 6 months the cover of *H. ovalis* increased followed by about 18 months of declining cover during which the cover of *H. spinulosa* increased to the point that it was the most abundant species, after which it too began to decline (Figure 2). This inter-annual pattern was reminiscent of earlier observations at the site by Loneragan et al. (2013). They reported that following Tropical Cyclone Vance in 1999 seagrass cover was reduced to less than 2% but then increased to 40% by 18 months after the cyclone and was maintained at that level for another 2 years before declining to around 5% (Figure 3). This inter-annual variability may be part of a post-disturbance pattern, in which seagrasses boom and then settle to background levels.

Table 1. Habitats where seagrass species are found in NW WA (Data from Waycott et al. 2004 & 2014, per. obs. authors)

Species	Clear	Turbid	Intertidal	Subtidal	Estuarine	Coastal	Reef	Deep	TOTAL
Hydrocharitaceae									
Enhalus acoroides	X	X	X	X	X	X	X		7
Halophila decipiens	X	X		X		X	X	X	6
Halophila ovalis[1]	X	X	X	X	X	X	X	X	8
Halophila spinulosa	X	X		X	X	X		X	6
Thalassia hemprichii	X	X	X	X		X	X		6
Cymodoceaeceae									
Cymodocea angustata	X	X	X	X	X	X	X		7
Cymodocea rotundata	X	X	X	X		X	X		6
Cymodocea serrulata	X	X	X	X	X	X	X		7
Halodule uninervis[2]	X	X	X	X	X	X	X		7
Syringodium isoetifolium	X	X		X	X	X	X		6
Thalassodendron ciliatum	X			X			X		3

[1]including *Halophila ovata*, *minor* [2]including *Halodule pinifolia*

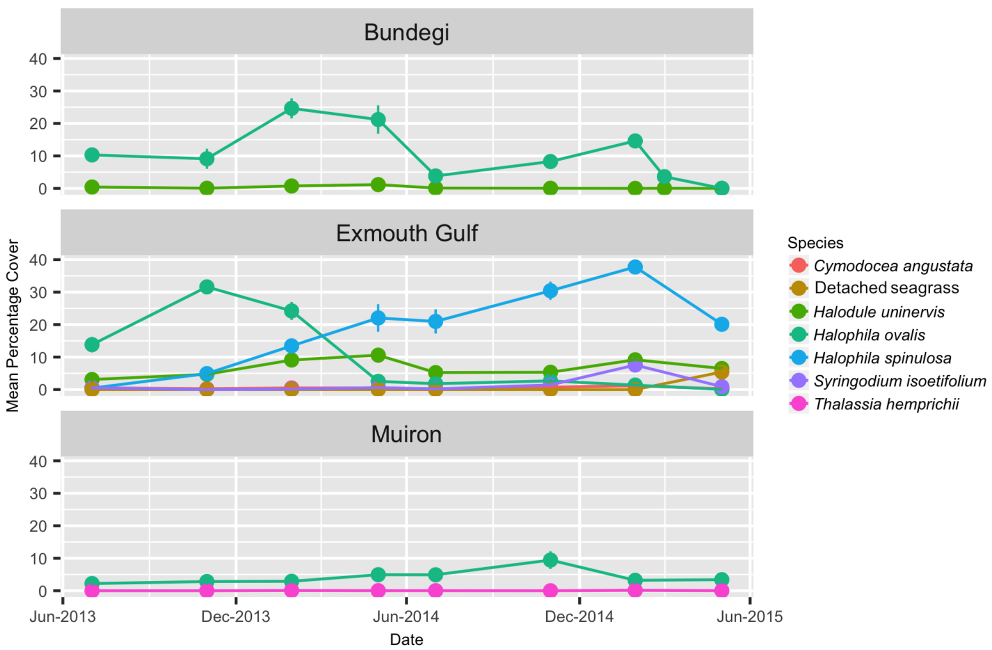

Figure 2. Percentage cover of each of the seagrass species identified on photographic transects at the Bundegi, Exmouth Gulf and Murion Islands locations from August 2013 to June 2015. The data are means of five transects at each of two sites within each location (NB: the figure includes zero cover data where a species was not recorded at a location).

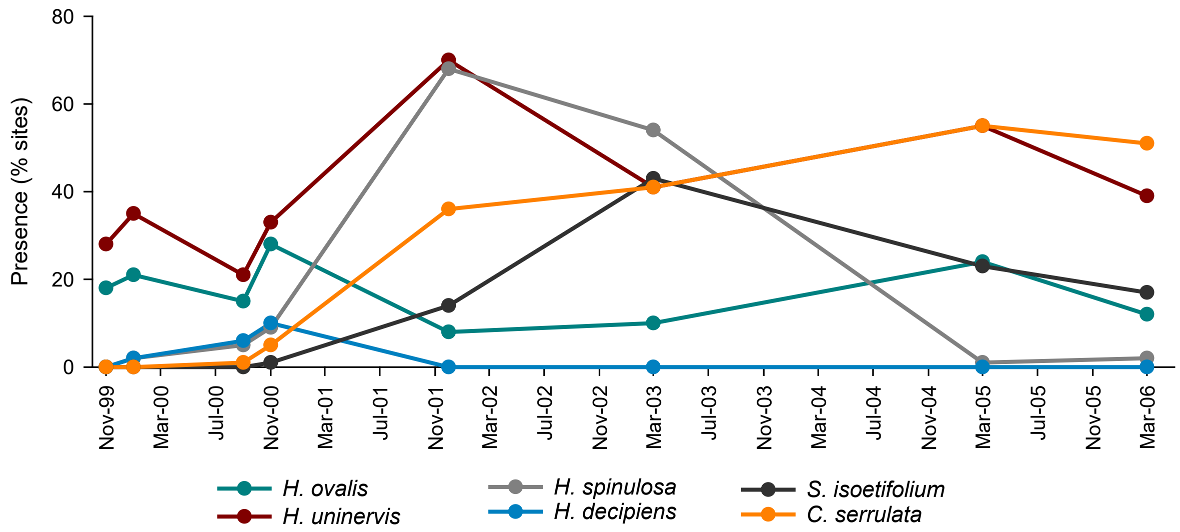

Figure 3. Distribution of seagrass species over time at sites in the Exmouth Gulf, following tropical cyclone Vance in 1999, which removed seagrass (adapted from Loneragan et al. 2013).

Flowering is an indicator of sexual reproduction, which is generally associated with potentially higher genetic diversity and associated increases in resilience. As with abundance, the number, timing and frequency of occurrence of flowers was highly variable. Flowering was recorded for *Halophila ovalis*, *Halophila spinulosa*, and *Syringodium isoetifolium*, mainly in November but also in February. However, it did not occur for every species in every year, and it only occurred at some places. *H. ovalis* fruits and *Halodule uninervis* seeds were present, but in very low abundances, and not at every site.

The project has provided a set of baseline light (photosynthetic photon flux density: PPFD) data that characterise sites supporting seagrass assemblages in the Exmouth region. The low light intensities known to induce physiological and growth responses in *Halodule uninervis, Halophila ovalis* and *Cymodocea serrulata* under laboratory conditions (see below) rarely occurred at the survey locations and there were few days when light intensity failed to exceed that needed to maintain maximum rates of photosynthesis (in the worse case, less than 6% of days). Analysis of data provided by industry indicated that around Barrow Island the total daily light (photosynthetically active radiation; PAR) at a site known to support seagrass for most of the year ranged from about 3 to 11 mol m^{-2} d^{-1} and was sufficient to support tropical seagrasses for most of the year. However, during periods of dredging, there was a reduction in total daily light of up to 65%. The magnitude of light reductions decreased with distance from dredging, with a 29% reduction relative to pre-dredging conditions up to 9 km from the dredge.

These findings have some significant implications for the management of dredging in the EPA (2016) framework, largely related to the significant spatial variability in seagrass composition, abundance and temporal dynamics. These implications are summarised in Box 1.

Box 1: Implications of the findings on seagrass natural dynamics for management of dredging under the EPA (2016) framework

- Because the temporal dynamics of seagrasses in the Pilbara, Kimberley and Gascoyne regions may be different, these regions should not be viewed as supporting a homogenous, northern seagrass assemblage; the species assemblages present, and their temporal and spatial variability are likely to vary. The baseline conditions, responses to dredging, and opportunities for environmental windows are likely to differ among the Pilbara, Kimberley and Gascoyne regions.

Pre- and Post-Development

- Site-specific surveys will be required to characterize the seagrasses likely to occur at any given site, ideally on several occasions. While seagrass cover is highly variable over time, the likelihood of detecting seagrass, as well as flowering, fruiting and seed banks, is greatest if surveys are undertaken between November and February.
- Disturbance history should be taken into account when selecting pre-development or compliance monitoring survey sites. The probability of observing seagrass in pre-development surveys will be increased by taking into account previous cyclone activity at potential survey sites, ideally avoiding cyclone-affected areas. Stochastic events (e.g. cyclones) appear to be important drivers of seagrass dynamics in the region, with changes in composition and abundance occurring over 2-5 years. Knowing the point in a longer-term recovery pattern that a site is at will allow more meaningful comparisons against, for example, post-dredging recovery monitoring data. If there is no option but to use cyclone-affected areas, repeating surveys over several years will increase the probability of detecting seagrass.
- Because appropriate pre-development survey will involve significant effort and resources, pilot surveys would be useful to focus the location and methods for the pre-development surveys.
- Even when seagrass is present it can be hard to detect. Diver operated still camera shots taken within 1 m of the sea bed proved to be the most effective means of detecting and surveying seagrass. Satellite or airborne remote sensing methods are unlikely to be useful tools for mapping or monitoring the distribution of seagrasses in the Pilbara. Similarly, remotely deployed video or still camera methods might not be appropriate for detecting seagrass in the Pilbara.
- Reference monitoring sites for use in compliance monitoring and management would ideally be located within 20 kilometres of sites potentially affected by dredging, and would be as similar as possible to the dredge sites in terms of wind speed, fetch, prevailing wind direction, sediment type and water depth. Most of the variance in seagrass cover was driven by differences among locations separated by tens of kilometres, and these differences corresponded with natural patterns in benthic light intensity, in turn a function of wind speed and direction (McMahon et al., 2017b). Pre-development surveys could usefully confirm that seagrass composition at monitoring and reference site are comparable.

Impact prediction and management

- Obtaining continuous light data over an annual cycle of pre-development conditions would provide a valuable baseline of the frequency and duration of light conditions that are suitable for seagrasses at a site and can form a reference condition for impact assessment modelling. Despite the differences in light availability among sites, all sites which consistently supported seagrass rarely had days when the intensities failed to exceed those which, based on our laboratory experiments (Statton et al. 2017a-d), were likely to cause sub-lethal impacts on seagrasses from the region (*Halodule uninervis*, *Halophila ovalis* and *Cymodocea serrulata*). However, during periods of dredging, light intensities are likely to fall significantly, even at sites previously considered sufficiently far from dredging to be valid Reference Sites (i.e. in the order of 10 km from the site of dredging).
- The consistency in the timing, but not frequency, of flowering indicates a potential window of environmental sensitivity for dredging. Pre-development surveys would be useful to confirm if and when flowering, fruiting and seed bank production occur.

3.2 Impacts of light reduction and burial

3.2.1 Tolerance to light reduction

The main mechanisms by which dredging is presumed to impact seagrasses are: deterioration in light availability caused by re-suspension of dredged sediments; altered spectral quality of light caused by re-suspended sediments (though this has rarely been examined); and burial or covering of seagrasses by deposition of sediments re-suspended during dredging. A series of controlled experiments were undertaken to examine each of these potential stressors on our three target species of seagrass *Cymodocea serrulata*, *Halodule uninervis* and *Halophila ovalis*.

Light reduction generally negatively affected the physiology, productivity, morphology and biomass of all three species, though the magnitude of the effects depended on the intensity and duration of light reduction, the pattern in which the light reduction was delivered (i.e. number of consecutive low light days) and the species of seagrass. Higher levels of shading generally resulted in greater impact on all three seagrass species though the amount of time it took for the responses to occur were species specific. *H. uninervis* was more sensitive to low light than *C. serrulata*, possibly due to the smaller carbohydrate storage reserves in *H. uninervis*; these reserves act to buffer plants against low light stress. Results for *H. ovalis* were inconclusive.

We identified four robust bio-indicators that are appropriate candidates for incorporation into monitoring programs to identify impacts of reduced light availability on a tropical seagrass assemblage: for individual species, ETR_{MAX}, total rhizome carbohydrate concentration and above-ground biomass; and for all species combined, total biomass. These variables were identified based on their sensitivity to stress (e.g. rapid response; see Figure 4, applicability to at least 2 of the 3 species studied, and their consistent direction of response with increasing intensity and duration of light reductions. Three others variables (leaf nitrogen, new shoot production/recruitment, leaf area) met most of the above criteria and could also be considered. In addition to considering the sensitivity of a variable to stress, the usefulness of that variable as a bio-indictor is also influenced by its practicality and cost-effectiveness. For example, physiological variables such as ETR_{max} can be difficult to measure in a reliable way in uncontrolled field settings, while carbohydrate analyses can require days to weeks to complete making them less suitable in a management response framework. Later in this document we present a set of light reduction thresholds for impact prediction and these are based largely on biomass variables since these are most likely to be applied in monitoring frameworks.

The findings from this initial light-reduction experiment are summarised in Figure 5. The plants initially displayed photo-physiological responses, reflecting attempts to alter their photosynthetic performance to cope with the lower light availability. With continued shading the plants began to draw down their carbohydrate reserves to maintain a positive carbon balance. Where these responses were not sufficient to offset the reduction in light availability, changes in plant production and biomass became apparent. Ultimately, the changes in biomass leads to loss of diversity in the seagrass assemblage as species are lost.

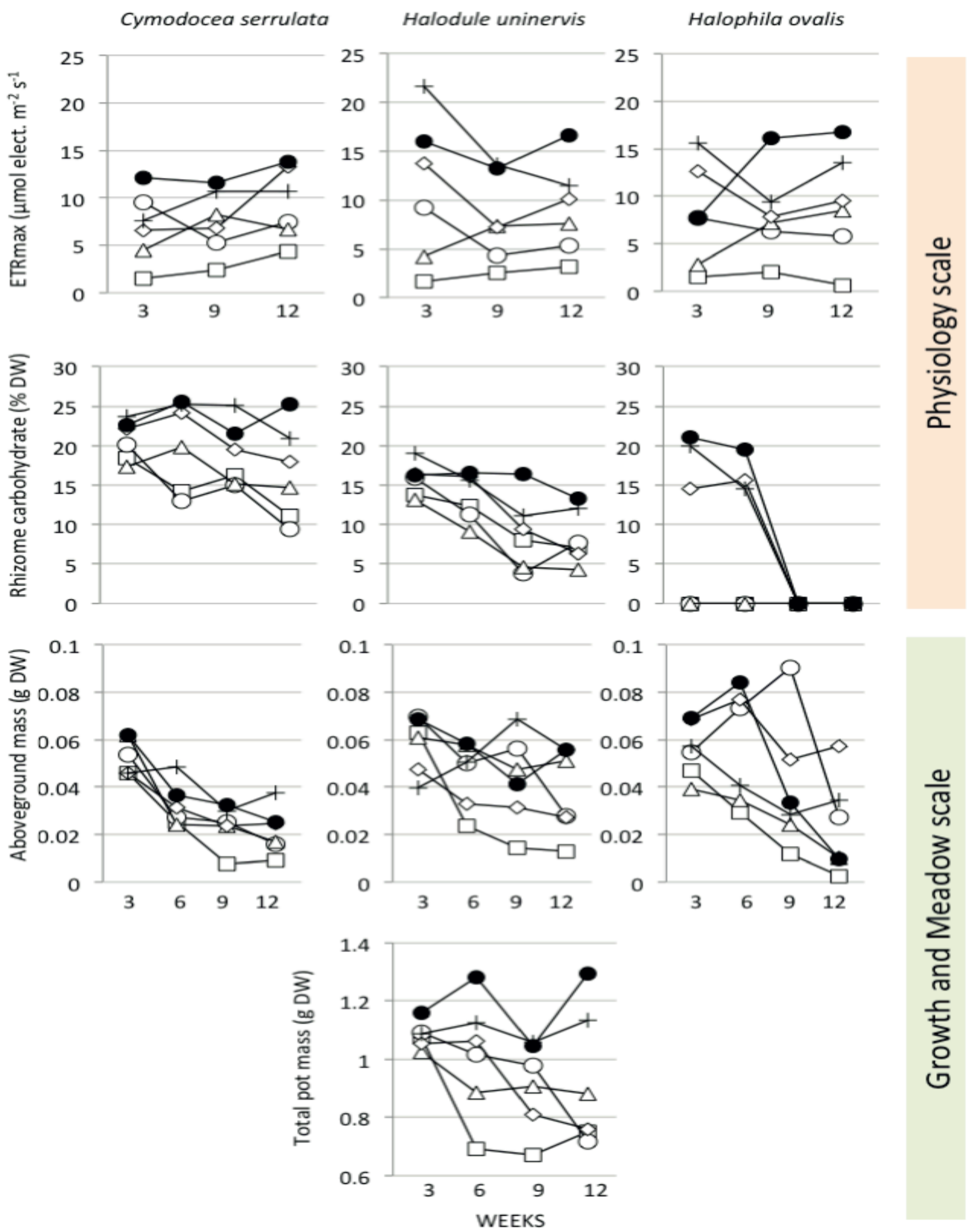

Figure 4. Plant responses pathway to different magnitudes and durations of light reduction. The graphs show the responses of the four variables that showed the most consistent responses to the light reduction treatments. Note that for carbohydrate data the most abundant form of carbonhydrates is shown (soluble carbohydrates for *C. serrulata* and *H. ovalis* and starch for *H. uninervis*).

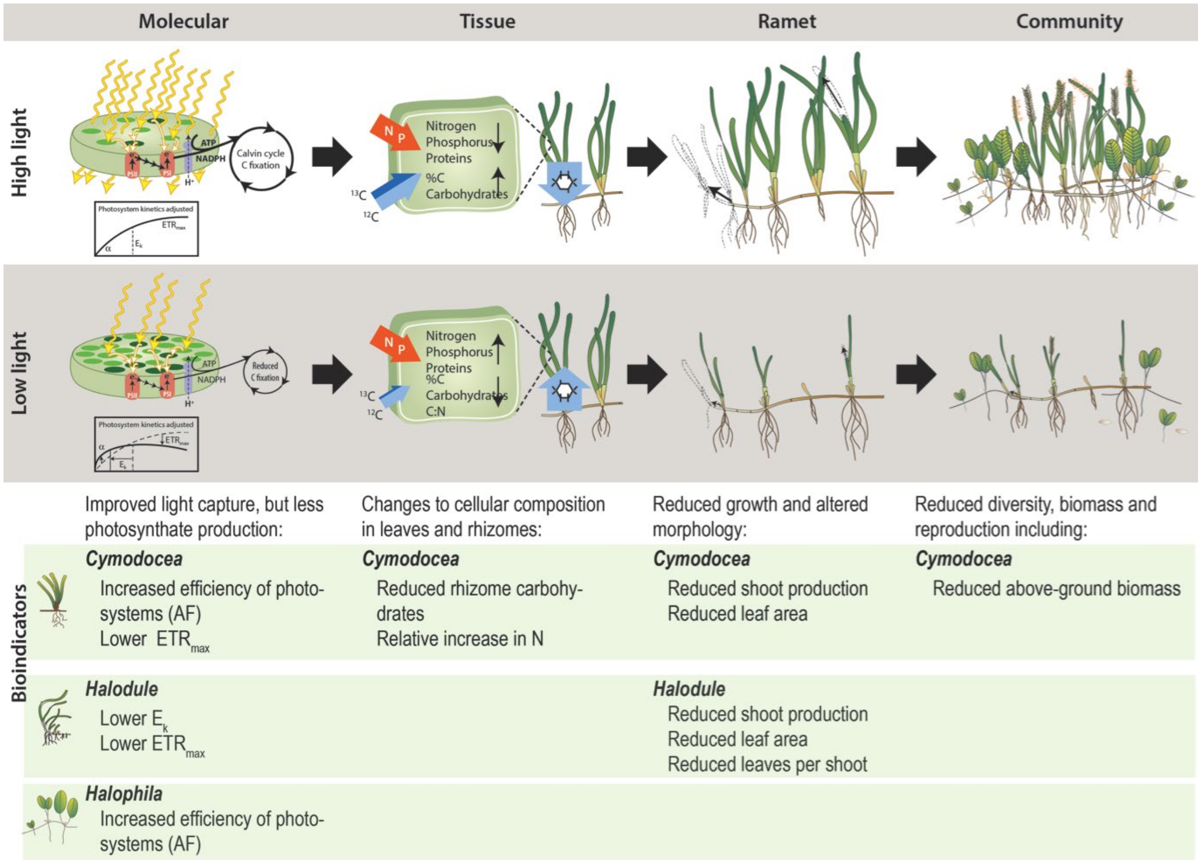

Figure 5. Plant and community response pathway to increased magnitude and duration of light reduction, based on the findings from the light reduction experiment.

A second experiment addressed the question of whether the impacts of dredging can be reduced by altering the frequency of dredging activities. For example, if a plant can cope with low light for one week but not two, would impacts be reduced by dredging in blocks of one week separated by a ‘no dredging period’ rather than in blocks of two weeks or over longer durations. The initial experiment, described above, indicated that plants were likely to show significant negative effects of shading if they received only about 4 mol photons m^{-2} d^{-1} of light. In this second experiment plants were subjected to treatments that approximately the same total light delivered over a twoweek period (~4 mol photons m^{-2} d^{-1}) but with different patterns of delivery that included different numbers of high, moderate and low light days (Figure 6).

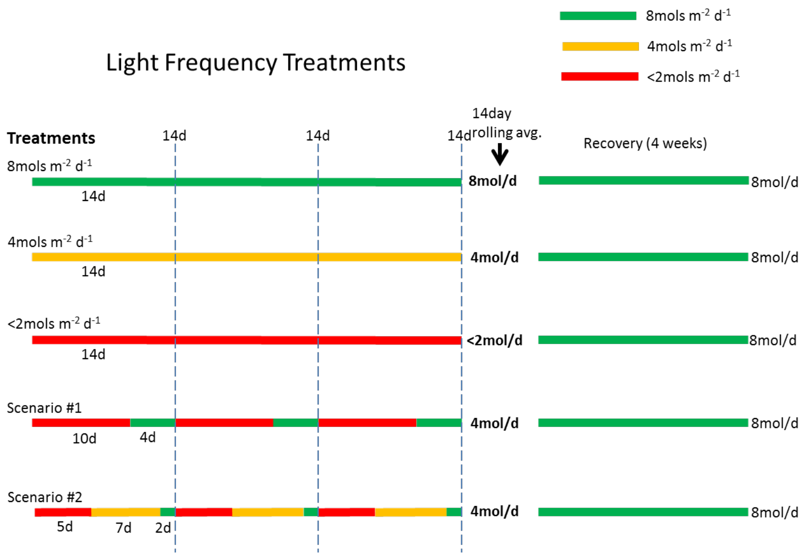

Figure 6. Experimental design for the light frequency experiment: continuous light shading treatments (top three treatments) and light delivery scenarios (bottom two treatments) over three sets of 14 days followed by a recovery period of 4 weeks.

This experiment confirmed that the pattern of light delivery affects how seagrasses respond to a reduction in light availability and their capacity to recover. When plants received moderate light (an average 4 mol photons m^{-2} d^{-1}) delivered as 10 days of low light followed by 4 days of high light, they were impacted in a manner similar to plants receiving a continuous supply of low light, that is an average of only 2 mol photons m^{-2} d^{-1} (Figure 7), and showed no significant recovery of biomass following removal of the light treatment. However, if plants received the same average light (4 mol photons m^{-2} d^{-1}) delivered as 5 days of low light, followed by 7 days of moderate light and 2 days of high light, the impacts were less severe and the plants had greater capacity for recovery. Therefore, the effect of extended periods of low light on recovery potential is not mitigated by short periods of high light but, with frequent intervening periods of moderate/high light, the potential for recovery is greater. Based on these findings, the number of continuous days of low light should be considered when developing impact prediction thresholds. Ten days of continuous low light was more detrimental than 5 days of continuous low light, even if over a two weeks period plants received the same total amount of light.

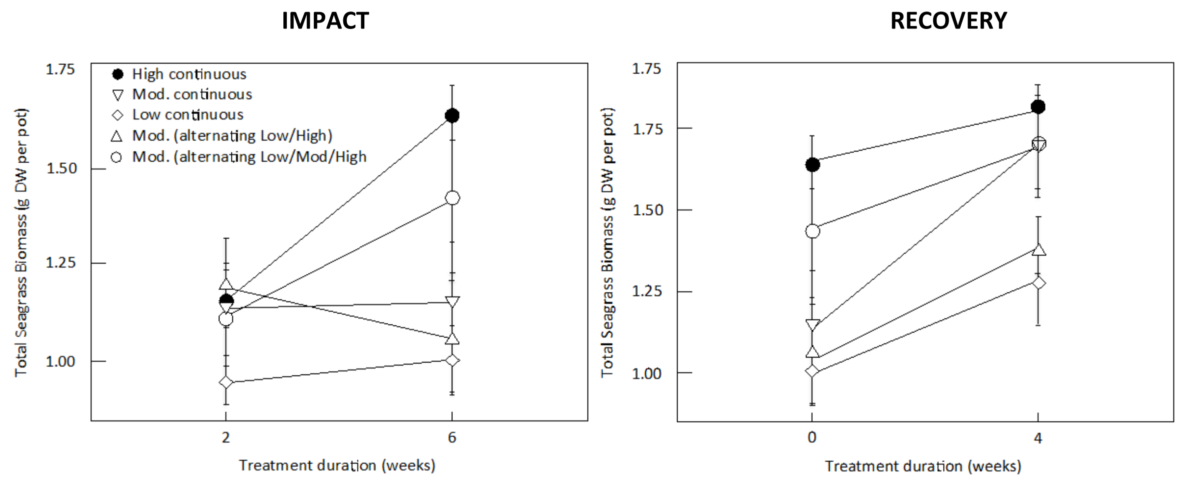

Figure 7. Effect of pattern of light delivery on seagrass biomass. Left: The figure shows the biomass of mixed seagrass assemblages grown in pots under different light intensities and delivery patterns. The Moderate (Mod) treatment received approximately 4 mol photons m^{-2} d^{-1} averaged over 14 days at constant intensity. The other two Moderate light treatments (alternating Low/High and Mod. alternating Low/Mod/High) also received approximately 4 mol photons m^{-2} d^{-1} but delivered in two different patterns with combinations of high, moderate and low light intensity days (see Fig. 4). High and Low light controls were also used, with approximately 8 and 2 mol photons m^{-2} d^{-1} respectively, delivered at a constant intensity. The main effect to observe is the difference in two Moderate treatments receiving alternating light treatments, despite receiving the same total light intensity over the 6 weeks. Right: The figure shows the recovery of seagrass biomass over four weeks following removal of the treatments.

The findings from the two light reduction experiments were used to develop a set of 'no-effect' impact prediction thresholds (Table 2). The thresholds specify the duration, intensities and number of consecutive low light days that will produce a measurable change in seagrass condition using a two weeks averaging period. The two weeks averaging period is used since this was the period used in the experiments that generated the data underlying the thresholds. Two sets of thresholds were developed: conservative and less conservative thresholds. This reflects our uncertainty regarding the number of low light days required to producing negative effects on the seagrass, which lies somewhere between 5 and 10 consecutive days. The conservative thresholds require that plants do not experience more than 5 consecutive days of low light (2 - 4 mol m^{-2} d^{-1}; based on the findings of our experiments; Statton et al. 2017a) within a two week period and the average daily light intensity for that two week period must be equal to or greater than a stated light intensity. The less conservative thresholds allow plants to experience up to 10 consecutive days of low light, but still meeting the two weekly average light intensity requirement. This approach could not be applied to *Halophila ovalis* as the plant's responses in some of the experimental treatments were inconsistent. However, interim thresholds are presented using an alternative approach, described in Table 2.

Because the 'No effects thresholds' define the amount and delivery pattern of light required to avoid measurable effects on seagrasses, they can be used in the context of the EPA's guidance framework for dredging impact assessment (EPA 2016) to define the boundary of impact zones. In particular, the thresholds can help to clarify the boundary between the Zones of Influence (the area in which predicted environmental quality changes associated with dredging have no detectable effect on seagrasses) and the Zone of Moderate Impact (the area within which dredging pressures result in a measurable, but not necessarily lethal, effect on seagrasses). It is important to note that the no-effects thresholds in Table 3 are based on the data from laboratory experiments. As such, they are presented as recommended default thresholds. Pre-development surveys and dredging-period monitoring data on light and seagrass condition could be used to appraise these default thresholds, and to refine and tailor them to the local conditions if necessary, to increase confidence.

Table 2. Recommended impact thresholds for *Cymodocea serrulata*, *Halodule uninervis*, *Halophila ovalis* and mixed seagrass assemblages. The Most and Less Conservative thresholds can be applied to predict the outer and inner limits of the Zone of Moderate Impact, respectively. For *Halophila ovalis* many of the experimental response were unreliable and so a different approach was used to develop thresholds (see table footnote 1).

	Two week averaging period		**Permissible low light periods within 2 wk averaging period**	
	Duration	Mean Light intensity mol photons m^{-2} d^{-1}	Duration	Mean Light Intensity mol photons m^{-2} d^{-1}
Cymodocea serrulata (based on Aboveground biomass)				
Most conservative*	12 wk	8.9	5 d	2 to ≤ 4
	9 wk	2.3	5 d	2 to ≤ 4
Less conservative#	12 wk	2.3	10 d	2 to ≤ 4
Halodule uninervis (based on Aboveground biomass)				
Most conservative*	12 wk	13.1	5 d	2 to ≤ 4
	6 wk	13.1	5 d	2 to ≤ 4
Less conservative#	12 wk	2.3	10 d	2 to ≤ 4
Mixed Meadow (based on total biomass of all species in a multi-species meadow)				
Most conservative*	12 wks	13.1	5 d	2 to ≤ 4
Less conservative#	12 wks	8.9	10 d	2 to ≤ 4
	6 wks	5	10 d	2 to ≤ 4
***Halophila ovalis*[1]** (based on Aboveground biomass)				
Most conservative	3 wks	0.9		

* *Most conservative reflects higher confidence of no impact to seagrass.*

Where the thresholds were the same for multiple durations, the longer duration is presented as the recommended threshold. For example, for H. uninervis *there was no difference in the 'Less conservative' thresholds for 6 weeks and 12 weeks data – for both, the 2-weekly running average was 2.3 mol m^{-2} d^{-1}. In this case, it is recommended that for any given period of 12 successive weeks, this average must be maintained in successive two weeks periods.*

[1] *The experimental data for H. ovalis were inconclusive and thresholds could not be developed using the approach for* C. serrulata, H. uninervis *and mixed meadows. Instead, an interim threshold was developed following the ANZECC and ARMCANZ guideline recommendations for biological indicators (ANZECC and ARMCANZ 2000), where impact conditions were compared to background or reference conditions. This approach simply indicates the amount of light reduction that would cause the median value for that variable at an 'impact' site to fall below the 20th percentile for that variable at a valid control site, a level of change that the guidelines suggests as an initial approach for environmental protection.*

3.2.2 Tolerance to changes in light quality

Most studies of dredging-related impacts on the light environment of seagrass have focussed on changes to the *quantity* of light seagrasses receive. However, dredging simultaneously alters the spectral *quality* of light, typically shifting the spectrum towards the yellow region. To date, no published studies have reported on the relative importance of changes to the quantity and quality of light for seagrasses. Part of the Theme 5 research program examined whether seagrasses are sensitive to changes in the spectral quality of light they experience and how this might relate to dredge plume conditions. Aquarium-based experiments were conducted to test whether *Halophila ovalis* responded to different spectral light quality treatments. In separate experiments adults, seeds or seedlings were subjected to monochromatic light treatments in the blue (λ 400 – 500); green (λ 500 – 560); yellow (λ 570 – 590); and red (λ 600 – 700) wavelengths with a control of full-spectrum light (λ 400 – 700). All treatments received 200 µmol photons m^{-2} s^{-1} of light, equivalent to 8.6 mol photons m^{-2} d^{-1}.

Adult *H. ovalis* plants grown under yellow, green and blue wavelengths had lower productivity than those grown in full spectrum (Figure 8a). Blue light induced photosynthetic responses and green light induced morphological responses. Early life history stages responded positively to red and yellow light treatments, with increased percentage germination of seeds (Figure 8b) and seedling survival.

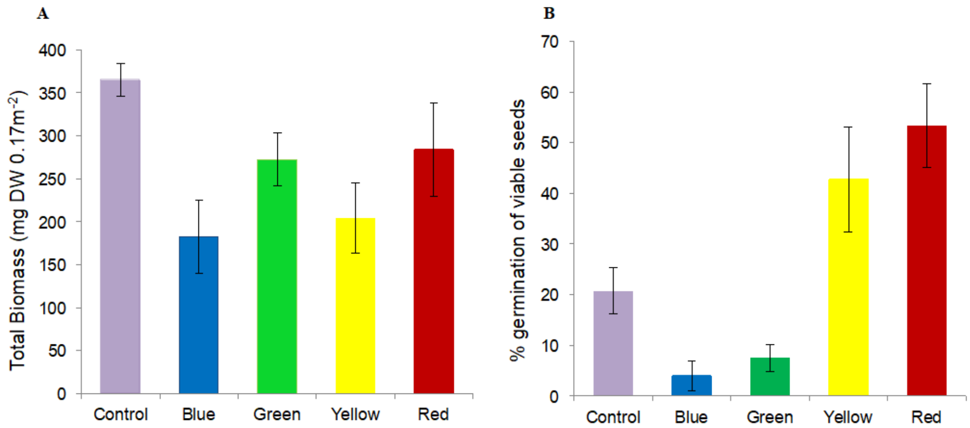

Figure 8. The effect of shifts in light quality on *Halophila ovalis*. The two figures show the biomass of adult plants (A) and the percentage germination of viable seeds (B) grown under different monochromatic light treatments and under full spectrum (control) light. Adult biomass was significantly less than controls when grown under yellow light but seed germination was significantly greater. Dredge plumes are typically expected to show a shift towards yellow light.

While the findings confirmed that seagrasses respond to monochromatic treatments these are not strong mimics of field conditions, where altered spectra would rarely be monochromatic. Nonetheless, given the negative response of adult plants to yellow light treatments, it was hypothesised that dredge plume conditions, which typically see a shift towards yellow light, would be unfavourable for seagrass growth. A second experiment subjected plants simultaneously to a reduction in light quantity (8.6 v 2.2 mol photons m^{-2} d^{-1}) and a shift in light quality, to a spectrum replicating that measured in a 15 mg L^{-1} TSS dredge plume during the Wheatstone Project near Onslow, Western Australia and a more realistic representation of a shift in light quality expected under dredging conditions. There was a significant effect of reduced light quantity on the adult *H. ovalis* plants but no effect of light quality and no interactive effect of quantity and quality (Figure 9). The specific dredge plume spectrum used in this study was based on a plume that contained 15 mg L^{-1} TSS and it cannot be assumed that there would be no effect in a denser plume or the same plume over a longer time period. Nor can it be assumed that all sediment types will have the same effect on light quality.

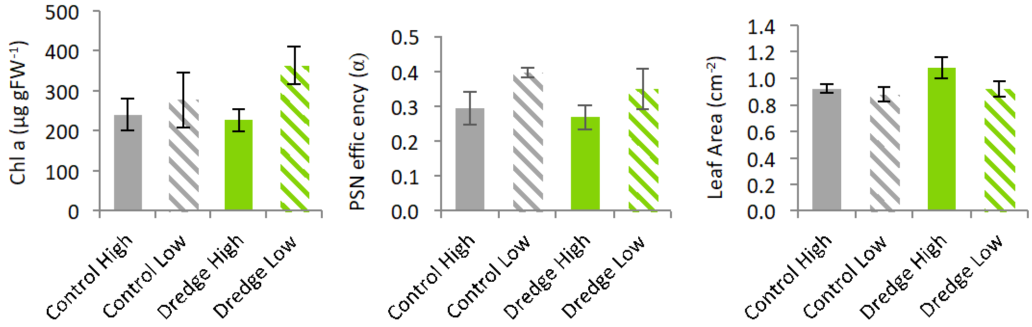

Figure 9. Response of seagrass (*Halophila ovalis*) to simultaneous reductions in light quantity and shift in light spectral quality. The graphs show three variables that typify the responses of all variables measured. While some pigments appeared to respond to shifts in light quality, this was not translated into any effect on photosynthetic characteristics or plant biomass. On the other hand, the reduction in light quantity did have a significant effect on pigments and photosynthesis.

3.2.3 Tolerance to burial

Seagrass plants were subjected to two different experiments testing the effects of burial. In the first experiment, plants were grown under natural light conditions and subjected to different sediment burial treatments using fine inorganic sands. This allowed us to identify the burial depths likely to have an effect on seagrass. The range of burial depths used (0-70 mm) mimicked covered that predicted to occur close to dredging operations (McMahon et al. 2017b) as well as covering a range expected to elicit a mortality response in tropical seagrasses determined from published research (Cabaco 2008, McMahon et al. 2017b).

Burial by up to 40 mm of inorganic sediments in ambient light had little effect on either species of seagrass. Above this depth, burial resulted significantly affects the plants' physiology, productivity, morphology and biomass (Figure 10), though the effects depended on the duration of burial and the species of seagrass. After 14 weeks of burial, *C. serrulata* showed reduced shoot density and biomass compared to controls, while *H. uninervis* demonstrated either no significant differences to controls or a positive effect of burial. These findings indicated that the threshold for sub-lethal effects of burial in *C. serrulata* was 40 mm burial for 14 weeks and for *H. uninervis* was 70 mm of burial for >14 weeks. Due to both species' rapid adaptive response to burial under the imposed light and sediment conditions we were unable to define lethal levels of burial.

Like the majority of studies investigating impacts of dredging, the above experiment focussed on burial in isolation from simultaneous effects that a sediment plume would have on light availability. Nor did it consider the nature of the sediment, despite knowledge that organic-rich sediments can produce conditions unfavourable to seagrasses. A second sediment burial experiment examined the effects of inorganic and organic-rich sediments under dredge-simulated conditions of severe light reduction (<2 mol photon m^{-2} d^{-1}) for 6 weeks. Seagrasses were subjected to sediment burial depth treatments (0, 5, 16 and 40 mm). The burial sediments either had 0% or 4% added organic matter, in the form of dried, ground seagrass leaves.

Under this second set of conditions, sediment burial depths of 40 mm did significantly impact shoot density (50% decrease) of both species of seagrass but only when added organic matter was present in burial sediments, contrasting the initial experiment using inorganic sediments. Another contrast was that vertical rhizome growth did not respond to the burial treatments, probably because the severe light limitation reduced the energy reserves of the plants, limiting their ability to support vertical growth. Consequently, this potential bio-indicator of burial stress is not an appropriate indicator under low-light conditions.

This work reveals potential synergistic effects of low light and burial stress. It also identified a burial threshold value for both species (40 mm) that was lower than that found in the initial experiment. Because burial stress will almost always be accompanied by some level of reduced light availability, the thresholds derived from the second experiment (Table 3) are recommend for application in impact prediction.

Table 3. Recommended sediment burial impact thresholds for *Cymodocea serrulata* and *Halodule uninervis*. The values represent the depths and durations that can be tolerated for burial in oprganic rich sediments (4% O.M.) and under low light conditions (2.45 mol photons m^{-2} d^{-1}). Neither species showed negative responses to burial by inorganic sediments under the same conditions.

Species	Maximum depth of sediment burial	Maximum period of burial	Sediment type (% organic Matter)
Cymodocea serrulata	<40 mm	6 weeks	<4% OM
Halodule uninervis	<40 mm	6 weeks	<4% OM

Placing these findings into a field context is made difficult by the almost total absence of reliable data on sediment deposition and re-suspension rates in the field. We were forced to estimate sediment deposition rates based on either sediment trap data or suspended sediment load data. In both cases, a number of assumptions were required which cannot be validated. Those estimates indicated that seagrasses were unlikely to experience the sorts of rapid and deep sediment burial they were subjected to in the mesocosm experiments. However, the absence of reliable sediment dynamics data under dredging and non-dredging conditions is a very significant information gap and therefore the following conclusions are provided with the caveat that they could well change if more data become available. On the basis of the observed plant responses, burial can affect seagrasses under reduced light conditions and if the sediment has at least 4% organic matter content. However, because the burial treatments required to produce these responses probably represent extreme events in the dredging far-field, burial is likely to pose a relatively low pressure to seagrasses in the far-field.

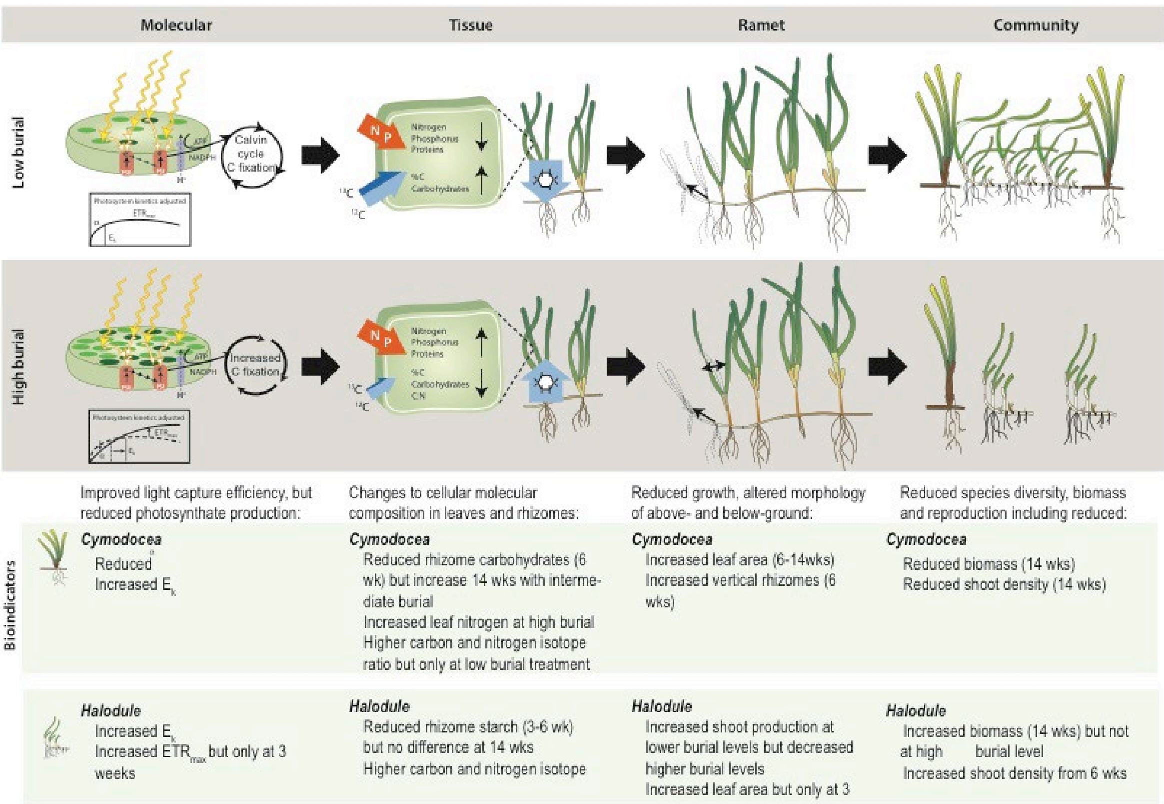

Figure 10. Plant and community response pathway to increased magnitude and duration of burial, based on the findings from the burial experiment.

Box 2 Implications of the findings on seagrass responses to light reduction and burial for management of dredging under the EPA (2016) framework

Pre-development Surveys

- A single species approach to threshold development is not appropriate for diverse seagrass assemblages, typical of NW WA. Applying thresholds relevant to one species may under- or over-estimate the potential for impact on other species and the meadow as a whole. Pre-development surveys provide the opportunity to identify the composition of mixed-species assemblages and to improve the predictability of the mixed assemblage response to impacts and aid in monitoring design, bio-indicator choice and threshold development.

- Pre-development surveys will offer the opportunity to gain an understanding of the baseline conditions at a site which dredging will be superimposed. This and previous studies have highlighted that there is currently almost no field data on background burial pressure or those induced by dredging relevant to seagrasses, and limited data on the background light climate. Appropriate pre-development surveys can:

  - Characterise the background light climate at the site as well as sediment dynamics (deposition, re-suspension) and characteristics (e.g. organic matter content);

  - Characterise seagrass species responses to previous sedimentation and light history (i.e. vertical rhizome elongation and rhizome carbohydrate concentrations) that are necessary to determine appropriate thresholds to apply in impact prediction. Vertical rhizome growth is a reliable indicator of burial stress, but only in situations of high light and low organic content sediments;

  - Improve our understanding of the natural variability of field sites, which is integral to the development of light-reduction impact thresholds when using the approach recommended by ANZECC/ARMCANZ (2000). Pre-development surveys provide the opportunity to determine the background natural variability of reference and impact sites with respect to the feasible bio-indicators.

  Gaining this understanding will increase the precision of threshold predictions for these bio-indicators and avoid over- or under-prediction of impacts which could result in a loss of species diversity and ecological function or unnecessary time, effort and financial costs to complete a dredging operation.

Impact Assessment

Bio-indicators & Thresholds

- We identified four robust bio-indicators of light-reduction stress and one potential indicator of sub-lethal burial stress (valid under some conditions):

  - ETR_{MAX} will be most be useful in situations where short-term changes in seagrass condition need to be monitored or to define the Zone of Influence of a sediment plume over relatively short time periods. Applying this indicator in an uncontrolled field setting may be problematic;
  - Carbohydrate concentrations in the rhizome will be useful in integrating changes in light climate over a longer-period than ETR_{MAX}. This could be applied to determine the boundaries of the zones of influence and moderate impact. Applying this indicator could be problematic in terms of the time required to undertake analyses;
  - Above-ground biomass and Total Biomass are useful indictors of detectable impacts on seagrass. As such, the thresholds based on these variables can be used in impact prediction to estimate the boundary of the Zone of Influence and Zone of Moderate Impact; and
  - Vertical rhizome growth will be useful in indicating a history of sediment burial at a site and sub-lethal impacts on seagrasses over week to month timescales if the site is not subject to very low light levels or organic-rich sediments.

  Understanding the cause of any loss of seagrass requires information on variables that respond earlier in the cause-effect pathway. Therefore, interpretation of bio-indicator data will be assisted by collecting information on all four variables, even if decision-making thresholds are not based on all of them.

- Given the species-dependent differences in responses to light reduction and sediment burial, extrapolating findings from one species to another or using one species as a surrogate for a mixed assemblage is not advised; it may lead to erroneous conclusions. The validity of impact predictions for a site will be improved by basing them on the species that have been observed at the site in pre-development surveys;

- Careful temporal design of dredging programs could minimise the impacts on seagrass. Designing the program to restrict intense light reduction to short periods interspersed with longer periods of moderate to low light reduction will reduce impacts and increase the recovery potential of the seagrasses. Seagrass might be able to survive beyond some of the thresholds provided in Table 2 if dredging is managed to include significant periods of moderate to high light intensities.

- While seagrasses in the dredging far-field are unlikely to experience the sorts of burial pressures that would produce mortality, it is feasible that under low light and organic-rich sediment conditions burial depths of 40 mm for 6 weeks could impact shoot density. The lack of reliable field data makes it difficult to determine how likely these conditions are.

Zones of Impact and Influence

- The EPA (2016) framework for managing dredging requires spatially-explicit zones of different levels of impact to be predicted: the Zones of Influence, Moderate Impact and High Impact. The threshold values provided in this study can be applied to define the boundary of the Zone of Influence/Zone of Moderate Impact, as provided in Table 2.

Implications for consideration of broader ecological effects of dredging

- Sub-lethal burial during dredging may not result in the loss of meadows but could lead to a shift in meadow composition away from slow-growing species such as *C. serrulata* to species like *H. uninervis*.

- *H. uninervis*, is an import food for dugongs. Under sub-lethal light and burial stress, its starch reserves (and therefore nutritional value) were reduced. Consequently, the forage value of *H. uninervis* for dugongs may be reduced during periods of low light. Herbivorous fish and turtles graze on seagrass leaves, whose forage value generally increases with an increase in leaf N (Goecker et al. 2005). Leaf nitrogen concentration increased with sub-lethal low light stress, suggesting that their forage value may be increased during periods of low light. This could result in a feedback loop that causes over-grazing. While it is difficult to provide any strong qualitative advice on these broader ecological effects, they may be worth considering from a conceptual perspective when predicting the impacts of dredging on seagrass communities.

Light quality

- Our limited evidence shows that while dredge plumes have the potential to affect seagrass through changes in light quality, this will not always be the case and is likely to depend on the sediment type and concentrations in the water column. A full understanding of the likely effects of dredging on seagrasses should include assessment of the likely changes to water quality, particularly where this could involve a significant shift towards yellow or blue wavelengths.

Post-Approval

- The seagrass indicators identified in this study are appropriate for application in compliance monitoring programs and in monitoring undertaken to guide the timing of monitoring. The reader is referred to the previous advice, above, on the timescales of variability and application of these variables.

3.2.4 Recover following disturbance

Prior to this research, environmental impact assessments commonly assumed that many of the seagrass species in NW WA would recovery relatively quickly (i.e. within months to 1-2 years) even if strongly impacted by dredging. This was particularly the case for *Halodule uninervis* and *Halophila ovalis*, which are colonising species with adaptations for recovery from disturbance, such as rapid growth and seed banks from which new individuals can repopulate the meadow. Despite these assumptions, there was almost no information on the recovery mechanisms and potential of NW WA seagrasses and information from northern QLD suggested a high degree of variability among seagrass populations in both the mechanisms and rates of recovery following disturbance.

Two projects (sub-projects 5.4, Vanderklift et al. 2017b; and 5.5.3, Statton et al. 2017c) examined the ability of seagrasses to recover following experimental impact treatments. The latter of these was presented in the previous section, and showed that seagrass biomass recovered over weeks following light reduction treatments, dependent on the magnitude of the impact (Figure 7). In that case, recovery was from vegetative re-growth, requiring the survival of some plant material at the end of the impact phase. In a real dredging campaign it is possible that all seagrass will be lost from a site and it was not clear how seagrass would recover under those conditions. To improve our understanding of recovery processes, a field experiment (Vanderklift et al. 2017b) was performed to examine the capacity, duration and mechanisms of recovery of seagrass from a severe localised disturbance, and in particular, whether seagrass recovery is by vegetative regrowth from rhizome extension (i.e. asexual) or recruitment from seeds (i.e. sexual).

At ‘Shallow’ (2 m) and ‘Deep’ (6 m) sites, circular plots (75 cm diameter) within seagrass meadows were cleared and the recovery compared in plots where re-invasion by rhizomes was prevented by a plastic barriers and plots with no barrier. It was originally intended to also manipulate the seed density in the plots but low numbers of seeds in the sediments made this impossible. This absence or extremely low abundance of viable seed banks was an important finding, bringing into question the validity of assumptions that seagrass routinely recover from seed banks. Seagrass cover in the plots was measured on multiple occasions over 208 days and showed clear evidence of recovery in plots without barriers via vegetative growth from outside the plot, after about 2 months (Figure 11). In contrast, the cleared plots with barriers (and which therefore depend on recovery from either seeds or fragments washing into the plot) never contained seagrass even at the end of the experiment. The findings were similar for both shallow and deep sites and indicated that the primary mechanism for recovery of seagrass (primarily *H. ovalis*) was through vegetative regrowth.

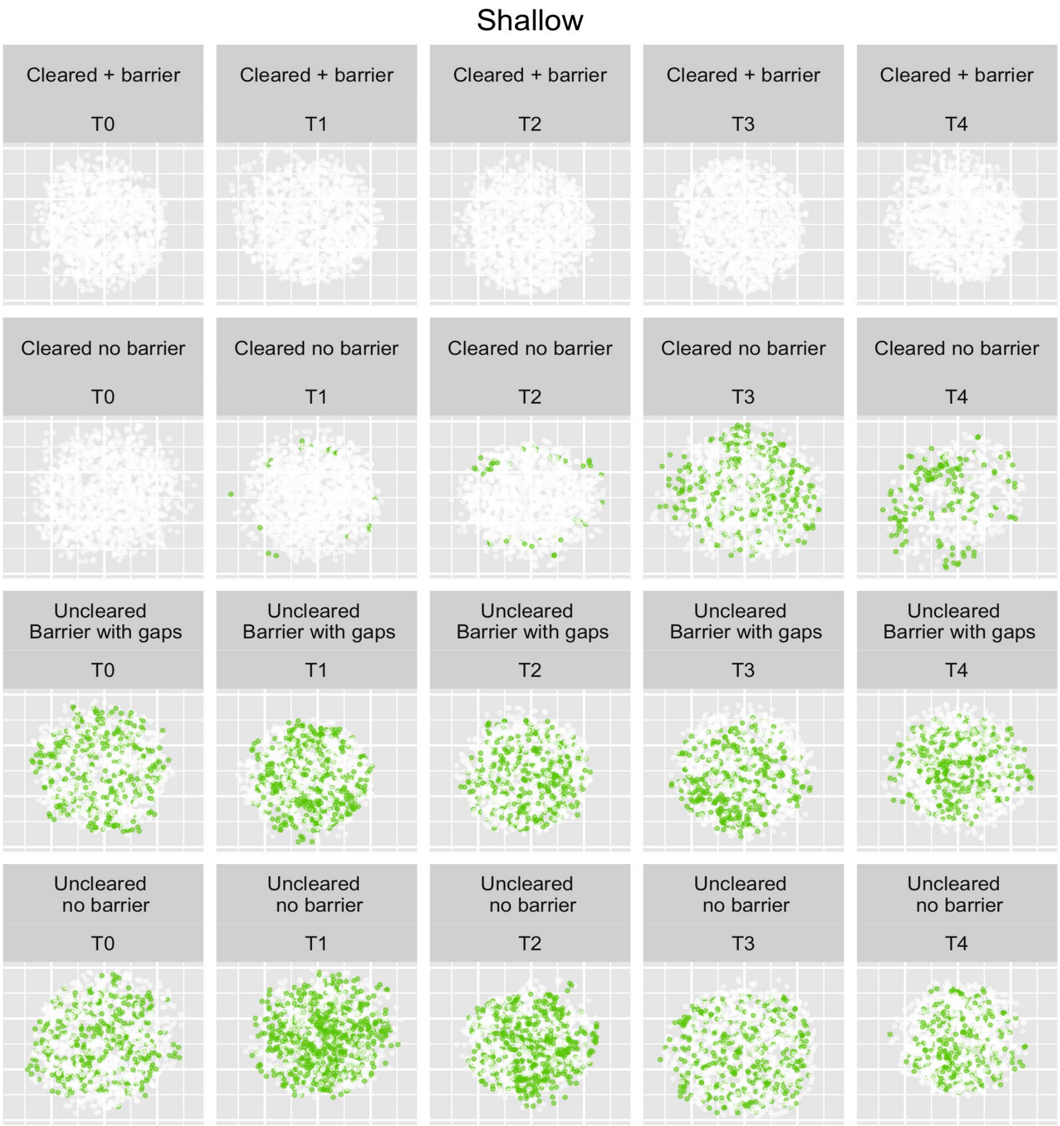

Figure 11. Plots showing seagrass presence (green dots) in cleared and uncleared seagrass plots at Thevenard Island (in 2 m water depth). T0 = 24 Nov and T1 = 8 d, T2 = 21 d, T3 = 59 and T4 = 104 d later. The diagrams demonstrate that in cleared plots with a barrier surrounding them (Top row) there was no recovery of seagrass over time but in similarly cleared plots without a border seagrass cover increased (Second row) the recovery commenced at the edges of plots, consistent with recovery through rhizome extension from the surrounding meadow. The bottom two rows were controls used within the experiment.

This experiment had limitations that need to be taken into account when extrapolating the findings to dredging programs. The most significant of these is that the clearances were in the order of 0.5 m^2 within otherwise undisturbed meadows from which vegetative regrowth could occur. Large commercial dredging programs would potentially produce seagrass loss over much larger areas, so recovery by rhizome extension from surrounding meadows might not be possible. Where seagrass loss occurs over a larger area, recovery might rely more heavily on immigration of plant fragments or seeds from distant sites, which will take longer. At this stage we have insufficient data to predict the time required for recovery in such situations.

Understanding patterns of genetic diversity can provide insights into the potential for seagrasses to resist disturbance or to recover from more extensive disturbance through immigration of seed or plant fragments. Greater diversity can enhance resistance and higher levels of gene flow between populations indicate ecological processes that promote dispersal of seagrasses and enhance the rate of recovery following complete habitat loss. However, for most seagrasses and in most parts of the world, extremely little is known about the genetic diversity and connectivity of populations. The genetic diversity of three species was assessed as part of the Theme 5 program: *Halophila ovalis*, *Halodule uninervis* and *Thalassia hemprichii* at a range of spatial scales. The main findings were:

- *Halophila ovalis* in the Exmouth region had moderate to high genetic diversity and both sexual reproduction and vegetative growth appeared to be important for maintaining population viability. High levels of migration were detected among sites within 2–5 km of each other, and low to moderate levels over larger distances. These characteristics indicate that the populations appear to be resilient from a genetic perspective.
- *Halodule uninervis* within in the Pilbara region had two types of meadow. Some meadows showed patterns similar to *H. ovalis*, with moderate to high genetic diversity and high connectivity among meadows 2–5 km apart. The second type of meadow had very low genetic diversity, with vegetative growth appearing to be more important for maintaining populations than sexual reproduction; these meadows may take longer to recover if there is complete seagrass loss. Long distance migration was detected but appeared to be rare. Overall, some meadows appear to be resilient from a genetic perspective, but others do not.
- *Thalassia hemprichii* was assessed in the Pilbara (over about ~200 km of coastline) and compared to populations in the Kimberley and Indonesia. The Pilbara populations were genetically diverse with moderate to high levels of connectivity, predominantly in a northerly direction.

Based on genetic theory and the data collected in the study, we developed a genetic resilience assessment for seagrass meadows in the Pilbara (Figure 12), Following this assessment, the least genetically resilient meadows were at Rosemary Island and the most genetically resilient meadows were at Exmouth Gulf, Barrow Island and Thevenard Island.

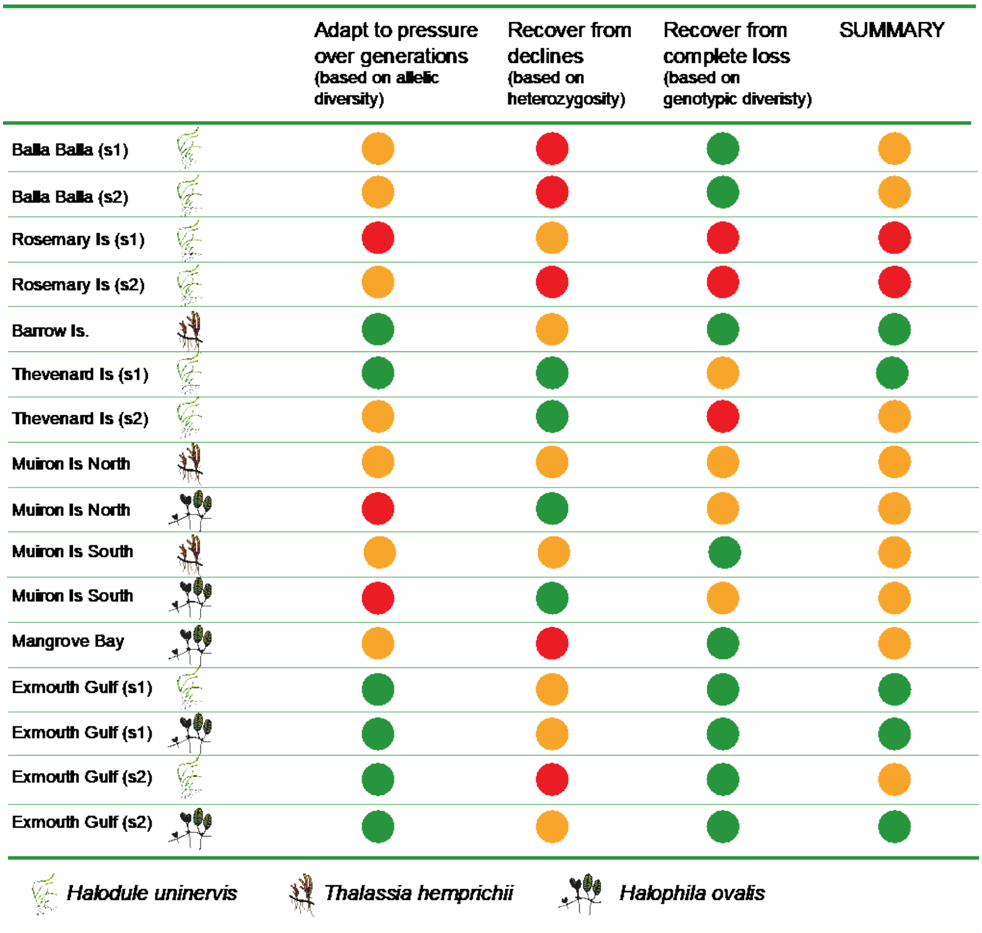

Figure 12. A summary of the genetic resilience of seagrass meadows in the Pilbara. The potential to adapt to pressures over generations was based on allelic richness, to recover from declines in a generation was based on heterozygosity and to recover from complete loss using seed banks was based on genotypic diversity (clonal richness).

Box 3 Implications of the findings on seagrass resistance to disturbance and their ability to recover for management of dredging under the EPA (2106) framework

Pre-development Surveys

- Assessing the risk that dredging poses to seagrasses will be aided by collection of relevant genetic data in pre-development surveys. The resilience of seagrass species to pressures can be influenced by the amount of genetic variation in a population. Seagrass meadows and species in NW WA display different levels of genetic diversity and so they may need to be managed differently. Pre-development surveys could usefully collect data on:
    1. which species of seagrass are present and likely to be influenced by dredging-related pressures;
    2. the genetic diversity of the seagrass meadows (i.e. clonal richness, allelic diversity, heterozygosity);
    3. the life-history traits relevant to recovery, e.g. sexual reproduction, seed banks; and
    4. the magnitude of gene flow and proximity of local populations (outside of the zone of impact) for repopulation.

Impact prediction

Predictions about recovery should not assume a rapid recovery from seed banks. While we cannot discount that seagrass populations could recover rapidly following disturbance, we have found no evidence in the Pilbara of persistent seed banks that provide the mechanism for that recovery;

- According to the EPA (2016) policy framework, temporary loss of seagrass meadows (through poor water quality) although undesirable is permissible in some zones, as long as the meadow recovers to pre-dredging levels within five years. The Theme 5 studies identified that:
    1. for most meadows, both sexual reproduction and vegetative growth are important for maintaining populations; and
    2. there was a reasonably high level of migration of genes over distances of 2–5 km, but lower levels over greater distances.

    Impact assessments should incorporate the possibility that meadows can be severely impacted in the short-term but recover in the longer-term through immigration or from seed banks. Pre-development surveys can quantify seed banks and levels of connectivity to other populations, increasing confidence in predictions of likely effects and recovery potential, and also allow the identification of higher risk situations – e.g highly isolated populations of genetically low diversity meadows.

- A primary mechanism for recovery is through extension of vegetative growth from surrounding meadow(s) into disturbed patches. Therefore, seagrass loss that encompasses relatively small areas, typical of that due to anchoring of vessels and deployment of equipment, is likely to be temporary in meadows comprised of colonising species, such as *Halophila* spp., and significant regrowth could be expected within a year.
- While it is plausible that complete recovery through rhizome extension is easily achieved for un-vegetated patches within meadows, this is less likely for disturbances that encompass hectares. Our findings indicate that although there can be short-term recovery (less than 1 year) from seed banks, this cannot be assumed, even at sites where sexual reproduction is considered important for maintaining the seagrass population. Managing for the retention of some vegetative material will increase the rate of recovery following dredging. Complete loss of all vegetation will result in longer periods required for recovery.

Post-Assessment

- A number of agent-based modelling approaches are commonly used to predict the re-growth of seagrass meadows. These models require input of the seagrass growth rates and branching patterns and may prove useful in estimating the recovery time of meadows based on vegetative growth. The data in this study on recovery rates can provide calibration or validation data set for such models focused on *H. ovalis* in the Pilbara region.

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