



Seagrasses of the north west of Western Australia: biogeography and considerations for dredging-related research

Kathryn McMahon^{1,3}, John Statton^{2,3} and Paul Lavery^{1,3}

¹ Edith Cowan University, Joondalup, Western Australia, Australia

² The Oceans Institute, The University of Western Australia, Crawley, Western Australia, Australia

³ Western Australian Marine Science Institution (WAMSI), Perth, Western Australia, Australia

WAMSI Dredging Science Node

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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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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.

Funding and critical data

Critical data



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Corresponding author and Institution: K McMahon (ECU). Email address: k.mcmahon@ecu.edu.au

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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 spinulosa* has large fleshy rhizomes which contain abundant starch reserves. These plants are an important food resource for both dugongs and turtles. (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: Dugongs have both high conservation and cultural significance and are largely dependent on seagrass habitats to support their dietary requirements. (Source: Kevin Crane)

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Executive Summary

This review was undertaken to identify which seagrass primary producers (species or different functional groups) that collectively cover the bio-geographic range of key primary producers in the north west of Western Australia (NWWA) are most appropriate for the focus of subsequent research into thresholds and indicators of response to dredging-related pressures (i.e. Theme 5). An assessment framework was developed based on six criteria: biogeographic range; ecological relevance (life-history strategy, habitats, natural dynamics and ecological services); current knowledge on thresholds and bioindicators; likelihood that species are sensitive and resilient to dredging related stressors; extent of improvement in applied knowledge; and likelihood of being able to grow seagrass species successfully in mesocosms. For each criterion, one or more assessment metric was developed. These were then used in a hierarchical decision-making process to identify the species most appropriate for the focus of subsequent research. The first step identified those species with the broadest biogeographic range, which were found in the most regions and habitats and which had the greatest ecological significance and prioritised the species for further investigation (Priority 1, 2 and 3). The second step identified species that encompassed a range of sensitivities and resilience to dredging and which, collectively, offered the greatest opportunity to improve our knowledge and understanding of primary producer responses to dredging-related pressures.

Two Priority 1 species were identified as those most appropriate for the focus of future research: *Halophila ovalis* and *Halodule uninervis*. However, because both these species have similar sensitivity and resilience to dredging related stressors, it is recommended that *Cymodocea serrulata*, a Priority 2 species, also be considered for future research effort; this species has a different sensitivity and resilience to dredging and will therefore broaden the applicability of the experimental findings. The review also identified that tropical seagrass meadows are commonly mixed-species assemblages. It is unclear whether single-species experimental studies are representative of plant responses in mixed-species meadows. Therefore, it is recommended that future research use a combination of single-species and mixed species experimental assemblages to improve our understanding of how tropical seagrasses respond to dredging related stressors.

Considerations for predicting and managing the impacts of dredging

Site-specific information on seagrass meadow characteristics

Site-specific information on seagrass meadow characteristics is required to improve our ability to predict impacts from dredging related stressors and to direct management and monitoring approaches. Currently, there is a limited capacity to draw models of seagrass responses to dredging-related pressures that can confidently be generalised across the NWWA; patterns and responses observed in one location are not necessarily transferable to other locations. Impact prediction, management and on-going monitoring need to take account of the species present, the community type and habitat characteristics of each site. Two key findings underline this recommendation:

- Seagrasses occur in a variety of habitats in the NWWA. As has been observed in other tropical regions, the dynamics of seagrasses are likely to vary across these habitats, due to the different environmental and biological drivers found in each habitat. Very little is known on the dynamics of NWWA seagrasses, but based on other locations, deeper water habitats are more likely to support annual (transitory) populations while shallow water and intertidal habitats are more likely to support enduring (persistent) populations. The temporal dynamics of the species are critical to their sensitivity and resilience to dredging. We are not yet in a position to state with confidence how transferable the phenology and longer-term temporal dynamics patterns of species are among different regions of Western Australia (WA). Until there is evidence to support the generality of the population dynamics, they need to be assessed on a site-specific basis. The site-specific information requirements will relate to the type of seagrass community present at a site and the habitat characteristics of the site. With respect to the

phenology and longer-term dynamics of seagrasses, key questions when assessing the risk of dredging to seagrass habitats are: when is the growing season; when does flowering occur; when does the seed bank, if applicable, develop; and when does seed germination occur?

- The seagrass habitats of NWWA are highly dynamic. A range of cyclical and stochastic events can significantly affect their presence or abundance but are likely to vary among sites. It is important that managers and proponents are aware of these dynamics at any given site since they can affect the presence of meadows and the recovery potential, and may drive considerations in the design of dredging programmes.

The relevance of thresholds for North West (NW) seagrass species needs to be tested.

Thresholds of tolerance for sediment burial and reduced light availability have been developed for some of the species that occur in NW Australia. However, these thresholds have not been derived from studies conducted in the NW or on plants collected from the NW. The absence of region-specific studies on the tolerances of seagrasses to dredging-related pressures, together with the uncertainty regarding the transferability of the limited studies from elsewhere, highlights the need for local studies, such as those forming part of the Western Australian Marnie Science Institution Dredging Science Node (WAMSI Dredging Science Node). This is in line with approaches set out in the Australian and New Zealand Environment and Conservation Council (2000) water quality guidelines, which recommended that site-specific information be used to develop appropriate guidelines particularly for variables such as light for primary producers, in acknowledgement of the inherent variation within the environment. While there is some indication that the same species from different locations respond in a similar way to dredging-related pressure (see WAMSI DSN Project 5.5.1 for comparison of *H. uninervis* from Shark Bay and Queensland, and Shark Bay and Exmouth (Statton et al. 2017)), the data are limited and are not part of a rigorous test of this question. In the absence of evidence to support their transferability, thresholds derived from other regions should be considered as indicative only.

Generally, intertidal seagrasses are considered less likely to be affected by dredging related pressures, particularly reduced light, as they are exposed at low tide. However, aerial exposure can be very stressful time for seagrasses, and may not afford them adequate respite from dredging related pressures. Managers should not consider them relatively resilient to dredging and instead should factor them into assessment in the same way as sub-tidal habitat.

1 Introduction

This review was undertaken to identify which primary producers (species or different functional groups), that collectively cover the bio-geographic range of key primary producers in WA, are most appropriate for the focus of subsequent research into thresholds and indicators of response to dredging-related pressures (i.e. Theme 5). In accordance with the Science Project Plan underlying Theme 5 of the WAMSI Dredging Science Node, the review is restricted to seagrasses and does not include macroalgae (seaweeds) or microalgae (phytoplankton or microphytobenthos). At least two priority species need to be selected for the development of thresholds and indicators of response to dredging-related pressure in WAMSI Project 5.5.

In this review, the range of potential seagrass species were assessed against six criteria to produce a list of priority species for future research:

1. biogeographic range;
2. ecological relevance;
 - a. life-history strategy,
 - b. habitats,
 - c. natural dynamics,
 - d. ecological services;
3. current knowledge on thresholds and bioindicators;
4. likelihood that they are species sensitive and resilient to light-reduction and sediment deposition;
5. extent of improvement in applied knowledge to be gained by focussing new research on the species;
and
6. likelihood of being able to grow seagrass species successfully in mesocosms.

A hierarchical decision-making process was applied to select the most relevant species for the focus of on-going research. The first step was to identify a subset of species from criteria 1 and 2 above that have the broadest biogeographic range, occur in a wide range of habitats and provide significant ecological services. The second step was applied to the resulting subset of species to select two species that represent a range of life-history strategies, sensitivities and resilience to dredging and will contribute most to improving our knowledge of thresholds and indicators of primary producer responses to dredging-related pressures.

Information for this review was sourced from: the published literature (as identified in searches of standard databases such as ISI Web of Knowledge and Scopus); information made available through Theme 1 of the WAMSI Dredging Science Node; and grey literature, including industry, state and federal government documents.

1.1 Seagrass species considered

Eleven seagrass species were considered in this review (Table 1). We focused only on those species that are commonly found in tropical areas and we follow the species names presented in Waycott et al. (2004), with the addition of the species *Cymodocea angustata*, which was not included in that book. These species conform with the Australian Plant Name Index (APNI 2013), except in the case where we group *Halodule uninervis* and *Halodule pinifolia*, called from here on in *H. uninervis* as it is very difficult to distinguish between these two species, and there is uncertainty in the species boundaries. *Halophila ovata* is considered a synonym of *Halophila ovalis*, and *Halophila minor* is difficult to distinguish from *H. ovalis* and there is also uncertainty in the taxonomy, therefore we group these into the *Halophila ovalis* 'complex', which from here on we call *H. ovalis*.

In the following five sections we evaluate the seagrass species against the criteria listed above. We then synthesise the findings to identify the priority species for research and address the management implications.

2 Results

2.1 Biogeographic Range

This review considered seagrasses in the north west of Western Australia (NWWA), defined here as a biogeographic area extending from Shark Bay in the south to the Northern Territory border in the north. All tropical seagrass species present in the region were considered with the exception of *Ruppia* spp., which is generally found in estuaries, not coastal habitats. This area was further divided into geographic sub-regions based on the Integrated Marine and Coastal Regionalisation of Australia - version 4.0 June 2006 (IMCRA v4.0), a national and regional planning framework to enable the systematic development of a comprehensive, adequate and representative National Reserve System (IMCRA 2006). Thirteen IMCRA bioregions occur within NWWA:

1. Shark Bay
2. Zuytdorp (north of Shark Bay only)
3. Ningaloo Reef
4. Pilbara Inshore (Exmouth Gulf to Cape Kerauden)
5. Pilbara Offshore (North of Ningaloo to Cape Kerauden)
6. 80 Mile Beach
7. Northwest Shelf
8. Canning (Broome to Cape Leveque)
9. King Sound
10. Kimberley (Cape Leveque to Cape Londonderry)
11. Bonaparte (Cape Londonderry to Wyndham)
12. Cambridge/Bonaparte (Wyndham to WA/NT border)
13. Offshore Shoals

The distribution of species was considered in two ways. First, by the number of bioregions each species is found (Table 1). The most widespread species were *H. ovalis* and *H. uninervis*, found in nine of the 13 regions, followed by *Halophila spinulosa*, *Halophila decipiens* and *C. serrulata*, in eight regions, then *Syringodium isoetifolium* in seven regions. Secondly, they were considered in relation to their global distribution (Figure 1). All species in NWWA have an Indo-Pacific distribution, apart from *C. angustata*, which is endemic to WA (Figure 1; Waycott et al. 2004, Waycott et al. 2014). Most species are found throughout NWWA apart from *Enhalus acoroides* and *Cymodocea rotundata*, which are restricted to the northern part of the area, and *C. angustata* which is restricted to the southern section (Figure 1).

Table 1. Distribution of seagrass species in the thirteen IMCRA subregions, arranged from south to north and seagrasses species arranged by family and then species.

IMCRA:	Shark Bay	Zuytdorp	Ningaloo	Pilbara near	Pilbara offshore	NW Shelf	80 Mile Beach	Canning	King Sound	Kimberley	Bonaparte	Cambridge Bonaparte	Oceanic Shoals	TOTAL NUMBER OF REGIONS
Species														
Hydrocharitaceae														
<i>Enhalus acoroides</i>					X			X		X	X			4
<i>Halophila decipiens</i>	X		X	X	X		X	X		X			X	8
<i>Halophila ovalis</i> ¹	X	X	X	X	X		X	X		X			X	9
<i>Halophila spinulosa</i>	X	X	X	X	X		X	X		X				8
<i>Thalassia hemprichii</i>				X	X			X		X			X	5
Cymodoceaceae														
<i>Cymodocea angustata</i>	X	X		X	X			X						5
<i>Cymodocea rotundata</i>								X						1
<i>Cymodocea serrulata</i>	X	X	X	X	X		X	X		X				8
<i>Halodule uninervis</i> ²	X	X	X	X	X		X	X		X			X	9
<i>Syringodium isoetifolium</i>	X	X	X	X	X			X		X				7
<i>Thalassodendron ciliatum</i>	X			X	X			X		X			X	6

¹including *H. ovata* and *H. minor*

²including *H. pinifolia*

References: (McMillan et al. 1983, Walker & Prince 1987, McCook et al. 1995, Wells et al. 1995, Schaffelke & Klumpp 1996, Walker et al. 1996, Osborne et al. 2000, Masini et al. 2001, Huisman & Borowitzka 2003, RPS 2005, McKenzie 2007, Huisman et al. 2009, Sinclair Knight Merz 2011, van Kuelen & Langdon 2011, Loneragan et al. 2013 and Huisman & Sampey 2014)

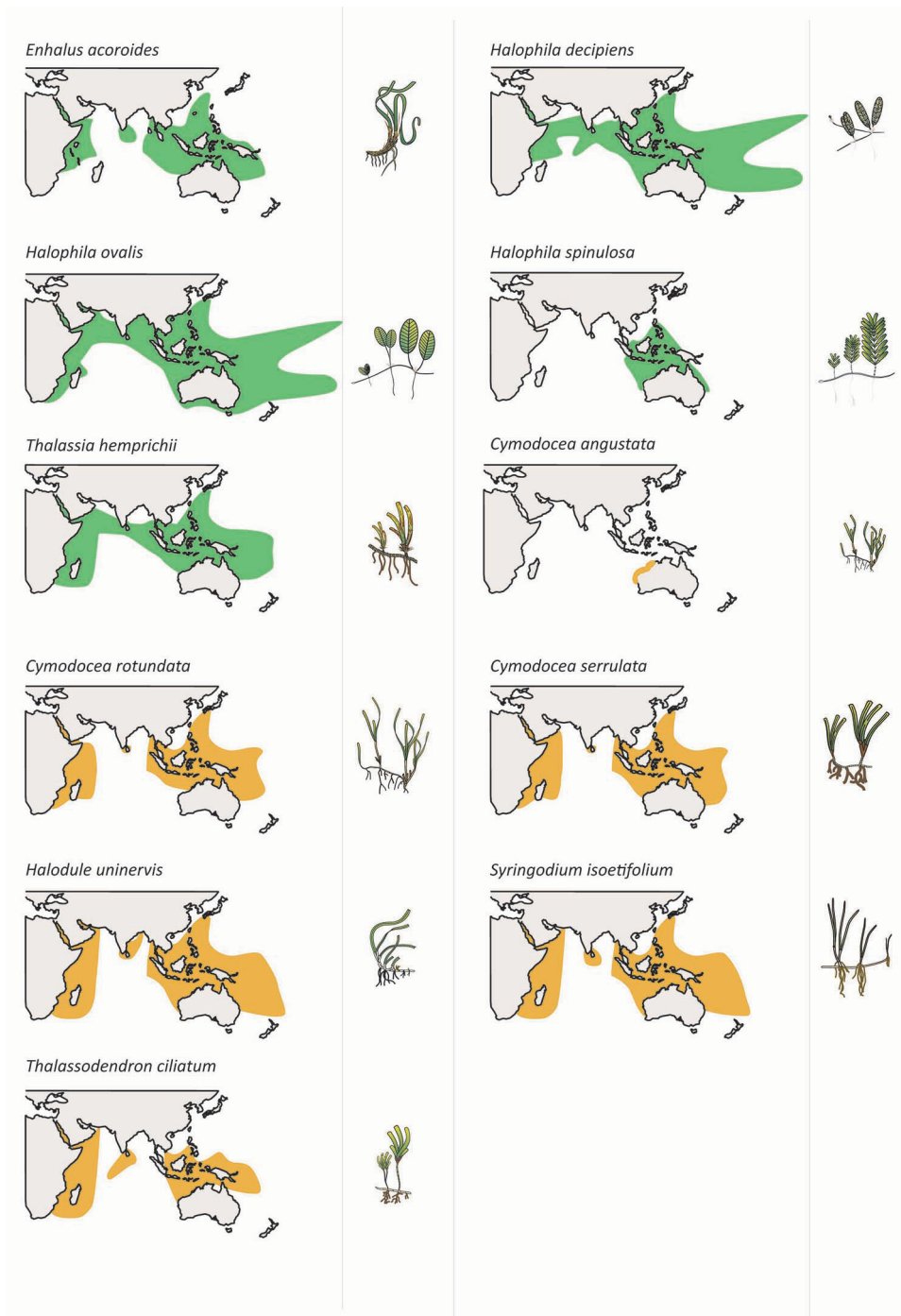


Figure 1. Biogeographic ranges of the seagrass species found in NWWA. Images adapted from Waycott et al. (2004) and Waycott et al. (2014). Distributions in green are for members of the Hydrocharitaceae; yellow is for Cymodoceaceae. *H. ovalis* includes *H. ovata* and *H. minor*, and *H. uninervis* includes *H. pinifolia*.

3 Ecological relevance

3.1 Life-history strategy

Among seagrasses there is considerable variation in the life-history traits of species (e.g. Walker et al. 1999, Carruthers et al. 2002a, Carruthers et al. 2007, Collier & Waycott 2009, Waycott et al. 2011). A life-history based functional classification has recently been proposed by Kilminster et al. (2015) which categorises genera based on life-history traits (shoot turnover, genet persistence, time to first sexual reproduction, seed dormancy) into persistent or ephemeral species along with an opportunistic, intermediate group (Figure 2). It is desirable to include at least two of these categories within our priority species list since the sensitivity to, and ability to recover from, dredging-related pressures is likely to vary among ephemeral and persistent seagrasses. There is much in common with these models and the traditional r-K model of species life-history traits (*sensu* MacArthur and Wilson 1967) or the C-S-R model adapted for plants of Grime (1979). Species that are ephemeral have short ramet turnover times (< months), a rapid-colonising growth, fluctuating total standing biomass, a high level of reproductive effort producing seeds and an ability to build up a seed bank, even a short-lived one. Typical ephemeral seagrasses found in the tropics are members of the genera *Halophila* and *Halodule* (Table 2). In contrast, species that are classified as persistent have long lived ramets (many months-years) and clonality from long lived genets (millennia in extreme cases e.g. Arnaud-Haond et al. 2012), stabilising and/or sediment trapping growth, high standing biomass, reproductive effort for seed production that is not compromising to vegetative growth and seeds that typically do not form a seed bank. Typical persistent, tropical seagrasses are from the genera *Thalassodendron*, *Thalassia* and *Enhalus* (Table 2). A number of genera combine core elements of both extremes of these strategies and these opportunistic seagrasses have both the ability to colonise, produce seeds or seedlings and also have the ability to gain significant, persisting biomass and clonality, while also rapidly recovering from seed (or new recruits) when necessary. Typical opportunistic, tropical seagrasses are from the genera *Cymodocea* and *Syringodium* (Table 2).

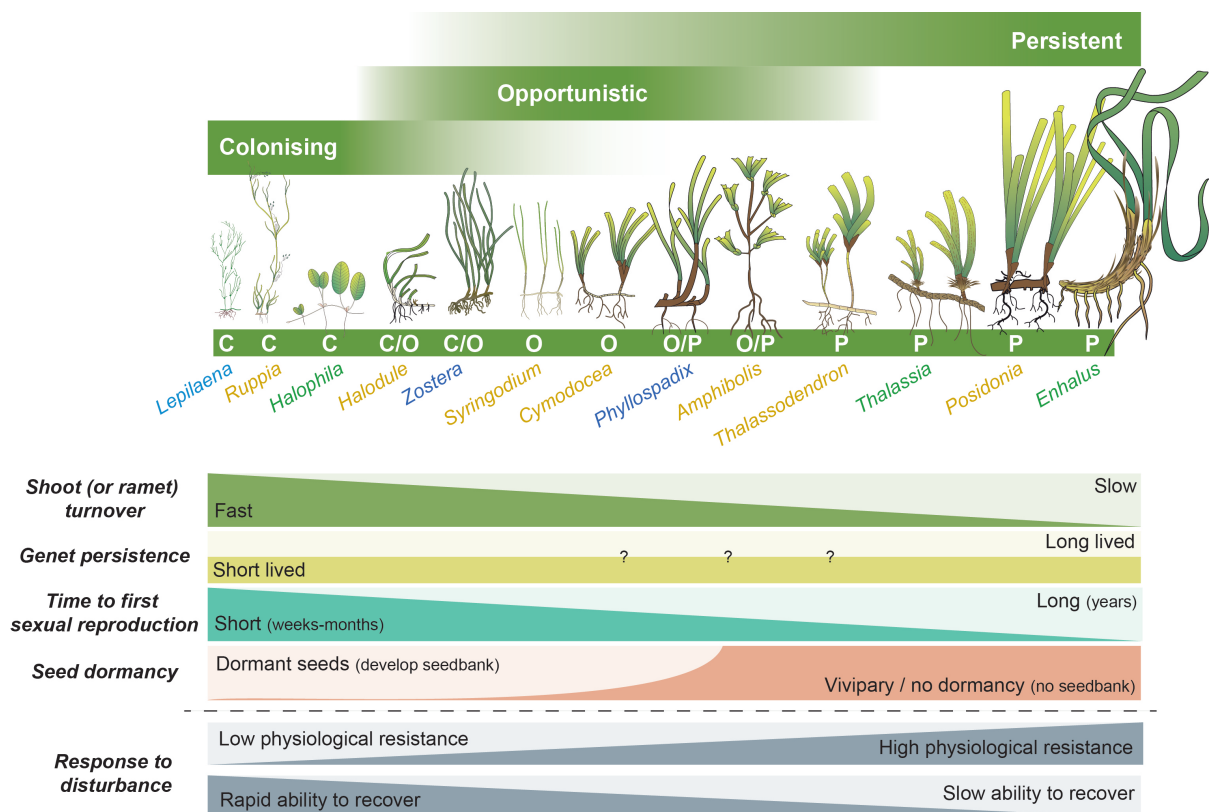


Figure 2. Life-history model of seagrasses (from Kilminster et al. 2015)

Table 2. The life-history strategy classification of tropical seagrasses from NWWA as defined by (Kilminster et al. 2015).

Species	Ephemeral	Opportunistic	Persistent
Hydrocharitaceae			
<i>Enhalus acoroides</i>			X
<i>Halophila decipiens</i>	X		
<i>Halophila ovalis</i> ¹	X		
<i>Halophila spinulosa</i>	X		
<i>Thalassia hemprichii</i>			X
Cymodoceaceae			
<i>Cymodocea angustata</i>		X	
<i>Cymodocea rotundata</i>		X	
<i>Cymodocea serrulata</i>		X	
<i>Halodule uninervis</i> ²	X		
<i>Syringodium isoetifolium</i>		X	
<i>Thalassodendron ciliatum</i>			X

¹including *H. ovata* and *H. minor*²including *H. pinifolia*

3.2 Habitats

The main habitats in which seagrass are found are categorised here on the basis of water clarity (clear or turbid) and by the habitat types following Waycott et al. (2004): intertidal, subtidal, estuarine, coastal, reef and deep. Water clarity is relevant to plant-responses to dredging since this may influence the degree of adaptation to low-light and high turbidity conditions, or the tolerances to additional stresses arising from dredging. Intertidal seagrass is exposed to air during at least some low tides whereas subtidal meadows are never exposed to air. Estuarine habitats occur in estuaries, while coastal habitats are all other soft-bottom habitats outside of estuaries. Reef habitats have a hard substrate, such as calcium carbonate. Deep habitat is defined as greater than 15 m water depth. It is desirable to select priority species that are found in as many different habitats as possible since this increases the potential transferability of research findings across the range of habitats where future dredging activity may occur.

The majority of species from NWWA are found in both clear and turbid waters, although there are no records of *T. ciliatum* in turbid water in this region (Table 3). All species grow subtidally but only seven are found intertidally: *E. acoroides*, *H. ovalis*, *T. hemprichii*, the three *Cymodocea* spp. and *H. uninervis*. *H. spinulosa* is not known from reef sites and *T. ciliatum* is not known from soft-bottom coastal sites. Only the three *Halophila* spp. are commonly found in deep habitat.

H. ovalis is found in all eight habitats, and the remaining species in 6–7 habitats, except for *T. ciliatum*, which is only found in four (Table 3).

Table 3. Habitats where seagrass species are found in the NW of WA (Data from Waycott et al. 2004, 2014 and per. obs. authors).

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

¹including *H. ovata*, *H. minor*²including *H. pinifolia*

3.3 Community dynamics of meadows

3.3.1 Drivers of variation in seagrass composition, abundance and productivity

The dynamics of tropical seagrass meadows are complex and vary spatially (Carruthers et al. 2002b). They are influenced by a number of factors operating at a variety of temporal and spatial scales. These factors include: environmental forcings, such as tides (daily-monthly), temperature (daily-decadal), sunlight (daily-monthly), wind strength and direction (daily-monthly), rainfall and runoff (monthly-decadal), storms and cyclones (monthly-decadal) and nutrients (monthly); and biological forcings, such as grazing and bioturbation (varied). All of these can affect seagrass dynamics by their influence on environmental conditions such as light, temperature and nutrient availability and through physical disturbance.

In NWWA the tidal range is highly variable from a maximum of over 11 m in Derby, 9 m in Broome, 7 m in Port Hedland, 2.6 m in Exmouth and 1.8 m around Carnarvon (Department of Transport 2014). Average monthly rainfall declines from Broome southwards (Figure 3, Bureau of Meteorology 2014). Most rain falls in the wet season, December to March, and this is the time of year when cyclones cross the coast. In the southern extreme, Carnarvon, there is a rainfall peak in May–June (Figure 3). Wind speed and direction also varies over space and time. This has been summarised by dominant wind strength category and direction in the wet season (October to April) and the dry season (May to September, Table 4). Due to the arid climate of this region, there are few rivers along the coastline, but they generally flow and discharge into the marine environment following rainfall events.

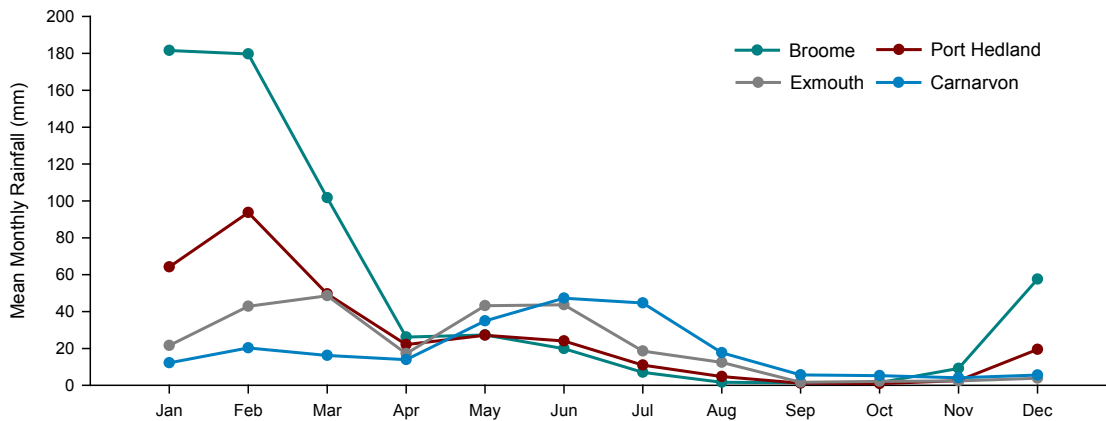


Figure 3. Average rainfall at four regions in NWWA WA, from Broome in the north to Carnarvon in the south. Data average rainfall from Bureau of Meteorology records. Extracted March 2014.

Table 4. A summary of the daily wind conditions in the wet (October to April) and dry season (May to September) from four regions in NWWA, from Broome in the north to Carnarvon in the south, including the dominant wind direction and the percentage of time it is from this direction and the average wind speed (km hr^{-1}). Data from Bureau of Meteorology records. Extracted March 2014.

Time and wind variable	Broome	Port Hedland	Exmouth	Carnarvon
Wet season				
Dominant wind direction	W	NW	SW	SW
Percentage of time	50%	50%	20%	50%
Dominant wind speed category	20-30	20-30	20-30	20-30
Dry season				
Dominant wind direction	W	N	NE	S
Percentage of time	30%	30%	20%	35%
Dominant wind speed category	10-20	10-20	10-20	20-30

Our understanding of how environmental factors, both abiotic and biotic, influence the dynamics of seagrasses in NWWA is poor. Here we outline some of the key factors influencing seagrass dynamics and the temporal scale over which they operate.

- Tidal cycles cause fluctuations in water level that can influence the light, temperature, salinity and carbonate chemistry that seagrasses are exposed to (Petrou et al. 2013, Cayabyab et al. in prep). These can then have direct impacts on growth and photosynthesis (e.g. Petrou et al. 2013, Cayabyab et al. in prep). Photosynthesis is maximised around the low tide for subtidal plants, and either side of the low tide for intertidal plants.
- Exposure at low tide is a stressful time for seagrasses due to temperature-, dessication- and light-stress and photosynthesis is inhibited (Petrou et al. 2013).
- Temperatures vary over seasonal cycles and decadal cycles (e.g. El Nino, El Nina) and productivity can follow these patterns in a positive way, with higher growth when temperature is greater (e.g. Collier unpublished data), or a negative way where over a decade reductions in cover were associated with higher

temperatures (Unsworth et al. 2012) or temperature spikes resulted in seagrass die-off (Campbell et al. 2006).

- High wind strength can resuspend sediment in shallow waters, resulting in lower light and reductions in seagrass cover (Petus et al. 2014).
- Turbidity associated with river runoff can also reduce light and cause reductions in seagrass cover (Collier et al. 2012b).
- Cyclones and storms can significantly affect seagrass cover by physically removing it or due to the associated turbidity resulting in seagrass loss (Birch & Birch 1984, Loneragan et al. 2013).
- Grazing can have a significant effect on the abundance and productivity of tropical seagrasses (Moran & Bjorndal 2005), depending on its intensity and frequency. Our understanding of seagrass – grazing interactions in NWWA is poor (see the section on ecological services which highlights our understanding of the distribution of key grazers).

3.3.2 Meadow types

Two main meadow types have been proposed for seagrasses – enduring and transitory meadows (Kilminster et al. 2015), (Table 5). Enduring communities persist over time, although there may be temporal variations in the species composition and abundance. All species and life-history categories can form enduring meadows

(Table 5). Enduring meadows dominated by persistent species such as *T. hemprichii* may have small seasonal variation in abundance (e.g. Guidetti et al. 2002, Figure 2a), whereas for enduring meadows of opportunistic and ephemeral species the magnitude of seasonal variation is often greater (Figure 4b) (e.g. Collier et al. 2012b). Ephemeral genera such as *Halophila* can also form enduring meadows which have a large seasonal variation (e.g. Hillman et al. 1995). In contrast, transitory communities are not persistent over time; at sometimes there will be no seagrass present, and only ephemeral and opportunistic species are able to form this community type (Table 5). Like enduring communities, transitory communities can also show variation in species composition and abundance over time. Clear examples of transitory communities are annual meadows that develop from the seed bank, grow, flower, set seed and dieback each year (Figure 4c), such as deep water meadows of *H. decipiens* in the Caribbean (Kenworthy 2000) or in Dampierland, Kimberley (Masini et al. 2009, Hovey et al. in review).

Meadows die-back when environmental conditions, such as temperature or light, are outside the species tolerance range and the meadows re-establish from seed when favourable conditions return. Transitory communities are not necessarily constrained to annual cycles but can fluctuate over longer or shorter times scales, i.e. be present for months to years. Some examples of these types of transitory meadows include: *H. decipiens* in the Caribbean which varies in abundance due to seasonal light conditions, but dies-back in some years, though not others, due to intense storms (Williams 1988), and at Abbot Point, QLD Australia where floods reduced deep subtidal seagrass to near-zero biomass three times within a 5 year period (with recovery in-between) (Rasheed et al. in press). The *Halophila* spp., particularly *H. decipiens* and *H. spinulosa* form ephemeral meadows in the Pilbara and Canning regions. *H. spinulosa* was observed in the Exmouth Gulf recovering after major seagrass loss following a cyclone and then declined after a number of years (Loneragan et al. 2013).

Clearly there can be a gradient in the community type from transitory to enduring meadows. Some meadows may be enduring for a number of years, but an extreme event such as a storm could completely remove the seagrass meadow (e.g. Preen et al. 1995). Over time the meadow may recover, but it may take a number of years to transition from an unvegetated area, to a transitory meadow to an enduring meadow. Due to this potential gradient from transitory to enduring meadows, and the interaction with stochastic events, from a management perspective it is useful to define the type of community based on an appropriate timescale. As such, an enduring community is defined here, as one that is present for five years or more under natural conditions.

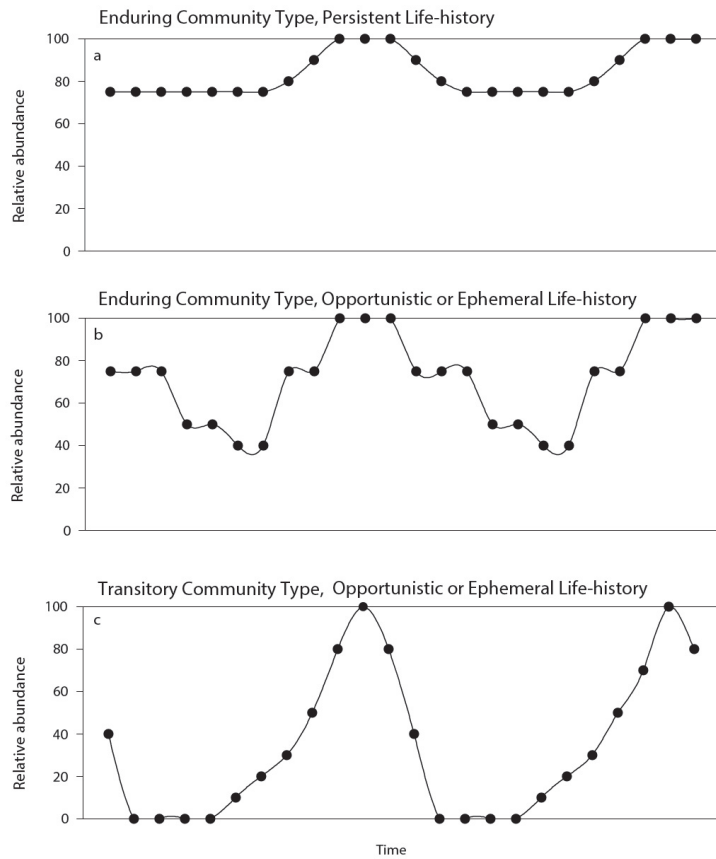


Figure 4. Hypothetical temporal patterns in the abundance of three different seagrass meadows consisting of (top) an enduring community with species of a persistent life-history strategy, (centre) an enduring community with species of any life-history strategy and (bottom) a transitory community type with species of an opportunistic or ephemeral life-history strategy. Adapted from Kilminster et al (2015).

Table 5. Community types formed by seagrass species in NWWA.

Species	Transitory	Enduring	TOTAL
Hydrocharitaceae			
<i>Enhalus acoroides</i>		X	1
<i>Halophila decipiens</i>	X	X	2
<i>Halophila ovalis</i> ¹	X	X	2
<i>Halophila spinulosa</i>	X	X	2
<i>Thalassia hemprichii</i>		X	1
Cymodoceaceae			
<i>Cymodocea angustata</i>	X	X	2
<i>Cymodocea rotundata</i>	X	X	2
<i>Cymodocea serrulata</i>	X	X	2
<i>Halodule uninervis</i> ²	X	X	2
<i>Syringodium isoetifolium</i>	X	X	2
<i>Thalassodendron ciliatum</i>		X	1

¹including *H. ovata* and *H. minor*

²including *H. pinifolia*

The various types of meadows are not usually found across all habitats. For example, transitory meadows can be found in all habitats, but occur mostly where environmental conditions vary considerably, such as deep-water habitats of *H. decipiens* in the Caribbean (Kenworthy 2000), *Halophila* spp. in the Great Barrier Reef (Coles et al. 2000) and *H. decipiens* near James Price Point, WA (Masini et al. 2009, Hovey et al. in review). A similar pattern has also been observed on the east coast of Australia in turbid, tropical environments (Unsworth et al. 2010). Enduring meadows can be found in a greater variety of habitats, but are most common in intertidal and shallow-subtidal habitats (e.g. Collier et al. 2012b).

Key questions when assessing the risk of dredging to seagrass habitats are related to the timing and seasonality of the key life-history processes such the growing season, flowering, seed bank development and seed germination. Based on a few case studies we give examples of what is known about these key life cycle processes in different community types found in NWWA. These patterns have been derived from a limited understanding of temporal dynamics; further research is required to be confident that they apply in other areas. It is possible that in different locations along the NW coast, different patterns occur due to the variation in local environmental conditions. For example, in some perennial meadows in the Great Barrier Reef, there are no predictable seasonal patterns (Lanyon & Marsh 1995).

Case study 1. Transitory meadow: ephemeral life-history: annual model at James Price Point

This case study of an annual meadow has been derived from seagrass near Broome, WA (~10-15 m water depth, Hovey et al. in review, Figure 5). Here plants germinate around March–May, seedlings develop and grow, reaching maximum biomass in October and November. At this time there is prolific fruiting and seed release into the sediments. Following this, the adult plants die back. This cycle is strongly linked to the light climate, where maximum light is observed in the dry season, and it reduces rapidly in the wet season when winds increase and storm frequency is greater. We predict that *Halophila* spp. would follow this pattern throughout NWWA, particularly in deeper water and turbid environments.

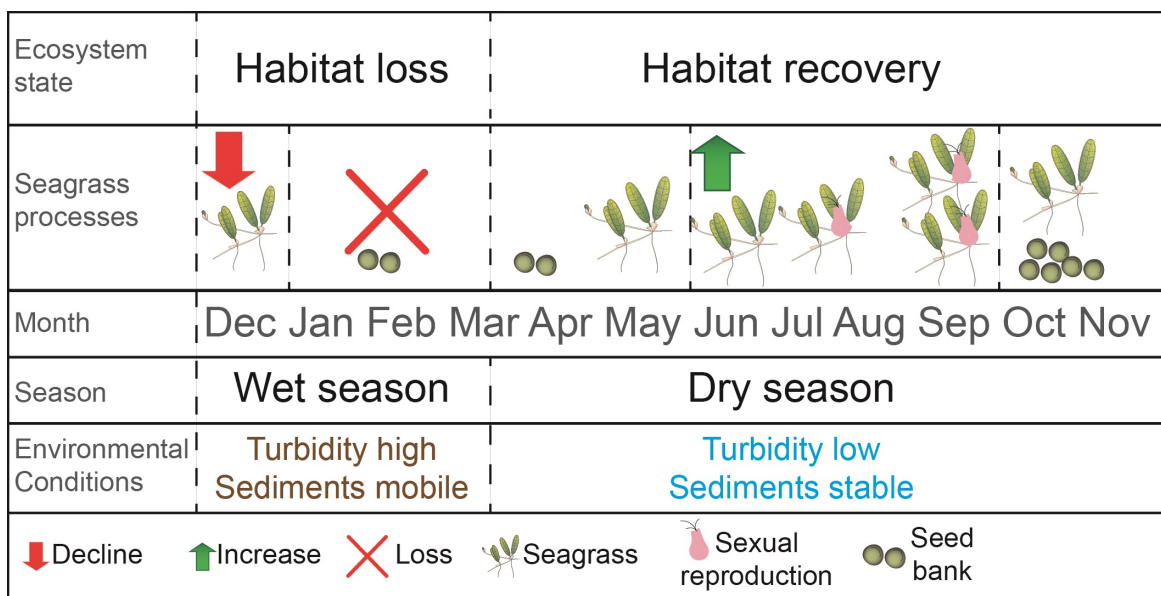


Figure 5. Temporal pattern in biomass, growth, flowering and seed production of annual populations of *H. decipiens* from James Price Point, WA (adapted from Hovey et al. in review).

Case study 2. Enduring meadow: ephemeral life-history – intertidal meadow at Broome

There is one case-study from a number of intertidal seagrass meadows in Broome, which documents the patterns in abundance of perennial meadows (Figure 6, Seagrass Watch 2014). However, there are no data on flowering or seed bank development. Here there are seasonal fluctuations from year to year, with maximum cover from October to January (the late dry to early wet season), and minimum cover from April to July, following the wet season and into the early dry season. Maximum cover coincides with the time of longest daylengths and when the water temperature begins to warm. We predict that flowering and seed set would occur around the time of peak biomass. However, it is possible that flowering occurs throughout the year, particularly for *H. ovalis* species (Waycott et al. 2004).

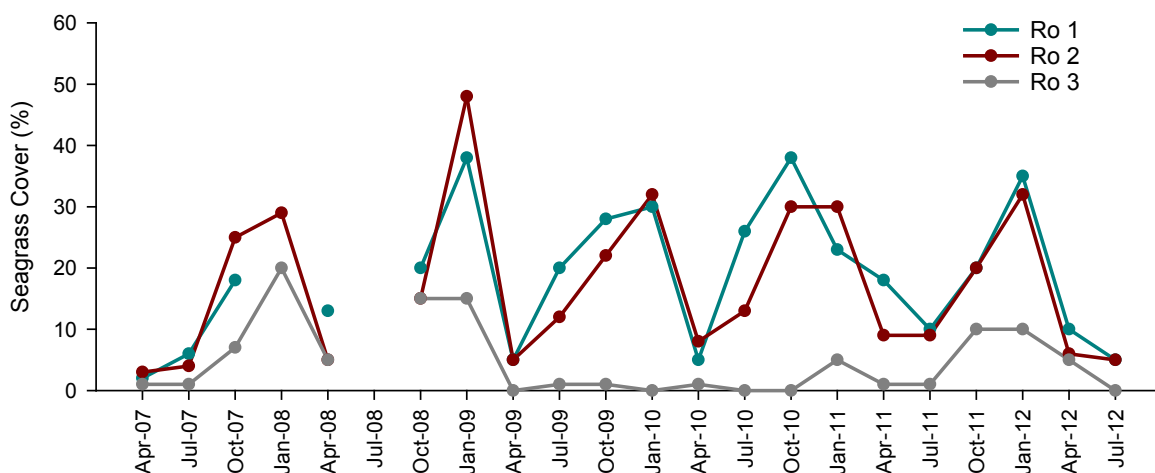


Figure 6. Temporal patterns in the abundance of an intertidal, enduring, mixed species meadow of *H. uninervis* and *H. ovalis* in Roebuck Bay, Broome (Data extracted from Seagrass Watch 2015). Points 1, 2 and 3 are three different sampling sites.

3.3.3 Our understanding of natural dynamics, abundance, reproductive phenology and productivity by region

Seagrass occurs throughout NWWA, but is most persistent and has the highest cover in protected areas such as Shark Bay, Exmouth Gulf, Roebuck Bay (Broome), Beagle Bay and Sunday Islands (near Cape Leveque). In these areas, cover is low, relative to temperate systems, but is similar to coastal waters in the Great Barrier Reef (Coles et al. 2000), in the range of 10–25% (see references below). Here we summarise our understanding of the species distribution, abundance, productivity and reproductive phenology in the main IMCRA sub-regions.

Oceanic Shoals

Four species of seagrass have been observed in the Oceanic Shoals bioregion. These are patchily distributed down to 10 m, with *H. decipiens* growing down to 20 m (Huisman et al. 2009). To our knowledge there are no data on the cover, biomass, productivity, reproductive ecology or phenology of seagrasses from this region.

Kimberley (Including King Sound, Bonaparte, Cambridge/Bonaparte)

There are 12 species of seagrass described from this region, with the most extensive and abundant meadows found so far around the Sunday Islands. In this region, the environment is highly dynamic with extreme environmental drivers (e.g. high tidal ranges and cyclones). These operate at a variety of temporal scales and it is unknown if there are annual, inter-annual or episodic patterns in seagrass cover, biomass and productivity. Where cover and biomass have been estimated it is low (< 15% cover, Seagrass Watch 2015) and there are no clear seasonal patterns, although this probably reflects a lack of data. Flowering of *T. hemprichii* has been observed in April (Kendrick personal communication).

Current research by Cayabyab et al. (in prep) in the Sunday Islands has measured the biomass, shoot density and productivity of seagrass from the intertidal to subtidal. Here *Enhalus* and *Thalassia* dominate the intertidal platforms, where water pools during low tide, and *Thalassia* and *H. ovalis* grow subtidally. The above-ground biomass of *Thalassia* ranges from 13–90 g DW m⁻², with the lowest biomass in the subtidal zone, though shoot density is similar across all habitats, with up to 1000 shoots m⁻². The above-ground biomass of *E. acoroides* ranges from 80–110 g DW m⁻², with 70–130 shoots m⁻². The biomass of *H. ovalis* was much lower at 1.5 g DW m⁻². Despite the extreme tidal conditions, productivity is high. Leaf growth for *Thalassia* and *E. acoroides* is 1–2 g DW m⁻² d⁻¹ but this is reduced dramatically in subtidal conditions. Rhizome extension is on average 1 mm apex⁻¹ d⁻¹ for *Thalassia* and 8 mm apex⁻¹ d⁻¹ for the faster growing *H. ovalis* (Cayabyab et al. in prep).

Canning

Within the Canning Region, larger seagrass meadows are found in protected bays such as Roebuck Bay and Beagle Bay, from intertidal to subtidal areas. The common species in intertidal habitat are *H. ovalis* and *H. uninervis*. These also occur subtidally with other species, such as *Syringodium*, and in deeper waters down to 20 m, where *H. spinulosa* and *H. decipiens* are also present (Seagrass Watch, 2015, James Price Point data supplied via WAMSI (Masini et al. 2009, Hovey et al. in review). In Roebuck Bay, seagrass cover of intertidal meadow ranges from 1–50% cover with a median value of 20%. The only available data on biomass in this region is from Hovey et al. (in prep) which peaks at an average of 12 g m⁻² in spring. Flowering has been observed in deeper subtidal regions during December (Masini et al. 2009) and here cover ranges from <5 up to 100% (Department of State Development 2010).

Seasonal dynamics in Canning: There are two sets of data on seasonal dynamics of seagrasses in the Canning Region: Seagrass Watch monitoring data for intertidal meadows from Roebuck Bay and Beagle Bay; and monitoring data that was part of the James Price Point assessment by Woodside and MScience in deep subtidal meadows. The annual dynamics can be summarised as:

- In Roebuck Bay seagrasses persist year round but with higher abundance from October to January (20–50% cover), the late-dry to early-monsoon season, and lower abundance from April to June (5–10% cover), the late monsoon to early dry season (Seagrass Watch 2015, Figure 6).
- In the deeper habitats around James Price Point, *H. decipiens* has been observed from April to December with maximum abundance from October to November, at the end of the dry season, after which the seagrass dies off (Hovey et al. in review, Figure 7). This data set has no observations in January so it is not possible to conclude that the high biomass period is the same as in Roebuck Bay. This biomass pattern conforms with the observations of Masini et al. (2009) on annual populations in this type of habitat and region. Flowers have been observed from July to August and fruits from November and December, and the seed bank density is greatest at this time (Hovey et al. in review, Masini et al. 2009).

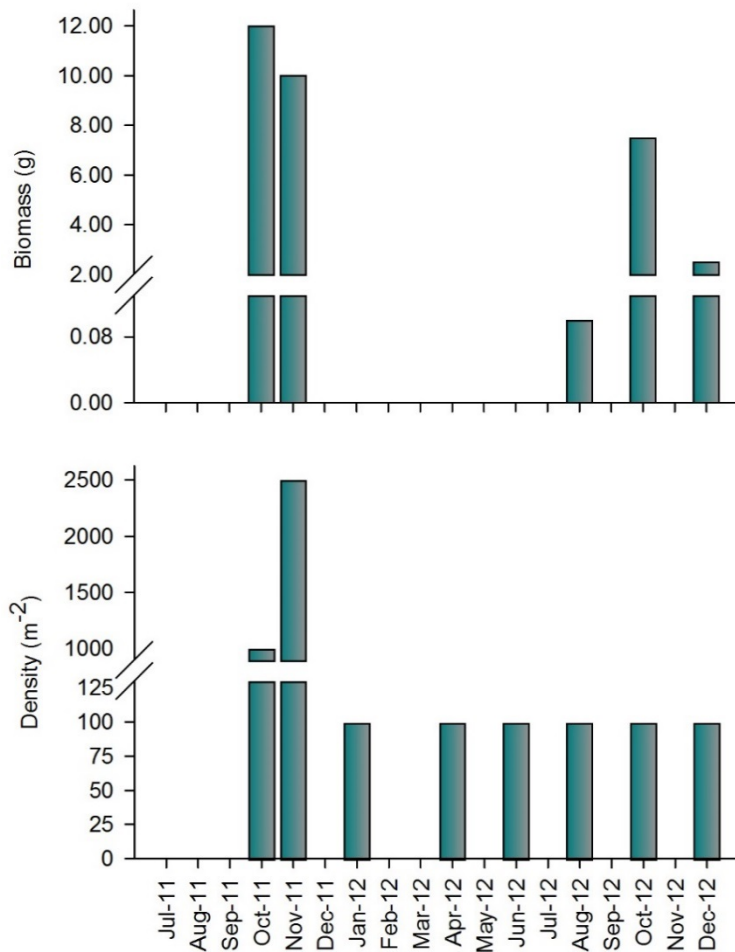


Figure 7. Temporal patterns in the abundance (measured as biomass) and seed bank density of *H. decipiens* at James Price Point. Adapted from Hovey et al. (in review).

The Seagrass Watch data from Roebuck Bay show consistent seasonal fluctuations from year to year, with maximum cover from October to January (wet season) and minimum cover from April to July (dry season). The patterns in cover are also relatively consistent across years (Figure 6; Site 1 and 2), though there are inter-annual variations in the absolute covers attained, ranging from 20–50% in any one year and in the timing of minimum cover between years (e.g. April and July in 2007, and 2011, but April in 2008–2010). However, even in this very spatially-limited data set there was a noticeably different trend at a third site (Site 3), where low cover was observed throughout the year (<5% from 2009–2011). This may be related to nutrient pollution from a local creek impacting seagrasses due to overgrowth of macroalgal and cyanobacterial blooms (Seagrass-Watch 2015).

Episodic events in Canning: To our knowledge, there is no documentation on changes in seagrass cover, biomass and productivity linked to episodic events in this region.

Pilbara (including nearshore, 80 Mile Beach)

Within the Pilbara region, waters tend to be more turbid and the seagrass sparse. Extensive areas of seagrass have been observed in Exmouth Gulf. Other areas with sparse seagrass cover include protected bays along the coast where meadows of up to 86 ha have been observed e.g. Onslow (RPS 2012), Balla Balla Creek (Geo Oceans 2013) and Port Hedland (SKM 2011) and in protected waters around island groups e.g. Dampier Archipelago (Huisman & Borowitzka 2003), Thevenard Island (pers. obs.), Barrow and Montebello Islands (Osborne et al. 2000, RPS 2005), Weerde Island, Finucane Island, North Turtle Island (Sinclair Knight and Merz 2009). In the less protected water between islands, seagrasses are sparse and believed to be ephemeral (RPS 2012).

The most commonly observed seagrass species in this region are *H. ovalis* and *H. uninervis*. They occur in intertidal and subtidal habitats, with *H. ovalis* also found in deeper habitats. *H. spinulosa* and *H. decipiens* are found in deeper waters, where they are more likely to be ephemeral. *C. serrulata*, *C. angustata*, *S. isoetifolium* and *T. hemprichii* are usually found in mixed meadows in protected bays and the lagoons around islands. Generally, cover of meadows of any of these species is less than 10% (McCook et al. 1995, RPS 2011, SKM 2011, RPS 2012, Geo Oceans 2013) but occasionally reaches 25–40% (McCook et al. 1995, Loneragan et al. 2013). Often seagrass is found mixed with macroalgae and filter feeding communities (Osborne et al. 2000). In the deeper water habitats, seagrass cover is even lower, on average 5% (Chevron Wheatstone unpublished data).

Biomass estimates range from <1–35 g DW m⁻² (Schaffelke & Klumpp 1996, RPS 2011, Loneragan et al. 2013), but most measures are towards the lower end of this range. The majority of the biomass is found below-ground. Leaf productivity has been estimated for *C. serrulata* and *T. ciliatum* with <1 mg shoot⁻¹ day⁻¹ and 1.5 mg shoot⁻¹ day⁻¹ respectively (Schaffelke & Klumpp 1996). There have been some observations of flowering and fruiting in December for *H. ovalis*, *H. decipiens* and *H. spinulosa* (RPS 2011, Chevron Wheatstone unpublished data, McMahon personal observations).

Seasonal dynamics in the Pilbara: Very little is known about the seasonal dynamics in this region. From reports where sampling has occurred multiple times in a year, it seems that biomass or cover increases from September to December, although this is not always the case. For example, in 2011 cover increased from 1.5% to 6% around one region of Onslow but decreased from 6% to <1% in another region (RPS 2011). These sorts of observations are usually based on only one year of sampling but over multiple sites making it difficult to generalise among years. Furthermore, with such low cover values it is difficult to be sure the pattern is not simply a sampling artefact. We are not aware of any seasonal sampling in this region, though the WAMSI Dredging Science Node Project 5.3 is gathering data at sites in Exmouth Gulf and the Muiron Islands.

Inter-annual patterns in the Pilbara: There are some data on the interannual patterns in seagrass, but these are related to recovery following seagrass loss due to cyclone activity and are presented below.

Episodic events in the Pilbara: Cyclones, with their associated physical disturbance and turbidity from river flows and resuspension of sediments, are believed to have significantly impacted seagrasses in this region, and specifically Exmouth Gulf (Loneragan et al. 2013). Immediately following a cyclone in 1999, seagrass cover was reduced to less than 2% but then increased to 40% cover 1.5 years after the cyclone. This cover was maintained for at least another 2 years, but then declined to around 5% (Figure 8). This may be part of a recovery pattern, where, after a disturbance, seagrasses boom and then settle to background levels. The cover of 5% is consistent with other areas in the region and previous surveys (McCook et al. 1995). Biomass was measured from 1999 and 2000, and ranged from 0.5 g DW m⁻² in 1999 up to ~8 g DW m⁻² in 2000.

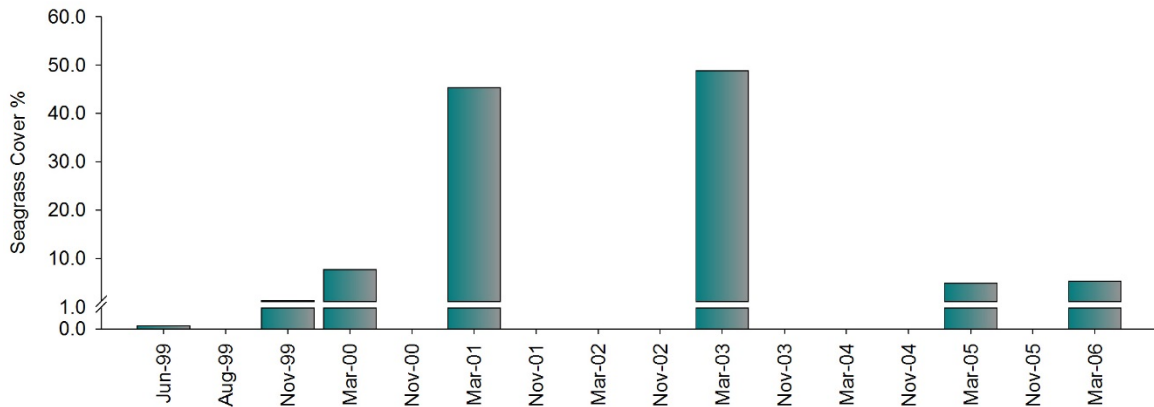


Figure 8. Temporal patterns in the cover of seagrass in Exmouth Gulf for 7 years following a cyclone which reduced seagrass cover (adapted from Loneragan et al. 2013).

The recovery of seagrass over 1999–2006 showed a succession of species (Figure 9). The first species were the small, colonising species such as *H. ovalis* and *H. uninervis*. *C. serrulata* increased its distribution in the first two years, from 30 up to 70% of sites, then declined to around 40% of sites. *H. ovalis* fluctuated from 8–28% of sites over the entire period. Interestingly, *H. spinulosa* was absent until one year after the cyclone, then increased its distribution up to 70% of sites 2 years post cyclone, but by 4 years post-cyclone was rarely found. *S. isoetifolium* had a similar dynamic: it was also absent post-cyclone, peaked in distribution 3 years post-flood (40% of sites) and then declined to about 20% of sites. In contrast, *C. serrulata* was observed one year after the cyclone and continued to increase in distribution up to 5 years post-cyclone. This shows a successional pattern from the dominance of small colonising to larger, slower growing species, with one opportunistic species that thrives two years post-flood and then declines.

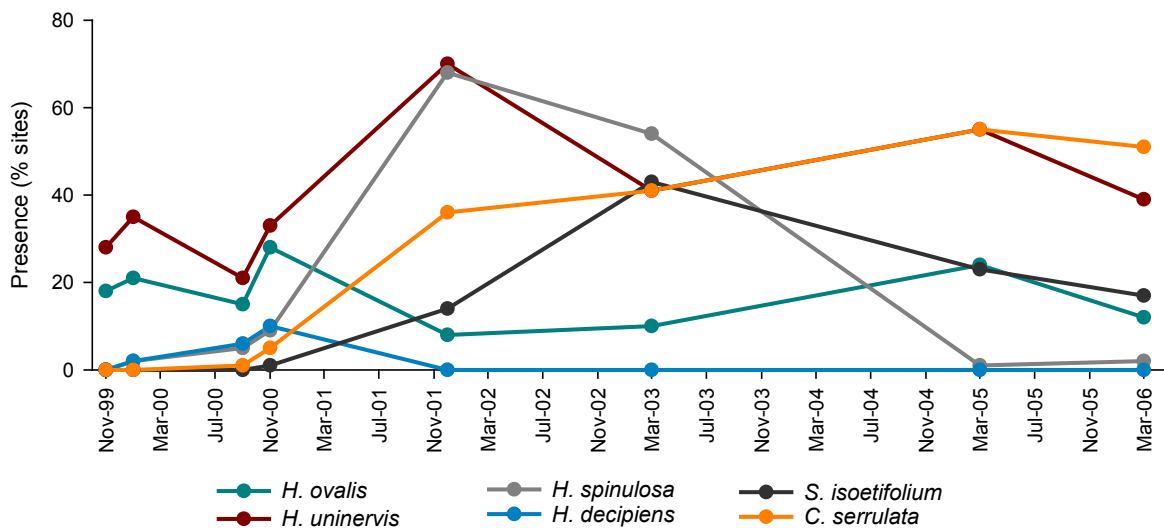


Figure 9. Distribution of seagrass species over time at sites in the Exmouth Gulf, following a cyclone which removed seagrass (adapted from Loneragan et al. 2013).

The reduction in cover of seagrass had significant implications for the prawn fishery, with reduction in catch a year after the cyclone (Loneragan et al. 2013). Recently (2012–13), there has been another significant reduction in prawn recruitment but there was no regular monitoring of seagrass to determine if there had been changes in seagrass cover. Personal observations (McMahon) in March 2013 revealed very little seagrass in Exmouth Gulf at the sites where the previous study was conducted. However, since that time, cover seems to be increasing at the location monitored in WAMSI Dredging Science Project 5.3, and there appears to be changes in species over

time, which is similar to the species successional pattern that has been observed previously, with *H. ovalis* and *C. serrulata* most common when seagrass was first observed, and *H. spinulosa* increasing in cover over time. Heat stress due to a recent marine heat-wave is suggested as a cause of this putative decline.

Ningaloo

H. ovalis is the most commonly found seagrass at Ningaloo, growing in sandy patches between coral heads, in and outside the lagoon and in intertidal flats e.g. Mangrove Bay. *H. uninervis* is the next most common species, often growing with *H. ovalis*. *S. isoetifolium* is also found mixed with *H. ovalis*, *C. serrulata* or grows alone. *H. spinulosa* is less common and has been found in deeper waters, whereas *C. serrulata* and *T. hemprichii* are rarely found (van Kuelen & Langdon 2011). Seagrass cover is rarely greater than 5% (van Kuelen & Langdon 2011).

To our knowledge, there is no information on the dynamics, biomass and productivity of seagrasses in this region. Despite the lack of knowledge on seagrasses in this region, dugongs are regularly observed moving through the area and feeding on the sparse seagrass meadows.

Shark Bay

Shark Bay has a high diversity of seagrass, supporting 12 species from temperate and tropical biomes (Walker & Woelkerling 1988). Temperate species, *Amphibolis antarctica* and *Posidonia* spp. form persistent stands. While many small tropical species can range from annual to ephemeral in other regions of Australia, in Shark Bay they tend to be persistent (Burkholder et al. 2013), but sparsely distributed (Walker & Woelkerling 1988, Burkholder et al. 2013). *H. uninervis* is the most widespread of the tropical seagrass species, found even in the more restricted waters of the southern Eastern Gulf (Burkholder et al. 2013). It typically grows on the sand flats, in blow-outs or as an understorey species. Monospecific stands occur in the very anoxic mud near the mouth of the Wooramal River (Walker & Woelkerling 1988, Masini et al. 2001). *H. uninervis* is however, absent from most of the coast of Dirk Hartog Island (Burkholder et al. 2013). *Cymodocea* spp. are found in sand patches and in the understorey of *P. australis* and *A. antarctica* but are generally patchily distributed (Walker & Woelkerling 1988, Burkholder et al. 2013). *Halophila* spp. (*H. ovalis*, *H. spinulosa*) tend to be found on sand flats, in blow-outs or on the edge of banks. *H. spinulosa* also occurs at the base of channels (Walker & Woelkerling 1988, Burkholder et al. 2013). *S. isoetifolium* is generally less widespread than most other tropical species in Shark Bay, inhabiting sand patches near the edge of canopy-forming species and also in isolated pockets (Walker & Woelkerling 1988, Burkholder et al. 2013). *H. uninervis* and *H. ovalis* inhabit the intertidal to 14 m depth but are often found as sparse stands (Walker & Woelkerling 1988, Burkholder et al. 2013). *Cymodocea* spp. and *S. isoetifolium* grow from 0–14 m, *H. spinulosa* from 3–14 m and *H. decipiens* has only been located in shallow waters, 3–5 m (Walker & Woelkerling 1988).

Shark Bay has been divided into different zones based on salinity and calcareous sediment types (Logan & Cebulski 1970) including, an oceanic zone (salinity 35–40 ppt), a metahaline zone (salinity 40–56 ppt), and a hypersaline zone (salinity 56–70 ppt). These zones influence seagrass abundance. *H. uninervis* can tolerate salinities as high as 64 ppt. Most *Halophila* species generally inhabit salinities less than 55, with the exception of *H. decipiens*, which has only been reported at 35 (Walker & Woelkerling 1988). *S. isoetifolium* occurs within a narrow salinity range (35–45 ppt), whereas *Cymodocea* spp. inhabit salinities ranging from 35–50 ppt (Walker & Woelkerling 1988).

Sediments in Shark Bay are mainly biogenic in origin, with invertebrates being a major source of calcareous sediments (Logan & Cebulski 1970). Most of the 12 species of seagrass in Shark Bay inhabit these calcareous sediments. *A. antarctica*, *P. australis*, *H. ovalis* and *Cymodocea* spp. also inhabit mud and silted sediments (Walker & Woelkerling 1988). In contrast to the majority of Shark Bay, sediments at the Wooramel Delta are very fine and anoxic, representing the influence from the infrequently flowing Wooramel River. Here, *H. uninervis* dominates (Walker & Woelkerling 1988, Masini et al. 2001).

Nutrient inputs into the embayment are dominated by exchange with oceanic water. It is assumed that the major source of phosphorus (P) for benthic communities in the eastern embayment comes from Indian Ocean water in the north, leading to an increase in P limitation southward into the bay (Smith 1984, Atkinson 1987, Fraser et al.

2012, Burkholder et al. 2013). Shark Bay's unique sediment biogeochemistry (dominated by calcareous sediments that adsorb available phosphorus, (Short 1987)) also contributes to low phosphorus concentrations (often at or below the detection level of 20 nM) and may limit the growth of seagrass (Smith 1984, Atkinson 1987, Fraser et al. 2012, Burkholder et al. 2013). In contrast, closer to the mouth of the Bay, large areas may be limited by N availability or are not limited by N or P availability (Burkholder et al. 2013). Slower growing seagrass (*A. antarctica* and *P. australis*) typically had lower nutrient content than faster growing tropical species (*H. ovalis*, *C. serrulata*, *Cymodocea* spp., and *S. isoetifolium*).

Seasonal dynamics in Shark Bay: Based on a single seasonal study of a community dominated by typically tropical species (Masini et al. 2001), seagrass growth occurs throughout the year, although biomass and productivity is greatest in summer relative to winter. Peak productivity coincides with the temperature maxima, but not light maxima and dugong grazing removes a significant proportion of the productivity, at some times of the year exceeding 50%. Biomass of *H. uninervis* seagrass ranges from 3–70 g DW m⁻² with the majority allocated to below-ground material (4–6 times that of the above-ground biomass) and productivity ranges from 0.1–1.6 g DW m⁻² d⁻¹.

Inter-annual patterns in Shark Bay: There is some data on the interannual patterns in seagrass, but these are related to the decline and recovery dynamics of *A. antarctica* after the 2011 marine heatwave (Pearce et al. 2011) and Wooramel River floods (Fraser et al. 2014) which are discussed below.

Episodic events in Shark Bay: Only one river discharges into Shark Bay, the Wooramel River, into the eastern embayment. However, periods of flow are episodic, following cyclonic events in the summer or winter storms (Smith & Atkinson 1983). Recently, the Wooramel River had a large flood event (Feb 2011 monthly average 300 000 ML) which coincided with a marine heat wave; the entire bay showed a 2–4°C increase above the long-term summer maximum in Feb 2011 (Pearce et al. 2011). There was some evidence that *H. uninervis* was impacted, though it reappeared shortly after (Statton personal observations) and no further changes in abundance were detected. All other species did not appear to be impacted. Apart from the recording of this flooding event (Fraser et al. 2014) there is little information on changes in water turbidity and fluxes of freshwater, nutrients and organic matter into Shark Bay from episodic flooding of the Wooramel River that could potentially influence adjacent seagrass communities.

3.4 Ecological services

Generally, seagrasses are known to provide valuable ecosystem services such as carbon storage (Lavery et al. 2013), filtering nutrients and particles from the water column (Agawin & Duarte 2002), stabilising sediments (Koch et al. 2006) and providing high primary productivity. Despite the low abundance and small stature of many of the seagrasses in NWWA, they can still significantly contribute to some of these ecosystem services such as carbon storage (e.g. Lavery et al. 2013) and sediment trapping (Agawin & Duarte 2002), though in some cases the ability of small seagrasses to trap sediments and nutrients has been questioned (e.g. Mellors et al. 2002).

Apart from the ecological services above, which have not been measured in NWWA, seagrasses in the north west region are also an important source of forage for the endangered dugong and green turtle and critical habitat for many species (Table 6). Dugongs are regularly observed in large numbers in Shark Bay and Exmouth Gulf, and smaller herds or individuals are observed around Onslow and up to the Dampier Archipelago, Balla Balla Creek and from Roebuck Bay to King George Sound. Green turtles are found throughout the region. Seagrasses are also linked to commercially important fisheries species, such as prawns in the Exmouth Gulf (e.g. Loneragan et al. 2013) and around the Dampier Archipelago, and blue swimmer crabs in Shark Bay. In these regions, dugongs are known to feed in meadows of *Halophila* spp. and *H. uninervis* whereas green turtles feed on these and other species, including *T. hemprichii*, *Cymodocea* spp. and *S. isoetifolium*. Prawns are known to inhabit meadows of most of the seagrass species, except for *T. hemprichii* and *C. rotundata*.

Table 6. Ecological services provided by different seagrass species in NWWA.

Species	Dugong Food	Green turtle food	Prawn habitat	TOTAL
Hydrocharitaceae				
<i>Enhalus acoroides</i>				0
<i>Halophila decipiens</i>	X	X	X	3
<i>Halophila ovalis</i> ¹	X	X	X	3
<i>Halophila spinulosa</i>	X	X	X	3
<i>Thalassia hemprichii</i>		X		1
Cymodoceaceae				
<i>Cymodocea angustata</i>		X	X	2
<i>Cymodocea rotundata</i>		X		1
<i>Cymodocea serrulata</i>		X	X	2
<i>Halodule uninervis</i> ²	X	X	X	3
<i>Syringodium isoetifolium</i>		X	X	1
<i>Thalassodendron ciliatum</i>				0

¹including *H. ovata* and *H. minor*²including *H. pinifolia*

4 Current knowledge on thresholds and bioindicators

Thresholds for sediment burial and low light stress, as well as information on bioindicators have been described in WAMSI DSN Project 5.1.1 (McMahon et al. 2017). Here we present the total number of studies that have developed thresholds and bioindicators for the different species in NWWA (Table 7). None of these studies have been carried out in NWWA, and it is not clear whether thresholds of tolerance derived from studies in other regions are transferable to NWWA. However, there is some indication that the same species from different locations respond in a similar way to light reduction (see WAMSI DSN Project 5.5.1 for comparison of *H. uninervis* from Shark Bay and Queensland (Statton et al. 2017)). This indicates that we may be able to transfer knowledge of thresholds from one location to another, at least for *H. uninervis*, the target species in this experiment, but further experiments are required to be confident of this.

The most well-studied species is *H. ovalis*, followed by *H. uninervis*, *C. serrulata*, *S. isoetifolium* and then *H. decipiens*.

Table 7. Summary of the number of studies on low light and sediment burial thresholds and bioindicators of response.

Species	Light Thresholds ^a	Light Bioindicators ^a	Sediment Thresholds & Bioindicators ^a	TOTAL Ranking (sum)
Hydrocharitaceae				
<i>Enhalus acoroides</i>	0	0	2	9(2)
<i>Halophila decipiens</i>	5	0	0	5(5)
<i>Halophila ovalis</i> ¹	3	8	3	1(14)
<i>Halophila spinulosa</i>	3	1	0	6(4)
<i>Thalassia hemprichii</i>	0	2	2	6(4)
Cymodoceaceae				
<i>Cymodocea angustata</i>	0	0	0	10(0)
<i>Cymodocea rotundata</i>	0	1	2	8(3)
<i>Cymodocea serrulata</i>	0	4	3	3(7)
<i>Halodule uninervis</i> ²	2	4	2	2(8)
<i>Syringodium isoetifolium</i>	0	4	2	4(6)
<i>Thalassodendron ciliatum</i>	0	0	0	10(0)

¹including *H. ovata* and *H. minor*²including *H. pinifolia*^aBased on WAMSI DSN Project 5.1.1 (McMahon et al. 2017).

5 Sensitivity to dredging related stressors

In relation to the sensitivity of NW Australian seagrass species to dredging related stressors, two different life-history phases have been assessed, adult plants and the juvenile plants, for two different stressors, low light and burial stress. We assess the sensitivity in two ways, by their ability to withstand dredging pressures (i.e. resistance) and by their ability to recover from dredging pressures. Considered together they provide an insight into the overall sensitivity of species across different life-history phases to dredging pressures. As minimum light requirement or light thresholds have not been developed for all species, we cannot use this approach as a way to determine resistance. Instead we use the function-form model of Walker et al. (1999), which ranks the response of seagrass species to perturbations from rapid to slow. Those species with a slow response would be more resistant to low light stress. Therefore, *E. acoroides*, *T. ciliatum* and *T. hemprichii* would have a high resistance to light reduction, the *Halophila* spp. a low resistance, *H. uninervis* a low to moderate resistance and the remaining species a moderate resistance to low light stress (Table 8).

The resistance to burial of adult plants has been reviewed by Cabaco et al. (2008). They found that mortality is affected by shoot size, with larger sizes more resistant, and by a size-independent trait, the vertical growth rate, whereby species with faster vertical growth rates are more resistant (Vermaat et al. 1995). Therefore, *E. acoroides* and *T. ciliatum* would have a high resistance to burial, *H. ovalis* and *H. decipiens* would have a low resistance to burial. *H. spinulosa*, *T. hemprichii*, *C. rotundata* and *C. serrulata* would have a moderate resistance to burial and the remaining species, due to their higher vertical rhizome elongation rates, would have a moderate to high resistance (Table 8).

Resistance to light stress for germinated seeds will likely depend upon the size of the nutrient storage reserves (endosperm) nourishing the seedling. Here, we use seed size as a proxy for resistance to light stress. Species that produce large viviparous seedlings (e.g. *T. ciliatum*, 35–50 mm) or species that produce large, fleshy seeds (e.g. *E. acoroides*, 10–15 mm) may show greater resistance to light stress compared to species with moderate sized seeds (e.g. *S. isoetifolium*, 4–8 mm) and small seeded species with low storage capacity for nutrient reserves (e.g. *Halophila* spp., 0.2–1 mm; *H. uninervis*, 2–3 mm) (Table 8).

Resistance to sediment burial for germinating seedlings will likely depend upon the maximum extension height of hypocotyls (Table 8). From the available data (based on germination studies under illuminated conditions), *Cymodocea* spp. found in the NWWA may tolerate a burial depth of up to 3 cm. Most other species found in this region may be intolerant of sediment burial beyond 1 cm. However, Birch (1981) reported that the hypocotyl for *H. spinulosa* could extend further under reduced light conditions, and this may also be the case for other species but, so far, is untested. While sediment burial impacts light availability, it also affects other environmental factors that can influence emergence success of a seedling, for example, the weight and cohesive force of the sediments. At present, there are no existing data for seagrass describing the maximum upward force a hypocotyl needs to exert to overcome sediment weight/binding capacity to reach the sediment surface.

The resilience of seagrass species to dredging related stressors has been inferred from their ability to recover via vegetative growth or through recruitment of new individuals via seeds. The faster growing species are considered to be able to recover faster. Those with a persistent seed bank are considered to be more resilient as they have a longer time window in which they are able to recover which is linked to the dormancy period of the seed.

We summarised the resistance and resilience of each species to dredging related stressors by averaging across the four categories for resistance and two categories for resilience. All *Halophila* species were least resistant, followed by *H. uninervis* and then *Cymodocea* spp. and *S. isoetifolium* (Table 8).

Table 8. Predictions for resistance and recovery from dredging related stressors to assess the overall sensitivity of NWWA seagrass species. Where H = High, M = Moderate and L = Low

Species	Resistance to low light stress		Resistance to burial stress		OVERALL Resistance	Recovery potential		OVERALL Recovery potential
Species	Adult Plant ^a	Seedling Survival ^b	Adult Plant ^c	Seedling Survival ^d		Rhizome extension rate yr ⁻¹ ^e	Seed bank persistence ^f	
Hydrocharitaceae								
<i>Enhalus acoroides</i>	H ₍₁₎	H	H	L(<0.5cm) ⁱ	M-H	L ₍₃₎	L _(I)	L
<i>Halophila decipiens</i>	L ₍₇₎	L	L	L(<0.8cm) ⁱⁱ	L	H ₍₂₁₅₎	H _(P)	H
<i>Halophila ovalis</i> ¹	L ₍₇₎	L	L	L _(N/A)	L	H ₍₃₆₀₎	H _(P)	H
<i>Halophila spinulosa</i>	L ₍₇₎	L	Mv	L _(0.3cm) ⁱⁱⁱ	L	H _(N/A)	H _(P)	H
<i>Thalassia hemprichii</i>	H ₍₂₎	M-H	Mv ₍₃₎	M ^{iv}	M-H	M ₍₆₀₎	L _(I)	L-M
Cymodoceaceae								
<i>Cymodocea angustata</i>	M ₍₅₎	M-H	M-H _{v(?)}	H _(N/A)	M-H	M _(N/A)	H _(P)	H
<i>Cymodocea rotundata</i>	M ₍₅₎	M-H	Mv ₍₁₎	H _(3cm) ^v	M-H	H ₍₂₁₀₎	H _(P)	H
<i>Cymodocea serrulata</i>	M ₍₅₎	M-H	M-Hv ₍₁₃₎	H _(N/A)	M-H	M ₍₁₅₀₎	H _(P)	M-H
<i>Halodule uninervis</i> ²	L-M ₍₆₎	L	Mv ₍₄₎	M _(N/A)	L-M	M ₍₁₀₀₎	H _(P)	M-H
<i>Syringodium isoetifolium</i>	M ₍₄₎	M	M-Hv ₍₈₎	M _(1cm) ^{vi}	M	M ₍₁₁₀₎	H _(P)	M-H
<i>Thalassodendron ciliatum</i>	H ₍₃₎	H	H	H _(N/A)	H	L ₍₁₅₎	L _(V)	L

¹including *H. ovata* and *H. minor*

²including *H. pinifolia*

a. Derived from the function and form model of Walker et al. 1999, number in brackets represents position along gradient.

b. Based on seed size and seed storage reserves from Larkum et al. (2006);

c. Based on Cabaco et al. (2008) thresholds and Vermaat et al. (1995) vertical rhizome growth. V=vertical rhizome growth and number in brackets is average length;

d. Based on length of hypocotyl: i. Dagapio and Uy 2011; ii. McMillan (1988); iii. Birch (1981); iv. den Hartog (1970); v. McMillan et al. (1983); and vi. McMillan et al. (1981). N/A = hypocotyle length unknown category based on congeneric species, except for *Halodule*, assumption made that moderate.

e. Based on vegetative rhizome extension rates (cm yr⁻¹) in Duarte et al. 2006), values in brackets are average growth rates and N/A indicates unknown, in this case the category was determined from the congeneric species, and was conservatively assigned to the lowest category;

f. Based on seed bank persistence from WAMSI DSN Project 5.1.1 (McMahon et al. 2017) I = indistinct, P = persistent, V = viviparous.

6 Extent of improvement in applied knowledge

In July 2013, the ISI Web of Science was searched to assess the number of references that mentioned each seagrass species, the number of these studies that were based in Australia and the number based in NWWA (Table 9). Globally, the most studied species across all disciplines is *H. ovalis* (232 references), followed by *T. hemprichii* (142) then *H. uninervis* (110). The remaining species had a similar number of references (68-83), with the exception of the two least studied species, *H. spinulosa* (25) and *C. angustata* (2).

The pattern of effort across species varied slightly in Australia, *H. ovalis* was the most studied (67), followed by *H. uninervis* (30), *C. serrulata* (19) and *S. isoetifolium* (15). All other species were mentioned in 10 or less articles. Finally, the references where studies were conducted in the NW of WA were mostly from Shark Bay, except for Walker and Prince (1987), which includes all species and was not included in the count here, and Loneragan et al. (2013) from Exmouth Gulf. For Shark Bay, the most studied species was *H. uninervis*.

For the Australian papers the number of publications that were of direct relevance to predicting or monitoring impacts of dredging were much lower. There were none for most species, two for *S. isoetifolium* and *T. hemprichii*, three for *C. serrulata*, four for *H. uninervis* and five for *H. ovalis*. No papers from WA were of relevance to dredging science.

Of course, numbers of papers alone does not necessarily imply that further, significant advances in knowledge relevant to the Theme 5 studies cannot be made. It is possible that a large number of papers focus on a single aspect of a seagrasses biology/ecology and other aspects are completely disregarded. Therefore, the ranking in Table 9 is indicative only of which species warrant further research effort and we have taken into account the nature of the published research when integrating these findings into the overall assessment through our summary in Table 7.

Table 9. Number of ISI referenced literature relating to each seagrass species found in NWWA, globally, within Australia and in the north west. Numbers in brackets indicate those that are directly relevant to research in the WAMS Dredging Science Node.

Species	Globally	Australia	Northwest (Shark Bay)	Ranking of least studied species globally
Hydrocharitaceae				
<i>Enhalus acoroides</i>	83	7 (0)	0	8
<i>Halophila decipiens</i>	81	7 (0)	1 (0)	7
<i>Halophila ovalis</i> ¹	232	67 (5)	4 (0)	11
<i>Halophila spinulosa</i>	25	10 (0)	2 (0)	2
<i>Thalassia hemprichii</i>	142	11 (2)	0 (0)	10
Cymodoceaceae				
<i>Cymodocea angustata</i>	2	2 (0)	2 (0)	1
<i>Cymodocea rotundata</i>	68	3 (0)	0	3
<i>Cymodocea serrulata</i>	78	19 (3)	1 (0)	6
<i>Halodule uninervis</i> ²	110	30 (4)	10 (0)	9
<i>Syringodium isoetifolium</i>	76	15 (2)	1 (0)	4
<i>Thalassodendron ciliatum</i>	77	3 (0)	0	5

¹including *H. ovata* and *H. minor*

²including *H. pinifolia*

NW papers: Anderson (1994), Anderson (1998), Burkholder et al. (2013), Cambridge et al. (2012), Fourqurean et al. (2012), Fraser et al. (2012), Loneragan et al. (2013), Masini et al. (2001) and McMillan et al. (1983).

Thresholds papers from Australia: Bite et al. (2007), Campbell et al. (2008), Eklof et al. (2009), Longstaff and Dennison (1999), Loneragan et al. (2013), Collier et al. (2012a), Pollard and Greenway (1993), Collier et al. (2011), Collier et al. (2012b) and Campbell et al. (2007).

7 Likelihood of success with culturability

The ranking of culturability was based on the authors' experience and understanding of the success of growing seagrass and keeping it both alive and in a physiologically healthy condition for months, and the time required to conduct laboratory experiments on thresholds of tolerance. We designated a score of three where we were most confident that the seagrass species could be cultured in a mesocosm environment, two where we were moderately confident, one where we were unsure, and zero where there was evidence that this species was very difficult to culture. We identified *H. uninervis* as easiest species to culture and *H. spinulosa* as the most difficult species to culture (Table 10).

Table 10. The likelihood of being able to culture seagrass species in a mesocosm environment for months.

Species	Culturability
Hydrocharitaceae	
<i>Enhalus acoroides</i>	1
<i>Halophila decipiens</i>	2
<i>Halophila ovalis</i> ¹	2
<i>Halophila spinulosa</i>	0
<i>Thalassia hemprichii</i>	2
Cymodoceaceae	
<i>Cymodocea angustata</i>	2
<i>Cymodocea rotundata</i>	2
<i>Cymodocea serrulata</i>	2
<i>Halodule uninervis</i> ²	3
<i>Syringodium isoetifolium</i>	2
<i>Thalassodendron ciliatum</i>	0

¹including *H. ovata* and *H. minor*

²including *H. pinifolia*

8 Priority species

From the data collated in this review, we recommend a number of seagrass species to focus on in this research program. Our recommendation is based on decisions made via a hierarchical decision-making process. We are most interested in those species that cover the greatest range, number of IMCRA regions, meadow and habitat types and provide the most ecological services. So the first step was to aggregate these data by summing columns 1-5 in Table 11. This approach identified three sets of species. The top two ranking species are *H. ovalis* and *H. uninervis*, with a total score of 23 and 22, respectively. These are considered Priority 1 species. The second set of species considered Priority 2 species all scored 20 and were ranked third: *H. decipiens*, *H. spinulosa* and *C. serrulata*. The remaining species, considered Priority 3 species all scored 17 and under. This group includes *S. isoetifolium*, the remaining *Cymodocea* spp., *T. hemprichii*, *E. acoroides* and *T. ciliatum*.

The second step was then to assess whether within the Priority 1 species a range of sensitivities and resilience to dredging were represented, as well as different life-history strategies, and the benefits for focusing on these species in terms of our current knowledge and potential to improve our knowledge. Both species in Priority 1 have a relatively low resistance (Low- *H. ovalis*, Low-Moderate *H. uninervis*), and a relatively high recovery ability (High- *H. ovalis*, Moderate-High *H. uninervis*) and both have life-history traits that classify them as ephemeral. In addition, they both have the greatest number of studies related to thresholds and bioindicators, and are relatively well-studied compared to other species. Thus, although they are the highly relevant species to study, focusing on these two species will not cover a range of abilities to cope with dredging and will not provide the greatest contribution to improving our understanding of seagrass response to dredging related pressures as they have a similar sensitivity and resilience to dredging, so will potentially respond in a similar way.

Ideally, it would be good to target species that have potentially different sensitivities to dredging. So the third step was to assess whether any of the Priority 2 species met this criterion, in combination with either *H. ovalis* or *H. uninervis*. *C. serrulata* is most likely to provide this contrast as it has a moderate resistance to dredging related stressors, and a moderate to high recovery potential. While *C. serrulata* is the third-best represented species in terms of developing thresholds and bioindicators to dredging related stressors, the two other Priority 2 species (*H. decipiens* and *H. spinulosa*) are most similar to the Priority 1 species and there is also concern with being able to culture *H. spinulosa*.

9 Summary of species selection

We considered two options for selecting species for experimental determination of thresholds and responses to dredging related stressors. First, as suggested above, including one of the two Priority 1 species, *H. ovalis* or *H. uninervis* with *C. serrulata*, from the Priority 2 list and conducting single-species experiments on each of the two species. Second, we considered including all three species in mixed species experiments. In tropical marine ecosystems (including NWWA), seagrass species co-occur as well-mixed stands. At present, existing approaches aimed at understanding seagrass responses to perturbations (e.g. dredging-related light reduction and sediment deposition) are based on the temperate zone seagrass species model (single species), which could potentially limit or underestimate the responses of seagrasses in multi-specific meadows. The advantage of using mixed-species experiments, therefore, is that this more closely represents the *in situ* assemblages. There are limited local field data to precisely define the relative contributions of each species in mixed meadows (see section 5.3.3) so we will arbitrarily assign the relative proportions.

When growing mixed species assemblages in culture, there is a risk that interactions (competition, antagonism, facilitation) will occur between species, thereby confounding experimental treatments. However, we are confident from our choice of priority species that this is unlikely to occur since (i) they naturally co-habit the same space; (ii) canopy height and leaf surface area of *C. serrulata* (largest of the three species) poses little threat to intercepting light from *H. uninervis* and *H. ovalis* when grown sympatrically; and (iii) maximum rooting depths differ for all three species, therefore we would expect negligible competition for nutrient resources. In the event we do observe clear interactions between species we will test this in a separate trial using combinations of species to identify the origin of the interaction.

In conclusion we recommend that the best approach for research in Theme 5 on dredging related thresholds will be to use a combination of single and mixed-species experiments, preferably combinations of *H. ovalis*, *H. uninervis* and *C. serrulata*. The approach for using mixed-species assemblages will be presented in 5.5.

Figure 10 depicts the southern limit of the distribution of the three priority species, which cover NWWA, with *H. uninervis* extending to Jurien Bay and *H. ovalis* down to the southern coast. The key habitats these species grow in are also identified.

Table 11. Summary of data from this review to prioritise species selection for experiments to derive thresholds for and bioindicators of dredging related stressors.

	1.Covers entire NW range	2. No. IMCRA Regions (13)	3. No. broad habitat types (8)	4. No. meadow types (2)	5. No. ecological services (3)	STEP 1 (Sum 1-5)	Life-history category	Resistance	Resilience	Current knowledge	Improved knowledge	Culturability
Species	Figure 1	Table 1	Table 3	Table 3	Table 6		Table 2	Table 8	Table 8	Table 7	Table 9	Table 10
Priority 1												
<i>Halophila ovalis</i> ¹	1	9	8	2	3	1(23)	Ephemeral	Low	High	1	11	Moderate
<i>Halodule uninervis</i> ²	1	9	7	2	3	1(22)	Ephemeral	Low-Mod.	Mod-High	2	9	High
Priority 2												
<i>Halophila decipiens</i>	1	8	6	2	3	3(20)	Ephemeral	Low	High	5	7	Moderate
<i>Halophila spinulosa</i>	1	8	6	2	3	3(20)	Ephemeral	Low	High	6	2	Low
<i>Cymodocea serrulata</i>	1	8	7	2	2	3(20)	Opportunistic	Moderate	Mod-High	3	6	Moderate
Priority 3												
<i>Syringodium isoetifolium</i>	1	7	6	2	1	6(17)	Opportunistic	Moderate	Mod-High	4	4	Moderate
<i>Cymodocea angustata</i>	0	5	7	2	2	7(16)	Opportunistic	Moderate	High	11	1	Moderate
<i>Thalassia hemprichii</i>	1	5	6	1	1	8(14)	Persistent	Mod.-High	Low-Mod	6	10	Moderate
<i>Enhalus acoroides</i>	0	4	7	1	0	9(12)	Persistent	Mod.-High	Low	9	8	Unknown
<i>Thalassodendron ciliatum</i>	1	6	3	1	0	10(11)	Persistent	High	Low	11	5	Unknown
<i>Cymodocea rotundata</i>	0	1	6	2	1	11(10)	Opportunistic	Moderate	High	8	3	Moderate

¹including *H. ovata* and *H. minor*²including *H. pinifolia*

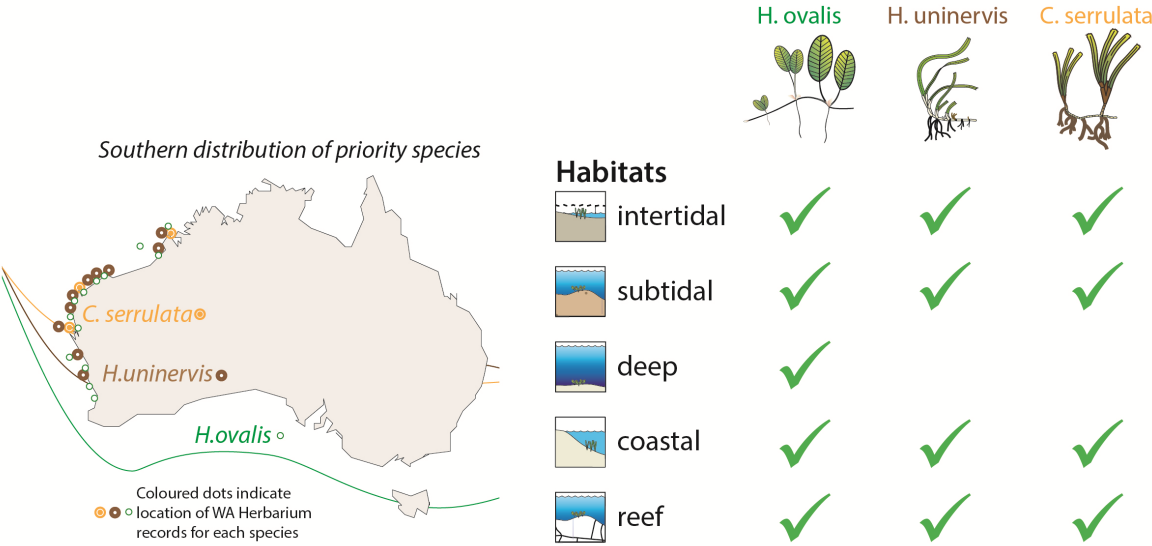


Figure 10. Southern limit of the distribution of seagrass species of focus for the WAMSI Dredging Science Node laboratory based experiments in Project 5.5 and the habitats they grow in.

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