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Current state of knowledge for dredging and climate change impacts on seagrass ecosystems to inform environmental impact assessment and management

A case study: Cockburn Sound and Owen Anchorage, Western Australia

Theme: Benthic Habitats and Communities

WAMSI Westport Marine Science Program

WAMSI WESTPORT MARINE SCIENCE PROGRAM

ABOUT THE MARINE SCIENCE PROGRAM

The WAMSI Westport Marine Science Program (WWMSP) is a $13.5 million body of marine research funded by the WA Government. The aims of the WWMSP are to increase knowledge of Cockburn Sound in areas that will inform the environmental impact assessment of the proposed Westport development and help to manage this important and heavily used marine area into the future. Westport is the State Government's program to move container trade from Fremantle to Kwinana, and includes a new container port and associated freight, road and rail, and logistics. The WWMSP comprises more than 30 research projects in the biological, physical and social sciences that are focused on the Cockburn Sound area. They are being delivered by more than 100 scientists from the WAMSI partnership and other organisations.

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DATA
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FRONT COVER IMAGE
Theme: Benthic habitats and communities
Front cover image: Seagrass (Posidonia australis) in Cockburn Sound. Photo courtesy of Rachel Austin (The University of Western Australia).

Contents

Figures

Tables

The WAMSI Westport Marine Science Program is a $13.5 million body of research that is designed to fill knowledge gaps relating to the Cockburn Sound region. It was developed with the objectives of improving the capacity to avoid, mitigate and offset environmental impacts of the proposed Westport container port development and increase the WA Government's ability to manage other pressures acting on Cockburn Sound into the future. Funding for the program has been provided by Westport (through the Department of Transport) and the science projects are being delivered by the Western Australian Marine Science Institution.

Current state of knowledge for dredging and climate change impacts on seagrass ecosystems to inform environmental impact assessment and management

A Case Study: Cockburn Sound and Owen Anchorage, Western Australia

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Executive Summary

This review summarises the findings from local (Australia) and global studies, that inform our understanding of the pressures imposed on temperate seagrasses from ocean warming and dredging, with a focus on seagrass responses and tolerance thresholds. The purpose of this report is to outline the current state of knowledge and identify key knowledge gaps, from both a scientific and industry perspective to be prioritised for research, which will improve impact prediction from coastal developments on seagrass ecosystems. The location of interest for this review is temperate southwestern Australia, an area of high seagrass diversity and abundance, where ocean surface temperatures are increasing at a rapid rate due to climate change and dredging activities are ongoing.

Here, we identify some of the main pressures associated with dredging and climate change known to impact seagrasses. For dredging, these include, but are not limited to; reduced light quantity and sediment burial. For climate change, gradual warming and marine heatwaves are two pressures which expose seagrasses to warmer waters, with heatwaves being pulse events which produce extreme conditions. The potential for these pressures to occur simultaneously is discussed and the need to predict and manage cumulative impacts. Responses of seagrasses to pressures is often species-specific and thresholds are presented for species that occur in southwestern Australia. For most pressures there is an absence of locally derived thresholds, with more gaps for burial, temperature and cumulative impacts compared to light. Limited data on the actual extent of pressures generated during dredging has been made available from previous dredging campaigns to include in this literature review, however the available literature has been summarised. Without threshold data and pressure fields, predicting and understanding how much of the seagrass response is attributable to individual pressures, or interactions among multiple pressures, remains difficult. However, using the EPA (2021) Dredging guidance document we applied the data collated in this review to indicate the relevant pressure thresholds for the different spatial management zones (e.g. Zone of Influence, Zone of Moderate Impact, Zone of High Impact) and highlighted considerations for the application of this data in an EIA&M context. The gaps identified from this review, to an extent, will be addressed via experimental studies in the WAMSI-Westport project. Therefore, the most current and up to date data from the WAMSI-Westport research should be utilised in conjunction with this review for Westport Environmental Impact Assessment and Management (EIA&M) and future dredging projects. New data generated will also be generated from the wider WAMSI-Westport project which will also be included in the final report produced at the end of the program. Knowledge gaps were derived from the literature as well as from interviewing experts from industry and research. Stakeholders were asked for their perspectives on knowledge gaps in relation to dredging predictions, the main seagrass species used for setting thresholds, the main environmental thresholds and efficacy of bioindicators. The findings of this consultation, as well as a summary of key knowledge gaps for managing seagrasses for dredging developments is presented.

Information gaps for Impact prediction and management of seagrasses for the Westport project that will be addressed by Project 2.2's during the WAMSI-Westport research program include:

- Improved understanding of burial pressures (level, duration) and the recovery time (only one species has been assessed locally);
- Temperature threshold studies under treatments that simulate temperatures that could emerge under future climate warming incorporating multiple species; and
- Threshold studies that incorporate multiple pressures and more accurately reflect the current context of local and global stressors (i.e. burial, reduced light and increased temperature).

1 Introduction

The WAMSI Westport Project 2.2: Pressure-response relationships, building resilience and future proofing seagrass meadows has two sub-projects: Pressure-response relationships of seagrass for Environmental Impact Assessment and Management (EIA&M) and building resilience and future proofing seagrass meadows. This review forms the first component of the Pressure-response sub-project to critically evaluate and prioritize the knowledge gaps and contemporary approaches for EIA&M of the Westport development. The focus of the review is on seagrasses which have been identified as a dominant habitat providing important ecosystem services (Orth et al. 2006), and multiple pressures including dredging, ocean warming and heatwaves, that have been recognised as a threat to temperate seagrasses (McMahon et al. 2011; Strydom et al. 2020; Wu et al. 2017). The approach for this review was to systematically assess scientific literature and reports, dredging management documents and consult with experienced practitioners to summarise the state of knowledge and highlight key gaps. The information compiled in this review will be used in other components of this sub-project, particularly to inform field and laboratory experiments.

1.1 Key anthropogenic pressures to seagrasses include dredging and climate change

Dredging activities to create coastal ports and channels can result in direct (removal) and indirect (e.g., light reduction and burial) impacts to seagrass, contributing to global decline (Erftemeijer and Robin Lewis, 2006). There is a general understanding of how seagrasses respond to the environmental changes as a result of dredging activities, however seagrass resilience and recovery varies greatly among seagrass species and therefore generic thresholds reduce confidence in the ability to predict and manage seagrass ecosystems to dredging pressures (Erftemeijer and Robin Lewis, 2006; Kilminster et al. 2015). In addition to dredging pressures, seagrass decline has also been attributed to global sea surface temperature rise and sporadic ocean warming events defined as heatwaves, where sea surface temperatures can reach 5°C above background (Hobday et al. 2016). These events are becoming more frequent, especially in south-west (SW) Australia (Oliver et al. 2018; Pearce and Feng, 2013). Temperature and light reduction impacts do not necessarily occur in isolation and the cumulative impacts of these pressures is predicted to adversely impact the quantity and quality of ecosystem services seagrass meadows provide (Adams et al. 2020).

1.2 Seagrasses are valuable indicators of environmental change

Seagrasses have different life history strategies and are commonly categorised into colonising, opportunistic and persistent species based on their ability to resist and recover from pressures (Figure 1; Kilminster et al. 2015). The smaller, faster growing colonising genera (e.g. *Halophila*) have a low physiological resistance to pressures (e.g., dredging), however they have a rapid ability to recover. Comparatively, the larger, persistent genera (e.g. *Posidonia)* have a greater ability to withstand pressures but are slower to recover and the opportunistic genera (e.g. *Zostera)* are intermediary. Seagrasses have an ability to partially withstand pressures by making physiological and morphological adjustments such as dropping leaves, slowing growth, utilising carbohydrates stored in their rhizomes to maintain metabolism, or increasing their photosynthetic efficiency (Ralph et al. 2007). Understanding the thresholds of different pressures at which seagrass meadows start to decline allows for greater confidence in predicting responses to pressures and optimising management (McMahon et al. 2013). Currently, there is some well-developed information on tolerance thresholds for the single pressure of light reduction for seagrasses (*Posidonia sinuosa* and *Amphibolis griffithii*) in the temperate region of Australia (Collier et al. 2007; Lavery et al. 2009), but not for all species and specifically not for cumulative pressures.

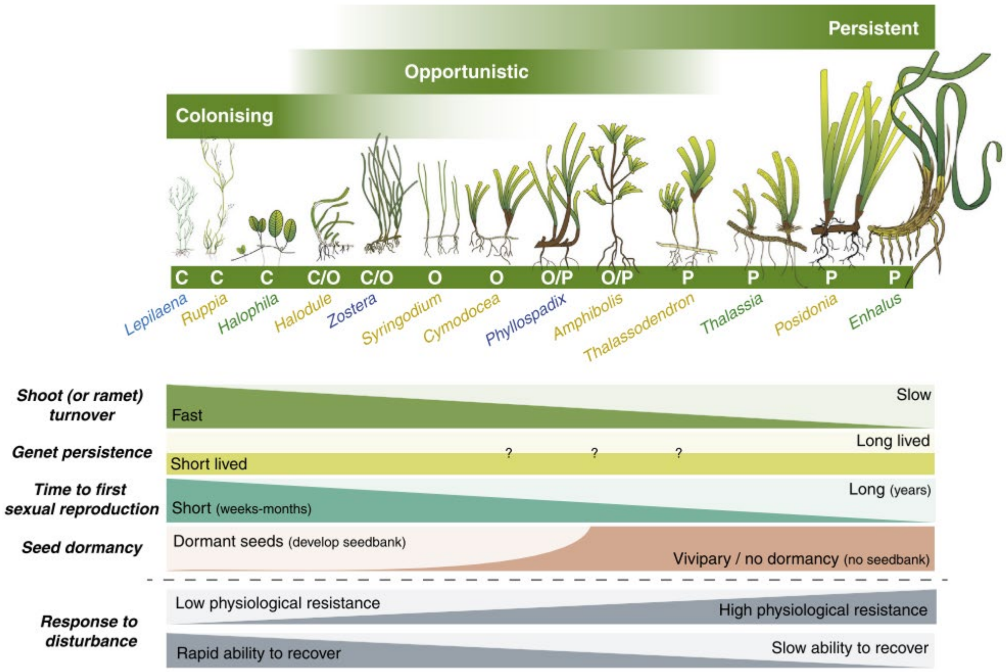

Figure 1. Diagram showing dominant traits among colonising (C), opportunistic (O) and persistent (P) seagrasses, with respect to shoot turnover, genet persistence, time to reach sexual maturity and seed dormancy. Source Kilminster et al. (2015).

1.3 Environmental Impact Assessment related to dredging

Environmental Impact Assessment and Management requires the prediction of pressure fields for a proposed development and then based on the severity, duration and timing of these pressure fields, a prediction of the impact (including spatial extent) to the key receptors. Knowledge of tolerance thresholds for the key receptors to pressures and the recovery timescales, helps to improve certainty with these predictions and develop management trigger levels. In Western Australia, predicting and managing the impacts of dredging is guided by the Environmental Protection Authority's (EPA) Technical Guidance: Environmental Impact Assessment of Marine Dredging Proposals (EPA 2021). There are three phases within the framework in which increased knowledge will be beneficial to inform on biological components of the marine ecosystem. Firstly, the Pre-development phase, which includes surveys and investigations to define the system in which dredging might occur. Secondly, the Impact Assessment phase, which requires understanding of the spatial extent, severity and duration of the dredging pressure and the predicted effects on sensitive components of the environment. This spatial assessment classifies the development footprint into three zones; **Zone of Influence (ZoI):** the area within which changes in environmental quality associated with dredge plumes are predicted and anticipated during the dredging operations, but where these changes **would not result in a detectable impact on benthic biota; Zone of Moderate impact (ZoMI):** the area within which predicted impacts on benthic organisms are **recoverable within a period of five years** following completion of the dredging activities. This zone abuts, and lies immediately outside of, the **Zone of High impact (ZoHI):** the area where impacts on benthic communities or habitats are predicted to be irreversible. The term serious damage means 'damage to benthic communities and/or their habitats that is effectively **irreversible,** or where any potential **recovery is unlikely to occur for at least five years'**. A detectable impact includes both sub-lethal and lethal impacts where lethal impacts from a seagrass perspective are loss of shoots and / or area of seagrass and sub-lethal impacts could be changes in productivity, growth or morphology of the plants. Areas within and immediately adjacent to proposed dredge and disposal sites are typically within zones of high impact. From this assessment, monitoring and management plans are developed. Thirdly the Post-approval phase, where the approved monitoring plans are implemented at reference and impact assessment sites to inform adaptive management and demonstrate compliance with conditions of approval (EPA 2021).

1.4 Temperate Western Australia, a 'hotspot' for seagrass, coastal developments and climate change

This review summarises the current state of knowledge regarding the nature of the pressures that dredging imposes on seagrasses in temperate Western Australia. More specifically as a case study we assess Cockburn Sound and Owen Anchorage, a regionally important environmental, social and economic area in Western Australia. Cockburn Sound has been highly industrialised; suffering from the effects of nutrient pollution and dredging from the 1960s to the early 2000s, and as a result there has been significant seagrass loss (~75%; 2920 ha to 721 ha; Kendrick et al. 2002). In the past 15 years water quality has improved, however there has only been a small increase in seagrass extent from 721 ha to 948 ha, with long-term monitoring indicating a decline in seagrass condition based on shoot density at some sites (Hovey and Fraser, 2018). BMT (2018) undertook an assessment of key pressures within Cockburn Sound and identified dredging and increasing water temperatures to be high impact pressures with high quality evidence, suggesting that these pressures would significantly affect the value of the region, with the projections indicating serious environmental degradation if the pressures are not addressed. Therefore, it is very relevant from an EIA&M perspective to be able to predict how cumulative pressures, such as how elevated temperature may influence the tolerance to other development related pressures (e.g., light reduction).

The primary purpose of this review is to:

1. Summarise the known thresholds for dredging pressures and temperature in relation to ocean warming and heatwaves for seagrass species occurring in temperate WA,
2. Summarise the intensity and duration of dredging pressure fields from previous coastal development projects in SW WA,
3. Summarise seagrass threshold data in relation to EIA&M and highlight considerations in applying threshold data, and
4. Identify the gaps in knowledge which limit confidence in predicting impacts to seagrass habitat from dredging pressures.

2 Dredging and climate change related pressures on seagrass

The following section provides an overview of some of the key physical and chemical conditions associated with dredging and climate change including single and multiple pressures that are likely to affect seagrass. In this review we focus on temperature as a relevant pressure for climate impacts and light reduction and sediment burial as relevant pressures for the indirect effects of dredging, specifically the effects of plumes from dredging and dredge material placement, as these are the pressures most regularly reported on in EIA&M.

Defining Pressures

2.1 Light reduction

The impacts of reduction in light availability on seagrass is the most understood pressure-response pathway and has been widely documented in Australia (Bulthuis and Woelkerling, 1983; Dennison et al. 1993; Ralph et al. 2007). Seagrasses have relatively high light requirements for photosynthesis in order to maintain a positive carbon balance (the ratio of carbon fixed in photosynthesis to that consumed through respiration), where growth and reproduction requires a net positive carbon balance. The minimum requirements for seagrass growth can be understood when light availability is insufficient to maintain a positive carbon balance. Under reduced light conditions, seagrasses make adjustments to maintain a positive carbon balance, with physiological changes usually the first to occur, however this leads to a loss in seagrass condition and eventually mortality if light reduction persists over time (Ralph et al. 2007). Light requirements and the duration of reduced light that seagrasses can persist under varies greatly with seagrass species (Ralph et al. 2007). Light quality is not discussed in detail in this report as there is limited information on this parameter, but it is important to note that light quality can also be altered in conjunction with light reduction by pressures such as dredging. A key finding is that both *P. australis* adult plants and seedlings were not negatively impacted by changes in light quality, whereas *H. ovalis* was both positively and negatively impacted by changes in light quality, and this differed with the life history stage (seedlings vs adults) (Strydom et al. 2018, 2017).

2.2 Sedimentation and burial

Dredging increases suspended sediment loads in the water column which can affect seagrasses. When suspended particles settle out of the water column, they can bury seagrass, but fewer studies have examined the effects of burial from dredging compared to alterations to the light climate (Erftemeijer and Lewis, 2006). Sediments will naturally resuspend and re-settle depending on the particle size, density, bottom velocity and shear stress. Seagrasses can effectively trap sediments, so the likelihood of sediment particles resuspending is lower once they are within a seagrass canopy (Contti Neto et al., 2022). Therefore, burial may occur from the direct settling of suspended particles or secondary deposition with natural sediment dynamics. The effects of burial on seagrasses will depend on the species, such as, whether a species has vertical rhizomes as well as the burial depth, duration and spatial extent of burial (Cabaço et al. 2008). Generally, larger species are more resilient to burial than smaller species e.g. *Enhalus acoroides* versus *Cymodocea serrulata* (Duarte et al. 1997). Plants can respond to burial through morphological changes to increase the amount of photosynthetic tissue above ground (Duarte et al. 1997; Mills and Fonseca, 2003; Vermaat et al. 1997), but if energy requirements exceed energy supply, then declines in shoot density via shoot mortality are likely (Cabaço et al. 2008). Moderate burial can stimulate vertical leaf growth in species that are capable of this such as *Syringodium isoetifolium* (Duarte et al. 1997; Statton et al. 2017b). In contrast, deeper burial depths tend to invoke adverse responses from seagrasses via light inhibition and increased sediment anoxia (Eldridge et al. 2004).

2.3 Temperature

Exposure to temperatures that are close to or exceed thermal limits, as would be expected under climate change, can disrupt important biological processes of seagrasses resulting in lower growth and mortality (Oliver et al. 2018; Pearce and Feng, 2013). Water temperature is considered a primary factor regulating seagrass growth given it affects the balance between carbon uptake (photosynthesis) and carbon consumption (respiration) (Bulthuis, 1987). The response of seagrasses to increased water temperatures depends on the thermal tolerance of the different species and their optimum temperature for photosynthesis (T_{opt}), respiration and growth (Short and Neckles, 1999). The trend of increasing seagrass productivity generally under increasing temperatures applies within a physiological optimum range from approximately 15-33°C that is species-specific and typically reflects their geographic region (Lee et al. 2007). Temperatures outside of this range can invoke physiological stress, productivity declines, growth inhibition, and prolonged exposure may result in mortality (Collier and Waycott, 2014). Increased temperatures have likely caused large scale loss of *Amphibolis antarctica* and *Zostera spp.* in southern Australia (Seddon et al. 2000), as well as *A. antarctica* in Shark Bay after a heatwave event increased average summer water temperatures by 2-5°C (Fraser et al. 2014; Strydom et al. 2020). *Zostera marina* (temperate species in northern hemisphere) experiments showed that a 5°C increase in the ambient seawater temperature caused a significant decline in shoot density; however, it seemed that a high genetic diversity within the meadows increased its potential to recover from such extreme temperatures (Ehlers et al. 2008; Reusch et al. 2005). Determining the contribution of thermal stress from heatwaves to seagrass response is difficult as *in situ* observations of mortality usually occur after the event, so the link between physiological changes and mortality may be less clear. Thus, controlled experiments are useful in that they allow seagrass response to be determined at multiple scales prior to, during and following the event which aids in the development of a mechanistic understanding (Collier and Waycott, 2014).

2.4 Cumulative pressures (light, sediment and temperature)

To date, many thresholds used to understand seagrass response to dredging are based on singular stressors, such as light reduction or burial, but these pressures often occur simultaneously, therefore considering their cumulative impact on seagrasses is relevant to EIA&M (Adams et al. 2020; Stockbridge et al. 2021). In addition, with increasing climate pressures, dredging activities are likely to coincide with more frequent extreme events, such as heatwaves. In this context, seagrasses will be exposed to multiple stressors which may act synergistically (Ontoria et al. 2019) or interactively (Collier et al. 2011), thus creating the potential for existing single pressure derived thresholds to be adjusted for multiple pressures. Dredging can also alter sediment composition by increasing the organic matter content in the sediment where it is deposited (Eldridge et al. 2004), or reduce oxygen exchange especially to deeper sediment layers that are low in oxygen, which can result in sediment anoxia (Hemminga and Duarte, 2000). When organic matter in the sediment is higher negative responses to burial occur at lower burial depths (Statton et al. 2017c). Sediments low in oxygen/ high in organic matter are more likely to contain sulphur in a reduced form (sulphide) that can invade seagrass tissues and decrease plant photosynthetic activity, leaf elongation rate, carbohydrate reserves and above-ground biomass or induce shoot mortality (Holmer and Bondgaard, 2001). Oxygen in the sediment is affected by multiple factors, including water temperature and movement. Higher water temperatures can reduce sediment oxygen by increasing microbial activity whilst calm conditions reduce reoxygenation of the water column and oxygen exchange between the surface and water column, and water column and sediment. In either of these scenarios, the respiratory load within the sediment may exceed the capacity of the plants to produce oxygen (Holmer et al. 2006). Therefore, seagrasses are more prone to sulfide intrusion during periods of warmer temperature and under reduced light availability. Information regarding the relationship between stressors and seagrass response is critical for improving predictions of future seagrass distributions under both natural and anthropogenic disturbance.

3 Temperate seagrasses in Western Australia: thresholds derived in relation to dredging and climate pressures

This section of the review focuses on intensity and duration thresholds that have been developed for light reduction, sediment burial and temperature as well as cumulative pressures for seagrasses.

3.1 Seagrass light thresholds

There are numerous threshold metrics related to light requirements which have been developed to assess seagrass survival and tolerance to light reduction (Table 1; Table 2). Light threshold analysis can be applied to different components of the environment including: light at the top of the seagrass canopy, expressed as instantaneous, mean daily or total daily irradiance (Collier et al. 2012; Gacia et al. 2012); the percentage of surface irradiance (%SI, e.g. Dennison et al. 1993, Kemp et al. 2004); the number of hours of saturating irradiance per day (H_{sat}, e.g. Collier et al., 2012); seagrass photophysiology parameters (I_c and I_k, e.g. Masini & Manning 1997; Table 2); light attenuation coefficients (e.g. Duarte et al. 2007); or measurements through the entire water column, such as Secchi disk depths (e.g. Nielsen et al. 2002). Although there is a range of measures to assess light tolerance or stress, these metrics cannot necessarily be directly compared. Commonly used thresholds in EIA to predict an impact to seagrass uses both the seagrass species minimum light requirement (MLR) and the duration under which the species can withstand the reduced light (e.g. BMT 2020). These may include the percentage of days below a particular mean daily irradiance (Collier et al. 2012), as well as the daily light integral (DLI; mol m^{-2} d^{-1}) over a set duration, normally days to weeks (BMT 2021, EPA 2021, Statton et al. 2017). The recommended unit for seagrass light thresholds is DLI (mol photons m^{-2} d^{-1}, hereafter abbreviated to mol m^{-2} d^{-1}), rather than percentage of surface irradiance (%SI), which is another light indicator commonly used. The reason for this is that DLI is the diurnally integrated light exposure and is affected by turbidity, cloud cover and/or other light reducing properties of the water. Therefore, it defines the light required for seagrass maintenance irrespective of the cause of light reduction. This distinction (from using %SI) is important for environmental impacts that could affect seagrasses, as it takes the light history and condition of the meadow into consideration rather than turbidity alone (Collier et al. 2016).

Also of importance is the duration of time in which seagrass species can survive under reduced light conditions and the recovery time, which is relevant to management when pressures persist over a period of time (e.g., dredging). Experiments have shown that seagrass species can survive below their minimum light requirements for some time, however the duration over which seagrasses can survive under reduced light conditions depends greatly on the species (Table 1). The smaller species with less carbohydrate reserves have a lower resistance, generally surviving less than a month under reduced light conditions (Longstaff and Dennison, 1999), in comparison to the larger species with more carbohydrate reserves surviving up to 3-10 months (Table 1; Lavery et al. 2009). Recovery has been observed or predicted within 5 years in some cases, but when there was significant light reduction for >3 months and significant seagrass loss, then recovery was not predicted (Collier et al. 2009; McMahon et al. 2011).

All ten species found in Cockburn Sound and Owen Anchorage (temperate region of WA) have had some form of light threshold or response pathways for light reduction developed from which thresholds can be extrapolated (Table 1, Table 2). One species (*P. sinuosa*) in Cockburn Sound has locally derived light thresholds (%SI, DLI mol m^{-2} d^{-1}), which include duration and recovery (Table 1), and five species have locally derived photophysiology light parameters (I_k, I_c) (Table 2). Within species, where the same metric and method is used to generate a threshold, the threshold value can vary with location, water depth and the time and duration of the light reduction imposed (e.g. Dennison et al.

1993, Collier et al. 2009, Lavery et al. 2009). For example, across studies of *P. sinuosa*, the MLR ranges from ~8.5-24.5% SI. The DLI at which a decline in shoot density occurs starts at 2 mol m^{-2} d^{-1} but the magnitude of decline increases with lower light, and the recovery time changes with meadow depth (Table 1; Collier et al. 2009).

Table 1. Light thresholds expressed as MLR (minimum light requirement; % surface irradiance) and experimental light intensity under varying light conditions to assess impact (response) over time (duration) for set indicators (sub-lethal to lethal), as well as recovery for seagrass species that inhabit the temperate Cockburn Sound and Owen Anchorage, WA. Study context included to aid in understanding of changes of impact or duration over seasons, locations, water depth and water temperature. Note that some species that occur in Cockburn Sound and Owen Anchorage have a broad distribution so the studies where data has been derived may occur outside temperate waters.

Seagrass species	MLR (%SI)	Light Intensity where there is no MLR %SI linked light values are experimental	Indicator	Duration	Response* Bolded = significant impact	Recovery blank cells = recovery was not assessed	Study context					Notes	Ref
							Plant Location	**Water depth (m)**	**Water temp (°C)**	**Season**	**Study type****		
P. sinuosa	24.5						Waterloo Bay, SA	2-7	14-18		R,O		1,8
	7.8	150 µmol m^{-2} s^{-1} (winter) 850 µmol m^{-2} s^{-1} (summer)					Cockburn Sound, WA	12	15.3-23.5	Winter summer	O	Epiphyte loading	2
	6.7	150 µmol m^{-2} s^{-1} (winter) 850 µmol m^{-2} s^{-1} (summer)					Cockburn Sound, WA	15	15.3-23.5	Winter summer	O		2
	8.5	0.6 – 20.5 mol m^{-2} d^{-1} (ambient)					Cockburn & Warnbro Sound, WA	1-9			O		3
		3.8 mol m^{-2} d^{-1} (86 % of ambient)	E_k	3.5 months	No impact	No significant impact	Cockburn Sound, WA	7-8		Impact: Spring/ Summer	F	No shoot density measures taken prior to 3.5 months	4
			Shoot density	3.5 months	No Impact								
			Shoot density	6.5 months	14% reduction								
		1.1 mol m^{-2} d^{-1} (26 % of ambient)	Areal leaf growth	3 weeks	**Reduction**								
			E_k	3 weeks	**Reduction**								
			Shoot density	3.5 months	**59% reduction**	Recovery minimal after 12.5 months. Predicted to take 5 yrs.							
			Shoot density	6.5 months	**78% reduction**								
		6.9 mol m^{-2} d^{-1} (88% of ambient)	Carbohydrate rhizome	3.5 months	**Reduction**		Cockburn Sound, WA	3-4		Impact: Spring/ Summer	F	No shoot density measures taken prior to 3.5 months	4
			Shoot density	3.5 months	24% reduction	No significant impact							
			Shoot density	6.5 months	[21%] no further reduction								
		2 mol m^{-2} d^{-1} (28% of ambient)	Carbohydrate rhizome	3.5 months	**Reduction**								
			Areal leaf growth	6.5 months	**Reduction**	12. 5 months							
			Shoot density	3.5 months	**69% reduction**	44% recovery after 12.5 months. Predicted to take 3.5 yrs.							
			Shoot density	6.5 months	**70% reduction**								
		0.6 mol m^{-2} d^{-1} (9% of ambient)	Carbohydrate rhizome	3.5 months	**32-52% reduction**								
			Areal leaf growth	3 weeks	**Reduction**	Did not recover							
			ETR_{max} & E_k	3 weeks	**Reduction**								
			Shoot density	3.5 months	**82% reduction**	24% recovery after 12.5 months. Predicted to take 4 yrs.							
			Shoot density	6.5 months	**93% reduction**								

Seagrass species	MLR (%SI)	Light Intensity where there is no MLR %SI linked light values are experimental	Indicator	Duration	Response* Bolded = significant impact	Recovery blank cells = recovery was not assessed	Study context: Plant Location	Water depth (m)	Water temp (°C)	Season	Study type**	Notes	Ref
P. sinuosa		1-20% of ambient	Productivity	2.5 months	**Reduction**	NA	Princess Royal Harbour, WA	3-4	15-21	Impact: Summer-Autumn	F		5
			Shoot density	4 months	**55% reduction**	NA							
			Productivity and Shoot density	10 months	**90% reduction**	Shoots did not recover to pre-shading densities. Predicted meadow collapse in 2 yrs.							
		50% of ambient	Leaf & Shoot density	6 months	Not significant					Impact: Winter	F		6
				9 months	**Reduction**								
P. australis		1-10% ambient or 1.7 mol m^{-2} d^{-1} (≤20 µmol m^{-2} s^{-1})***	Growth rates	3 months	**~80% reduction**		Jervis Bay, NSW	3-4		Impact: Spring Sep-Dec	F		7
			Shoot density		**~45% reduction**								
			Growth rates	3 months	**49% reduction**					Impact: Autumn-winter Mar-Jun			
			Shoot density		**19% reduction**								
			Growth rates	1 month	**~56% reduction**					Impact: Summer Dec-Mar			
			Shoot density	3 months	**~69% reduction**	Wide scale mortality predicted after 1 year. After 17 months recovery no significant increase in shoot density at all times							
			Shoot density	6 months	**Further reduction**					Mar-Jun			
			Dead rhizomes & no flowering	9 months						Jun-Sep			
P. angustifolia	24.5						Waterloo Bay, SA	2-7	14-18		O		8
	6.0										R		9
P. coriacea	24.5						Waterloo Bay, SA				R		1
	8.0										R		9
A. antarctica	24.5						Waterloo Bay, SA	2-7	14-18		O		8
A. griffithii		4.3-7.4 mol m^{-2} d^{-1} (13-19% of ambient)	Leaf extension	3 months	**85% reduction**		Jurien bay, WA	4.5		Summer	I	No measures taken prior to 3 months	10, 11
			Carbohydrates		**67% reduction**								
			Leaf biomass		**57% reduction**	10 months							
			Carbohydrates	3 months	**25% reduction**					Winter			
			Leaf biomass		No impact								
			Leaf extension	6, 9 months	**Reduction**					Summer & Winter			
			Leaf biomass		**>81-99% reduction**	> 2 years (no recovery)							
		2.7-4.7 mol m^{-2} d^{-1} (5-11% of ambient)	Carbohydrates	3 months	**Reduction**					Summer & Winter			
			Leaf extension		**85% reduction**								
			Leaf biomass		**>66% reduction**	10 months							
			Leaf Biomass	6, 9 months	**94-100% reduction**	> 2 years (no recovery)							

Seagrass species	MLR (%SI)	Light Intensity where there is no MLR %SI linked light values are experimental	Indicator	Duration	Response* Bolded = significant impact	Recovery blank cells = recovery was not assessed	Study context					Notes	Ref
							Plant Location	Water depth (m)	Water temp (°C)	Season	Study type**		
		5.2-36.6 mol m^{-2} d^{-1}					Warnbro Sound, WA	3.5	15.3 – 22.2	Summer & Winter	I		12
A. griffithii		12% of ambient	Leaf biomass	3.5 months	**reduced by 30%,**	After 42 days recovery leaf biomass & cluster density was similar to controls.	Jurien Bay, WA	4 – 4.5		Summer	I	Epiphyte load was included in this study	13
			Leaf cluster density		**reduced by 50%**								
			Leaves per cluster		**reduced by 60%**	After 42 days remained significantly lower than controls							
S. isoetifolium		50% of control 30% of control 20% of control 15% of control 5% of control	Shoot productivity	30 days	significantly lower in all treatments compared to control		Moreton Bay, QLD		20	Winter	A		14
H. ovalis		~0 mol m^{-2} d^{-1} (<1% ambient)	Total biomass	24 days	**64% reduction**		Moreton Bay, QLD	NA	22	Winter	M	Dark only Exp.	15
		~0 mol m^{-2} d^{-1} (<1% ambient)	Total biomass	15 days	**25% reduction**	No recovery. Further reduction of biomass, stabilised to 6%	Moreton Bay, QLD	NA	27	Spring	M	Dark-Recovery Exp.	15
				30 days	**100% mortality**	No recovery							
		~0 mol m^{-2} d^{-1} (<1% ambient)	Growth rates	14 days	**81% reduction**	No recovery after 18 days	Moreton Bay, QLD	0.5		Summer	I	*In situ* Dark-Recovery Exp. (shallow & deep locations)	15
			Biomass		**59% reduction**								
			Leaf density		**51% reduction**								
			Growth rates	14 days	**67% reduction**	No recovery after 18 days		2.5					
			Biomass		**59% reduction**								
			Leaf density		**62% reduction**								
		0-3.3 mol m^{-2} d^{-1}	Growth rates	1-4 weeks	**Reduction**		Magnetic Island, QLD		23	Spring-Summer	M	Water temp under experiment conditions.	16
		3.3 mol m^{-2} d^{-1}	Shoot density	14 weeks	**100% reduction**								
		1.6 mol m^{-2} d^{-1}		12 weeks									
		0 mol m^{-2} d^{-1}		6 weeks									
		0-3.3 mol m^{-2} d^{-1}	Growth rates	1-4 weeks	**Reduction**				28				
		3.3 mol m^{-2} d^{-1}	Shoot density	11 weeks	**100% reduction**								
		1.6 mol m^{-2} d^{-1}		4 weeks									
		0 mol m^{-2} d^{-1}		2 weeks									

Seagrass species	MLR (%SI)	Light Intensity where there is no MLR %SI linked light values are experimental	Indicator	Duration	Response* Bolded = significant impact	Recovery blank cells = recovery was not assessed	Study context					Notes	Ref
							Plant Location	Water depth (m)	Water temp (°C)	Season	Study type**		
H. ovalis		13.1 mol m^{-2} d^{-1}	Leaf $\delta_{13}C$	6 weeks	**Reduction**		Shark Bay, WA		27	Autumn - Winter	M	3 weeks earliest measures	17
			Biomass	12 weeks	No impact								
		0.9-5.0 mol m^{-2} d^{-1}	Leaf $\delta_{13}C$	6 weeks	**Reduction**								
			Biomass	3 weeks	**Reduction**								
				12 weeks	**50% reduction**								
		0.9-2.3 mol m^{-2} d^{-1}	ETR_{max}	3 weeks	**Reduction**								
		0.1 mol m^{-2} d^{-1}	Biomass	24 days	**80% reduction**		Karumba, Gulf of Carpentaria, QLD	0.1-1.5		Dry season (Winter-Autumn)	I	Intertidal	18
				38 days	**100% mortality**								
Z. nigricaulis		30% ambient	Shoot density	60 days	Not significant		Port Phillip Bay, Victoria	4.5		Autumn - Winter	I		19
				90 days	**61% reduction**	After 71 days shading further decline in shoots after assessed 40-day recovery.							
				134 days	**84% reduction**								
Zostera tasmanica complex	2-9						Adelaide, SA				R		9
		25-35% of ambient	Leaf density	14 months	**25-50% reduction**		Western Port, Vic	1	up to 24	Summer-Winter	I	Intertidal	20
		9% of ambient	Leaf density	2 months	**65-75% reduction**					Summer			
				2 months	Not significant					Winter			
				10 months	**100% reduction**								
		2% of ambient	Leaf density	1 month	**50% reduction**					Summer			
				2 months	**100% reduction**								
				2.5 months	**60% reduction**					Winter			
				4 months	**100% reduction**								
	20.0						Waterloo Bay, SA	2-8	14-18		O		8
	4.0						Spencer Bay, SA	3.8-39			R		1
	5.0						Victoria	3.8-9.8			R		1

References: 1. Dennison et al. 1993; 2. Masini et al. 1995; 3. Collier et al. 2007; 4. Collier et al. 2009; 5. Gordon et al. 1994; 6. Neverauskas 1988; 7. Fitzpatrick & Kirkman 1995; 8. Shepherd & Womersley 1981; 9. Westphalen et al. 2005; 10. Lavery et al. 2009; 11.McMahon et al. 2011; 12.Carruthers & Walker 1997; 13. Mackey et al. 2007; 14. Grice et al. 1996; 15. Longstaff et al. 1999; 16. Collier et al. 2016b; 17. Statton et al. 2018; 18. Longstaff & Dennison 1999; 19. Kirkman et al. 2012; 20. Bulthuis 1983.

*Where significance is stated, this is based on statistical analyses.

**Study type categories: R - review of other studies; O - observational study; F - field experiment; A - indoor aquarium experiment; I - in situ measure; M - outdoor mesocosm experiment.

***Conversion approximated as 1 µmol m^{-2} s^{-1} = 0.0864 mol m^{-2} d^{-1}. This conversion is valid under continuous light, converted values are an approximation only due to the variable nature of daily sunlight.

Table 2. Light compensation (I_c), Half saturation (I_k) and the hours of saturating photosynthesis (H_{sat}) required for seagrass species that inhabit the temperate regions of Cockburn Sound and Owen Anchorage. Note that some species that occur in Cockburn Sound and Owen Anchorage have a broad distribution so the studies where data has been derived may occur outside temperate waters.

Seagrass species	Experimental water temp range (°C)	I_c (µmol m^{-2} s^{-1})	I_k (µmol m^{-2} s^{-1})	H_{sat} (hrs)	Season	Location	Ref #
P. sinuosa	13	20	37			Cockburn Sound - WA	1
	18	23	55				
	23	26	55				
	18	23 ± 1	58 ± 5		Summer	Albany - WA	2
P. australis	13	17	33			Cockburn Sound - WA	
	18	17	44				
	23	20	51				1
	18	25 ± 1	90 ±4		Summer	Albany - WA	2
*P. angustifolia**							
*P. coriacea**							
A. antarctica	13	17	32			Cockburn Sound - WA	1
	18	19	32				
	23	23	41				
A. griffithii	13	14	24			Cockburn Sound - WA	1
	18	18	35				
	23	17	54				
				800		Jurien Bay	3
S. isoetifolium	27		180 ± 23			Dravuni Kadavu, Fiji	4
H. ovalis	17	33 ± 1	117 ± 5		Autumn	Southwest - WA	5
	23	33 ± 6	129 ± 17				
	28	48 ± 2	112 ± 2				
	17	36 ± 4	131 ± 5		Summer	Cockburn Sound - WA	
	23	41 ± 6	105 ± 22				
	28	37 ± 2	99 ± 4				
	17	18 ± 4	114 ± 9		Winter	Cockburn Sound - WA	
	23	36 ± 2	81 ± 8				
	28	36 ± 3	71 ± 8				
	17	24 ± 1	96 ± 6		Autumn	Jurien Bay - WA	
	23	32 ± 2	104 ± 4				
	28	41 ± 4	85 ± 6				
	17	42 ± 3	115 ± 5		Autumn	Coral Bay - WA	
	23	38 ± 3	150 ± 8				
	28	41 ± 4	156 ± 12				
		8	273-293			Negeri Sembilan, Malaysia	6
*Z. nigricaulis**							
*Zostera tasmanica complex**							

References: 1. Masini & Manning 1997; 2. Masini et al. 1995; 3. Lavery et al. 2009; 4 . Pollard 1999; 5. Said et al. 2021; 6. Mohammad et al. 2006; 7. Pollard & Greenway 2013.
*There are no known data available for these species.

3.2 Seagrass sedimentation and burial thresholds

Deriving burial thresholds is complex, as seagrass responses can be influenced by multiple factors. Generally, responses to burial can differ among and within seagrass species; the latter due to the environmental regimes of their local environment so site-specific studies are warranted for accurate threshold development (Collier et al. 2016). Cabaço et al (2008) reviewed the effects of sediment burial for 15 seagrass species and found that burial depths ranging from 2-19.5 cm resulted in 50% mortality. The timing of the burial and the duration of burial can also impact the ability of seagrasses to respond. For instance, 100% mortality of *P. oceanica* was induced by burial of 15 cm after 200-300 days (Manzanera et al. 1998). Experimental studies of burial impacts often apply a constant depth treatment as very little is known about the duration of burial stress associated with dredging. Deposition and resuspension of sediments is likely to be variable over time dependent upon the exposure of the location, hydro- and sediment dynamics (Manzanera et al. 1998). This is a recognised issue with regards to the transferability of burial thresholds to a dredging context, however, burial depths can still act as guides for impact assessment of seagrasses. Further, it is important to note that sediment quality (e.g. % organic matter) can impact the response to burial and reduce tolerance. Only one study reported the effects of sediment quality in Table 3. For tropical species organic matter of 4% had more negative impacts to seagrasses than no organic matter (Statton et al. 2017a; 2017b).

The level of burial that species can cope with has been studied for 8 out of 10 species that occur in Cockburn Sound and Owen Anchorage, with simulated burial depths ranging from 0.25 – 60 cm (Table 3). However, it is important to note most of these studies were done outside of WA and therefore, there is an absence of locally-derived thresholds. Taking into consideration the species size, growth form and life history, we might expect that burial treatments in the range of 2 – 60 cm to induce effects ranging from the lowest observable to sublethal and lethal effects. The number of days it took for 50% mortality to be observed varied between species and ranged between 14 – 60 days (Table 3). Within Cockburn Sound, *P. sinuosa* is the dominant species. A study undertaken in WA showed *P. sinuosa* experienced 50% mortality under burial levels of 15.4 cm (Table 3). Coupland (1997) assessed the effect of burial on *A. griffithii* in Shoalwater Bay, WA (neighbouring Cockburn Sound) and concluded there was no effect of burial at depths of 12 cm or 16 cm. However, the proportion of above-ground (AG) to below-ground (BG) biomass was significantly different in the 16 cm burial treatment compared to the control at the end of the experiment (2 months), suggesting that *A. griffithii* was impacted by burial within a 2-month period. A significant loss in AG-biomass proportional to BG-biomass would be suggestive of a lethal response in the above ground biomass or leaf clusters, however since leaf clusters was not assessed in this study, we have interpreted the loss of AG biomass to be indicative of a burial impact for 12 cm.

Table 3. Sediment burial thresholds and experimental period (duration) for seagrass species that inhabit temperate regions. Meadow-scale impacts are indicators at 50% and 100% mortality. Recovery data included where available, as well as study location, sediment conditions, and study type.

Seagrass species	Experimental burial levels (cm)	Experimental period (days)	Sediment conditions/ quality	Indicator	50% mortality		100% mortality		Recovery	Location	Study type**	Notes	Ref #
					Burial level (cm)	Duration (days)	Burial level (cm)	Duration (days)					
P. sinuosa	10, 15, 20, 30	50		Shoots	15.4	50				WA	-		1
P. australis	10, 15, 20, 30	50		Shoots	19.5	50				WA	-		1
	4, 8, 16	180		Shoots			16	180		Cockburn Sound, WA	I	Transplants	2
P. angustifolia	60	120	Anaerobic	Shoots			60	14		Adelaide, SA	I		3
*P. coriacea**													
A. antarctica	≤10	120	Aerobic	Growth						Adelaide, SA	I	Unaffected in terms of growth rates by burial of up to 10cm.	3,4
A. griffithii	≤10	120	Aerobic	Growth							I	As per above	3,4
	12, 16	56		Stems AG:BG biomass	16 cm significantly impacted. Mortality and duration not reported.					Shoalwater Bay, WA	I	Significant change in proportion of AG to BG biomass.	5
S. isoetifolium	2, 4, 8, 16	60, 120, 300		Leaf shoots	8	60				Philippines	I		7
	2, 4, 8, 16	27	Mean organic matter 3%	Biomass			8, 16	27		Pulau Tinggi, Malaysia	I		6
H. ovalis	2, 4, 8, 16	27	Mean organic matter 3%	Biomass	8	27	16	27		Pulau Tinggi, Malaysia	I		6
	2, 4, 8, 16	60, 120, 300		Leaf shoots	2-4		2-4		4-10 months	Philippines	I	Authors state burial of >4cm likely impacted *H. ovalis*, however recovery was rapid.	7
	0.25, 0.5, 0.75, 1, 1.25,1.5	30		Shoot density	Not reported					Port Curtis, QLD	M	Significant decline in shoot density for 0.5-0.75 cm. Low to no growth for burial of ≥ 1 cm.	8
Z. nigricaulis	1, 2, 4, 8, 16	14		Biomass	4, 8	14	Did not occur		Partial recovery after 30 weeks winter/spring. No recovery 8 weeks summer/autumn	Port Phillip Bay, Victoria	I		9
Zostera tasmanica complex*													

References: 1. Cabaço et al. 2008; 2. Chisholm 2009; 3. Westphalen et al. 2005; 4. Clarke 1987; 5. Coupland 1997; 6. Ooi et al. 2011; 7. Duarte et al. 1997; 8**.** Benham et al. 2019**;** 9. Hirst et al. 2017**.**
*There are no known data available for these species.
**Study type categories: R - review of other studies; O - observational study; F - field experiment; A - indoor aquarium experiment; I - in situ measure; M - outdoor mesocosm experiment

3.3 Seagrass temperature thresholds

Photosynthetic temperature thresholds assessing a species physiological optimum (T_{opt}) and maximum (T_{max}) temperature range are not well studied for seagrasses. Only one study (Collier et al. 2017) has generated such thresholds. In the absence of these data, the temperature range in which seagrass species grow can indicate their thermal limits (Table 4) or experiments that manipulate temperature have also been used to generate seagrass temperature thresholds. As seagrass species have broad distributions, it is possible that the optimum temperature for a species as identified in Table 5 may vary with location. It is also important to note that the optimal temperature for photosynthesis is often higher than the optimal temperature for growth, and therefore temperatures past T_{opt} for seagrass photosynthesis can be considered as detrimental to seagrass health (Bulthuis 1987; See Table 5 in Lee et al. 2007). Collier et al. (2017) generated T_{opt} thresholds for net plant photosynthesis (P_{max}) for three species, two tropical species (*Cymodocea serrulata* and *Halodule uninervis*) and one species which is more commonly found in sub-tropical to temperate regions (*Zostera muelleri*), for the Great Barrier Reef. *Zostera muelleri,* the more temperate species, had a T_{opt} for P_{max} of 31°C, which was lower than the two tropical species, at 35°C, suggesting that seagrass species are adapted to water temperature within their broad species distributional range (Collier et al. 2017). However, when comparing latitude and season for the two tropical species, thermal optima within a species showed limited acclimation to ambient water temperature and the variation did not follow changes in ambient water temperature (Collier et al. 2017). This suggests that deriving thermal optima for seagrass species across latitudes will allow for a greater understanding of the present and future vulnerability of seagrasses to ocean warming, where species may have limited ability to acclimate. Furthermore, higher thermal optima for plant gross photosynthesis (G_{max}) than that of P_{max}, suggests that both above-ground and below-ground material needs to be taken into consideration when calculating thermal optima for seagrass species (Collier et al. 2017).

None of the ten species found in Cockburn Sound and Owen Anchorage have had temperature thresholds developed (T_{opt} and T_{max} via photosynthesis-temperature curves), although there is data indicating the thermal optimum rates for photosynthesis. These were generated by measuring photosynthesis over a range of set temperatures (e.g. 13, 18, 23°C) and across multiple locations from photosynthesis-irradiance curves for *Posidonia*, *Amphibolis* and *Halophila* (Table 5).

Table 4. Distribution and associated range of reported temperature for seagrass species that inhabit the temperate Cockburn Sound and Owen Anchorage.

Seagrass species	Distribution	Lower distribution, Temperature (°C)	Upper distribution, Temperature (°C)
P. sinuosa	Temperate marine, sheltered embayment's and shallow to deep waters (1)	Southern Australia (1), 13 (4,5)	Geraldton (1), 24 - 25 (3, 6, 7, 8)
P. australis	East coast confined to estuaries and lagoons, west coast occurs in range of habitats (1)	Southern Australia (1), 13 (4, 5)	Shark Bay (1), 27 (2)
P. angustifolia	Endemic to southern Australia (1)	Southern Australia (1), 13 (4,5)	Shark Bay (1), 27 (2)
P. coriacea	Exposed coastline which have strong, persistent swells (10)	South-west WA (10), 15(2)	North of Coral Bay (3), 29 (2)
A. antarctica	Endemic to southern Australia (1)	Southern Australia (1), 13 (9)	North of Coral Bay (13), 29 (2)
A. griffithii	Endemic to southern Australia (1)	Southern Australia (1), 13 (9)	Geraldton (1), 24 - 25 (3, 6, 7, 8)
S. isoetifolium	Temperate – tropical (1)	South-west WA (1), 15 (2)	Indo pacific (1), 29 (2)
H. ovalis	Intertidal to deep oceanic waters, Temperate – tropical (1)	Southern Australia (1), 13 (4,5)	Indo pacific (1), >29 (2)
Z. nigricaulis	Subtidal bays and inlets (10)	Southern Australia (11), 13 (4,5)	Dongara (11), 24 (12)
Zostera tasmanica complex	Estuaries, coastal lagoons and embayment's (1)	Southern Australia (1), 13 (9)	Jurien (10), 24 - 25 (3, 6, 7, 8)

References: 1. Waycott et al. 2014; 2. DBCA unpublished; 3. Pers comm.; 4. Bye 1976; 5. de Silva 1987; 6. Pearce et al. 2011; 7**.** Abdo et al. 2012**;** 8. Crossland 1984; 9. Bryars 2008**;** 10. Kilminster et al. 2018; 11. Womersley 1984; 12. Pearce et al. 1999; 13. Vergés et al. 2018; 14. Collier et al. 2017

Table 5. Temperature thresholds (T_{opt} and T_{max}) for photosynthesis seagrass species in that inhabit the temperate Cockburn Sound and Owen Anchorage. Note that some species that occur in Cockburn Sound and Owen Anchorage have a broad distribution so the studies where data has been derived may occur outside temperate waters.

Seagrass species	Experimental water temp range (°C)	T_{opt} (°C)	T_{max} (°C)	Experiment type**	Location	Ref #
P. sinuosa	13, 18, 23	18-23	>23	P-I curve	Cockburn Sound - WA	1
	13, 18, 23	18-23	>23	P-I curve	Albany - WA	2
P. australis	13,18,23	≥23	>23	P-I curve	Cockburn Sound - WA	1
	13,18,23	≥23	>23	P-I curve	Albany - WA	2
*P. angustifolia**						
*P. coriacea**						
A. antarctica	13,18,23	≥23	>23	P-I curve	Cockburn Sound - WA	1
A. griffithii	13,18,23	≥23	>23	P-I curve	Cockburn Sound - WA	1
	13,18,23	≥23	>23	P-I curve	Albany - WA	2
*S. isoetifolium**						
H. ovalis	17,23,28	≥23-28 17-28 >17, <28 ≥28	>28 >28 >28 >28	P-I curve P-I curve P-I curve P-I curve	Southwest - WA Perth - WA Jurien Bay - WA Coral Bay - WA	3
	10-40	25-30	37.5-40	Aquaria	Taylor's Bay - NSW	4
	22-42	30-31	37-40	P-T curve	Chek Jawa Wetlands, Singapore	5
Z. nigricaulis*						
Zostera tasmanica complex		30	40	P-I curve	Victoria	6

References: 1. Masini & Manning 1997; 2. Masini et al. 1995; 3. Said et al. 2021; 4. Ralph 1998; 5.Kong et al. 2020; 6. Bulthuis 1983**.**

*There a**re** no known data available for these species.
**Photsynthesis-irradaince (P-I) curve, photosynthesi-temoperture (P-T) curve

3.3 Cumulative thresholds (light, sediment and temperature)

The effects of multiple pressures occurring at the same time, or cumulative impacts, are not well studied for seagrasses, especially those occurring in temperate regions (Table 6). Two studies have looked at cumulative impacts of light reduction and temperature for temperate species, both of which were for *Z. muelleri* (does not occur within Cockburn Sound region but has been included in Table 6). These studies showed that where temperature is outside of a species optimum, the impact of temperature is significant regardless of light (Collier et al. 2011; York et al., 2013). In contrast, the effect of increasing temperature at saturating light was positive for the photosynthesis of *H. uninervis* (a tropical species) with temperature having no effect under low light, which suggests *H. uninervis* thermal optimum is likely above 33°C (the highest temperature tested; Collier et al. 2011). As marine heatwaves are expected to increase in magnitude and frequency, EIA for seagrasses need to consider that impacts on seagrasses from combined pressures may differ compared to if these stressors occurred in isolation.

Cumulative impacts of sediment (biogeochemistry and burial) to seagrasses with light reduction is largely unquantified. No studies have looked at cumulative impacts of sediment and light on temperate species, but there are some data available for tropical species (Table 6). Statton et al. (2017a; 2017b) found no sublethal impacts on *H. uninervis* for burial rates up to 7 cm over 14 weeks, however when the sediment was enriched with organic matter (>4%) there were sublethal effects with 4cm of burial at 6 weeks. Dredging can introduce sediments with higher organic matter and/or increased microbial activity; which reduces the oxygen available in the sediments and can increase the likelihood of sulfide toxicity in seagrasses (Holmer et al. 2006). Further, as far as we know, there are no studies looking at the interactive effects of temperature, light and sediment (burial or biogeochemistry), this is an important knowledge gap as seagrasses may be more vulnerable to sulfide intrusion under the cumulative pressures of higher temperature and dredging impacts including low light and burial (Pedersen et al. 2004; Brodersen et al. 2017). The effects of cumulative pressures have further been assessed for other pressures (e.g. salinity, grazing), but are not presented in this report as they were not the main focus of this review (Hernan et al. 2017; Ontoria et al. 2020).

Table 6. Cumulative experimental impact studies relating to light, temperature and sediment (burial and biogeochemistry) pressures for seagrass species that inhabit temperate regions. Species ('other species') in temperate and tropical regions outside of Cockburn Sound and surrounds have been included due to the limited amount of research on cumulative pressures.

Seagrass species	**Pressures**					**Cumulative impact**	**Notes**	**Ref**
	Light ($\mu mol\ m^{-2}\ s^{-1}$)**	**Temperature (°C)**	**Burial (cm)**	**Organic matter (%)**	**Nutrients (g)**			
*P. sinuosa**								
*P. australis**								
*P. angustifolia**								
*P. coriacea**								
*A. antarctica**								
*A. griffithii**								
*S. isoetifolium**								
*H. ovalis**								
*Z. nigricaulis**								
*Zostera tasmanica complex**								
Other species								
Z. muelleri	40,400	27,20,33				Yes		1
	47,112,162,231	24,27,30,32				No		2
H. uninervis	40,400	27,20,33				No	no cumulative impact at temperatures assessed	1
	2.4 mol $m^{-2}\ d^{-1}$		0, 0.5, 1.6, 4	0,4		Yes		3
C. serrulata	2.4 mol $m^{-2}\ d^{-1}$		0, 0.5, 1.6, 4	0,4		Yes		3
P. oceanica			0,4,10		0, 40,80	Yes	Nutrients was fish fodder	4

References: 1. Collier et al. 2011; 2. York et al. 2013; 3. Statton et al. 2017b; 4. Ceccherelli et al. 2018.
*There was no known data available for these species
**Light is experimental and in $\mu mol\ m^{-2}\ s^{-1}$ unless otherwise stated

4 Historical seagrass loss and dredging activities in temperate Western Australia: Cockburn Sound and Owen Anchorage

The purpose of this section is to summarise historical seagrass loss and dredging activities in Cockburn Sound and Owen Anchorage to understand the pressures generated during dredging campaigns (e.g. magnitude and duration of light reduction and/or burial) and the associated seagrass responses. This will help to guide realistic experimental designs (e.g. burial amount or light reduction) and give context to thresholds that are developed as part of Project 2.2.

4.1 Cockburn Sound and Owen Anchorage History: Industrialisation and seagrass

Cockburn Sound, a marine embayment in Western Australia, is home to ten seagrass species, comprised mainly of *Posidonia* (*P. sinuosa* 33% of area, *P. australis* 6% of area) and *Amphibolis* genera (<1% of area) which form both monospecific and mixed meadows (BMT, 2018; Hovey and Fraser, 2018). Other seagrasses such as colonising genera (*Halophila*) and opportunistic genera (*Zostera, Syringodium*) are present in lower abundance. Owen Anchorage is a high energy environment, bordering Cockburn Sound and is adjacent to the main port in Fremantle. This area has a similar seagrass diversity to Cockburn Sound, but the dominant species are *P. coriacea* and *Amphibolis* spp. The seagrass meadows within Cockburn Sound and Owen Anchorage have been recognised as having strong economic and social value due to their role as a nursery habitat and spawning areas for recreational and commercially fished species (e.g. pink snapper and blue swimmer crab; CSMC 2009, Fraser et al. 2018). Cockburn Sound is one of the most intensively used marine areas in Western Australia. It is highly industrialised, with jetties and terminals for surrounding facilities such as alumina and oil refineries, as well as the Perth Seawater Desalination Plant (Figure 2). Up until the late 1970's industrial and residential effluent was directly released into Cockburn Sound, resulting in major nutrient pollution. This caused significant seagrass loss from the 1960s to early 2000s, when extent declined from 2920 ha to 721 ha (Kendrick et al. 2002; Figure 3). Nutrient pollution has since largely been addressed and water quality environmental guidelines generally indicate good quality, however in the last 15 years there has only been a minor (23%) increase in seagrass extent, from 721 ha to 948 ha (Hovey & Fraser 2018). Further, long-term monitoring of seagrass condition indicates decline (based on shoot density) at some sites (CSMC, 2018). A proposed reason for this decline could be attributed to warming conditions combined with poor sediment quality and low water flow (Fraser and Kendrick, 2017; Martin et al. 2020; Olsen et al. 2018). There are continued concerns (BMT, 2018; Fraser et al. 2015) for the lag in seagrass recovery across Cockburn Sound, particularly considering potential cumulative impacts from both further development and ocean warming and heatwaves.

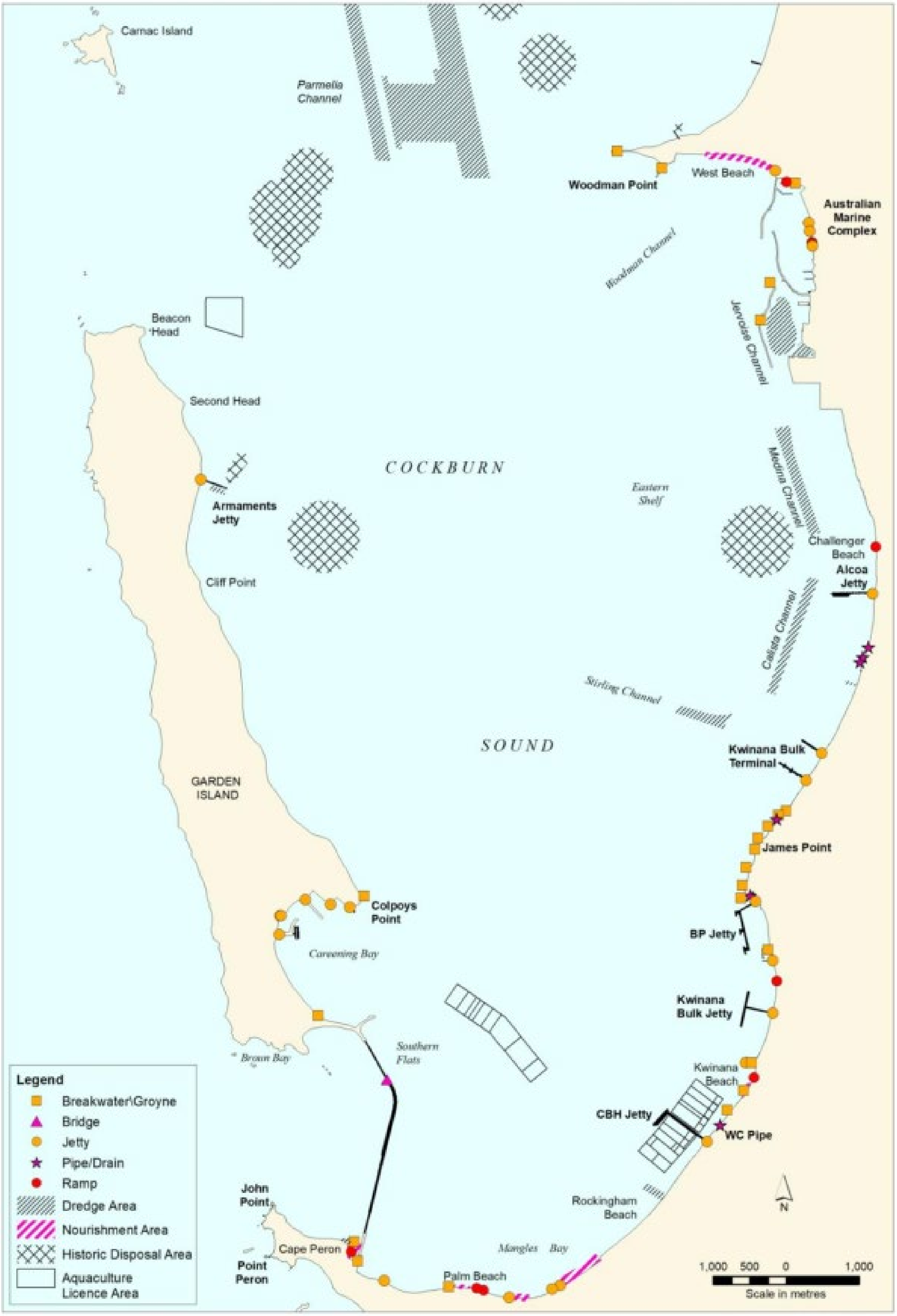

Figure 2. Coastal modification in Cockburn Sound and Owen Anchorage. Source BMT (2018).

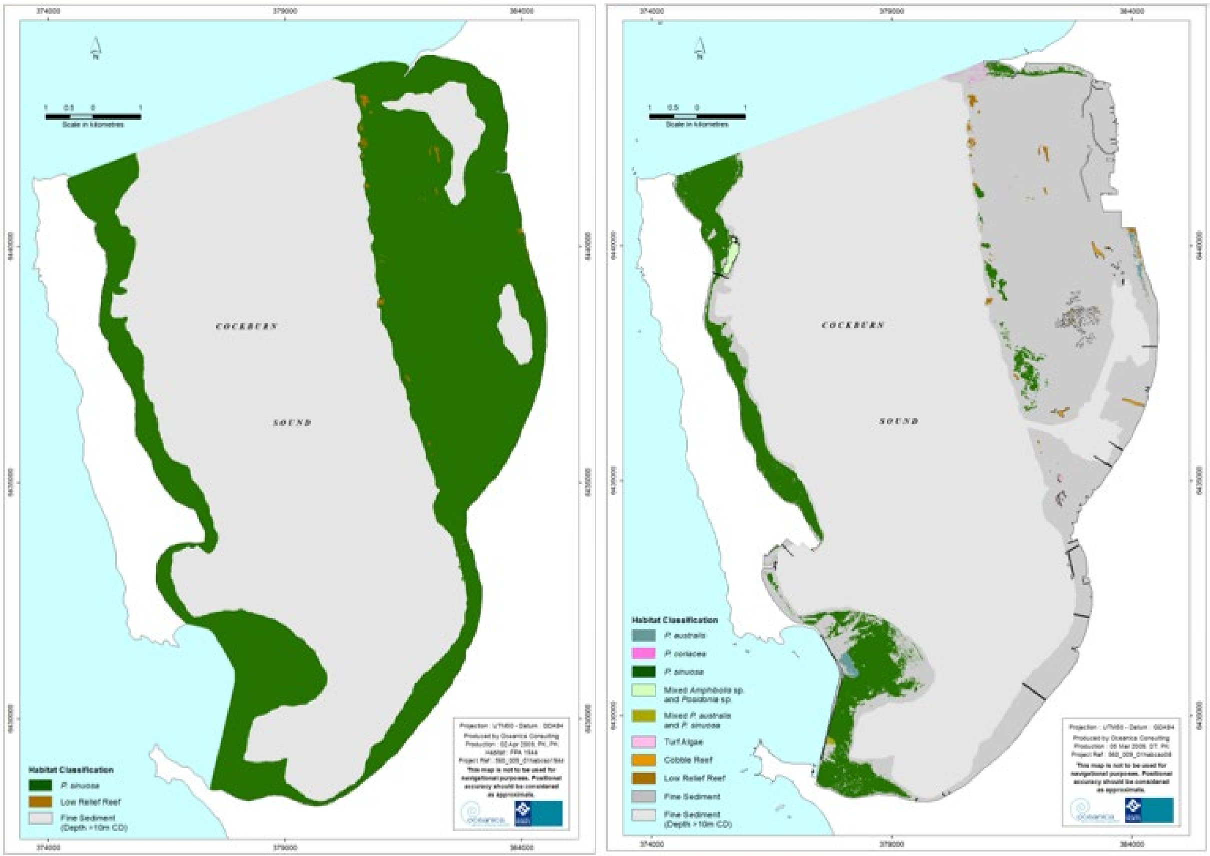

Figure 3. Seagrass extent in Cockburn Sound in 1944 (left) and 2008 (right). Source BMT (2018).

4.2 Historical Environmental Impact Assessment, Management and Monitoring of dredging in seagrass habitat in Cockburn Sound and Owen Anchorage

The EPA proposal search tool (webpage) and WAMSI-Westport database were used to conduct a literature review for dredging related proposals in Cockburn Sound and Owen Anchorage, specifically focusing on those assessed to have a potential impact on benthic communities which included seagrasses. Nine dredging projects between 1994-2016 were identified and assessed (Table 7). Other dredging campaigns have occurred prior to 1994 based on published literature (e.g. Cambridge & Mccomb 1984, BMT 2018), however the EIA documents for these campaigns were not available to be included in the review. For example, since the 1950s, dredging and nourishment works have been undertaken within Cockburn Sound for the purposes of navigation and shoreline management. Additionally, Cockburn Cement has been dredging for shellsand on Parmelia and Success Banks (Owen Anchorage) since 1972 under a State Agreement Act (BMT, 2018). In 1971 there was a direct loss of ~400 ha of seagrass from a combination of coastal development including from Woodman Point along a sewage pipeline, Southern Flats along a shipping channel, Stirling Channel, Armaments jetty and Parmelia Bank and from dredging for limesand in Parmelia Bank (Cambridge and Mccomb, 1984).

For dredging projects evaluated in this review (Table 7), project proposals were either assessed and approved, approved with conditions, or the impacts predicted on seagrass were insignificant and therefore the EIA was not formally assessed by the EPA. The total predicted loss of seagrass across the projects assessed and approved by the EPA in Cockburn Sound was ~321 ha (Table 7).

Not all compliance assessment reports were available and therefore predicted vs actual impacts are not formally reported here. However, as an example, The Fremantle Ports Inner Harbour and Channel

Deepening EIA undertaken by SKM (2009) predicted 25 ha of Benthic Primary Producer Habitat (BPPH) loss, with the majority of the loss occurring in the dredging footprint, spoil disposal ground and reclamation area, and loss outside of these areas was predicted to be minimal. The compliance report (Oceanica 2012) assessed the associated impacts after the dredging operation and estimated 19.9 ha of seagrass was lost in total across the Offshore Disposal Area, and surrounding zones which was within the 25 ha of BPPH predicted loss. Oceanica (2012) suggested that the majority of seagrass loss (15.4 ha; 76%) within the bounds of the Offshore Disposal Area was likely from burial by disposed sediments. In the 'zone of potential effect' and in the 'zone of potential loss' there was a further 3.4 ha and 1.2 ha of seagrass lost from each zone, respectively. The Oceanica (2012) report suggested this was likely due to plumes at the time of disposal and/or sediment resuspension and redistribution of dredged materials causing indirect smothering and/or light limitation of seagrass.

Table 7. Literature review of EIA summaries for EPA dredging related operations influencing benthic communities in Cockburn Sound and Owen Anchorage. Summary table includes document type, EPA assessment outcome, proposed dredging operation, proposed dredge monitoring and management pre-and-post dredging, seagrass species within project area, seagrass thresholds in relation to EPA defined zones, and predicted modelling and impact to dredging based on thresholds. Where boxes are blank there was no information in assessed documents.

Project/Reference	**Doc type ***	**EPA outcome**	**Proposed dredge operation**	**Proposed Pre-dredge monitoring**	**Proposed monitoring during dredge program**	**Proposed Post-dredge monitoring/ management**	**Seagrass species in area (Minimum light requirement)**	**Zone of Influence (ZoI)**	**Zone of Moderate Influence (ZoMI)**	**Zone of High Influence (ZoHI)**	**Predicted modelling/impact**
Fremantle Ports Inner Harbour and Channel Deepening, Reclamation at Rous Head and Offshore Placement of Dredged Material (SKM, 2009)	PER	Approved with conditions	**Dredge footprint:** reclamation area 27ha, dredging area 169 ha, **Duration**: 20-26 weeks starting in November **Dredge**: Cutter Suction Dredge (CSD) & Trailing Suction Hopper **Disposal:** dredge spoil to Rous Head and Gage Roads (area 150 ha)	Shoot density, epiphyte loads		Shoot density, epiphyte loads. If water quality thresholds exceeded monitoring to occur monthly.	*H. tasmanica* (4.6%), *P. angustifolia* (6.1%), *P. coriacea* (8%), *P. sinuosa* (8.5%), *A. griffithii* (>11%)	**TSS**: <2 mg/L and <1 mg/L predicted. 100% of the minimum light requirements for *P. sinuosa* 50% of daylight hours over 5 months[1]	**TSS**: 30% of the minimum light requirements for *P. sinuosa* for 50% of daylight hours over 5 months[2]	TSS: 1% of the minimum light requirements for P. sinuosa for 95% of daylight hours over 5 months[3]	• TSS identified as major impact factor. TSS Concentrations likely to reach peaks of 25-30 mg/L • Sedimentation: Max 30 mm (3 cm) • Predicted loss expected to be minor outside dredging footprint, spoil disposal ground & reclamation area. • 25 ha loss BPPH (inc. corals and algae)
Mangles Bay Marine Based Tourist Precinct (Strategen Environmental Consultants, 2012)	PER	Assessed and approved with conditions	**Dredge footprint:** 5.66 ha (marine), **Duration**: 3 months in May to July **Dredge**: CSD **Disposal:** Pumped onshore via floating pipelines, some overflow discharged into Mangles Bay	Seagrass monitoring (Inc. shoot density) with assessment made from CSMC monitoring EQS's	Seagrass health and water monitoring and adaptive management	Seagrass transplanting and monitoring	*P. sinuosa* *P. australis* *P. coriacea* *Amphibolis sp.*	**TSS**: 100th percentile of the area where TSS threshold of 2 mg/L was exceeded	**TSS**: 99th percentile contour for TSS concentration of 5 mg/L	**TSS**: Comprising the development footprint (direct losses due dredge footprint, and indirect loss due to a 15 m halo effect around the breakwaters)	No indirect losses of seagrass due to TSS. Expected 5 mg/L occurring only outside channel footprint for 1% of the dredging duration. 0.4 ha predicted seagrass indirect loss, 5.66 ha direct loss.
Maintenance Dredging at Stirling Naval Base Garden Island WA (Aurecon Australasia Pty Ltd, 2016)	AR	Potential significant effects of indirect impacts to seagrass were identified. Document not formally assessed;	**Dredge footprint**: 2.6 ha **Reclamation:** 2.9 ha **Duration:** 10-14 days in Autumn **Dredge**: Proposed CSD **Disposal**: Disposal of spoil (~7,500 m^3) material direct to seafloor via downpipe linked to floating	• Condition of seagrasses in the vicinity • TBT in surface sediments at spoil ground	• Maintain daily record of plume dispersal and direction extent • Opportunistic aerial photography of plumes during works to confirm that the ZoI affected by turbid plumes is as predicted	• Condition of seagrasses in the vicinity		Used calculations from APASA 2003; calculation of the distance that is required to reduce TSS concentrations to 3 mg/L			No predicted impacts

Project/Reference	**Doc type** *	**EPA outcome**	**Proposed dredge operation**	**Proposed Pre-dredge monitoring**	**Proposed monitoring during dredge program**	**Proposed Post-dredge monitoring/ management**	**Seagrass species in area (Minimum light requirement)**	**Zone of Influence (ZoI)**	**Zone of Moderate Influence (ZoMI)**	**Zone of High Influence (ZoHI)**	**Predicted modelling/impact**
		Impacts deemed insignificant.	pipeline (in the event that a CSD is used)		• Monitoring of condition of seagrass to nearest seagrass meadows (cover) • Water quality sampling downstream of spoil discharge			(background concentration in Cockburn Sound during Autumn).			
Henderson (BSD Consultants Pty Ltd, 1999)	CER	Approved	**Dredge footprint:** 2.6 ha **Reclamation:** 2.9 ha **Dredge volume**: 80,000 m^3 **Duration**: NA **Dredge**: Dredge and dredge spoil management plan **Disposal**: 'as above'		Water quality monitoring		*Halophila* genera	Seagrass not assessed as an impact. Proposed development construction contained to the Northern Harbour where previous seagrass meadows have been lost, with no expected impacts to seagrass meadows near Garden Island and Success Bank. Report states 'some' seagrass plants predominantly H*alophila* genera will be lost.			Seagrass not assessed
Henderson Facility Expansion (Dredging) (Worley Parsons Service Pty Ltd, 2013)	EMP	Potential significant impacts for marine fauna and water quality impacts	**Dredge Footprint**: 13,000 m^2 **Dredge volume**: 22,500 m3 **Duration**:4 weeks in September **Dredge**: Backhoe **Disposal**: Dredged material placed on shore and bunded		There are no sensitive receptors adjacent to the dredge footprint; however, the dredge plume should be monitored visually on a daily basis to confirm that the plume is not spreading outside the industrial precinct.						No direct seagrass loss
James point port: stage one (D.A. Lord & Associates Pty Ltd, 2001)	PER	No direct impact loss. Does not use EPA zones	**Dredge footprint:** 911,000 m3/ 21.5 ha **Duration**: Dredge and Reclamation management Plan **Dredge**: 'as above' **Disposal**: 'as above'		Light climate of closest seagrasses (2 km NW of development)	Turbidity, suspended sediment concentration, size and orientation of plume	In Stirling Channel; *P. sinuosa, P. angustifolia*	EPA Zones not used. For seagrasses looked at LAC (derived from MLR for *P. sinuosa*) and Chlorophyll a			No impact to seagrasses in the region
Short-term shell-sand dredging, Success Bank, Owen Anchorage. PER unavailable. Information sourced from: (EPA 1996)	CER	Approved with conditions	**Dredge footprint:** 67 ha **Duration**: Over 2 years **Dredge**: Suction Dredge **Disposal**: Material deposited on shore and used			Research being undertaken into seagrass regrowth & rehabilitation	1670 ha of seagrass 75-100% cover. *Posidonia spp* *Amphibolis spp* *Heterozostera* *Halophila spp* *Syringodium spp*				EPA has assessed predicted loss of 2% of seagrass in area (33 ha).

Project/Reference	**Doc type** *	**EPA outcome**	**Proposed dredge operation**	**Proposed Pre-dredge monitoring**	**Proposed monitoring during dredge program**	**Proposed Post-dredge monitoring/ management**	**Seagrass species in area (Minimum light requirement)**	**Zone of Influence (ZoI)**	**Zone of Moderate Influence (ZoMI)**	**Zone of High Influence (ZoHI)**	**Predicted modelling/impact**
Medium-Term Shell-Sand Dredging Owen Anchorage (Unknown 1996)	R&R EPA	Approved with conditions	**Dredge footprint:** 147 ha	Continued monitoring of Dredge Management Plan (DMP); seagrass dynamics, seagrass mapping		Shoreline monitoring, annual monitoring of seagrasses, seagrass mapping. Seagrass restoration.	Species on Success and Parmelia Banks: *P. australis, P. sinuosa, P. coriacea, A. antarctica, A. griffithii, H. tasmanica, H. ovalis, S. isoetifolium*	EPA Zones not used. Plume dispersal and quantify light attenuation characteristics on a temporal and spatial basis downstream of the dredge. Details of this study are reported in LSC (1990). The results indicated that increased light attenuation due to the dredging plume was temporary and intermittent. It was concluded that although light levels were at times reduced below the requirements of the seagrass, the reduction was of insufficient duration to create significant stress on seagrass.			44 ha dense *A. griffithii/P. coriacea* meadow, 46 ha of patchy *P. coriacea*
Long-term Shells and Dredging Owen Anchorage (D.A. Lord & Associates Pty Ltd, 2000)	ER& MP	Approved with conditions	**Dredge footprint:** *Stage 1*: 52 ha from Parmelia Bank and 19 ha from Success Bank. **Duration**: Maximum 8 years for stage 1 and stage 2 is 20 years. **Disposal**: used for sandshell mining- dumped on shore			Detailed environmental management plan and seagrass transplanting (BMT Oceanica, 2013). Further decommissionin g plan (Oceanica Consulting Pty Ltd, 2011).	*P. sinuosa, P. coriacea Amphibolis spp*				Estimated direct loss of 50 ha of sparse *Amphibolis*, 19 ha of dense *P. coriacea* and 98 ha of *P. sinuosa*

- The EPA reviewed the marine dredging guidance document in 2016 and 2021 to recommend assessing impacts of dredging by using different zones (ZoI, ZoMI, ZoHI). Zones in the SKM 2009 report are termed: area of potential influence[1], area of potential effect[2] and area of potential impact[3].
- Document types include Public Environmental Assessments (PER), Consultative Environmental Review (CER), Environmental Management Plan (EMP), Amendment to Referrals (AR), and Environmental Review and Management Plan (ER&MP), Report and Recommendations of the Environmental Protection Authority (R&R EPA).*

4.1 Dredge Monitoring in Cockburn Sound and Owen Anchorage

Cockburn Sound and Owen Anchorage have a history of dredging operations (detailed in Section 4.2), some of which have been characterised by light (total PAR) and sediment accumulation rates. These two parameters are particularly useful as they directly relate back to seagrass literature and help inform the pressure-response relationship. This data from the dredging campaigns was requested as part of this literature review but was not made available for use within this report. However some data on total suspended solids (TSS), turbidity and Light attenuation coefficient (LAC) collected during previous construction and operational phases of these dredging projects in Cockburn Sound were available and are presented in Table 8.

TSS during the dredging projects ranged between of 1.5-140 mg/L depending on the location in which the sample was collected from, with the higher values closer to the dredge cutter head (Oceanica data sourced from SKM 2009). Turbidity ranged from 0 NTU in the Fremantle Ports Success and Parmelia Long Term Maintenance Dredging to 94 NTU in the Fremantle Ports Inner Harbour Maintenance Dredging. The light attenuation coefficient was only available from the AMC construction monitoring program which was estimated to be <0.4 m^{-1}, 600 m from the dredge discharge and <0.1 m^{-1} at other monitoring sites.

Table 8. Indicative TSS, Turbidity and light attenuation coefficient (LAC) from dredge plumes in Cockburn Sound from previous dredging projects. Table adapted from SKM 2009.

Data source	Parameter	TSS (mg/L)	Turbidity (NTU)	LAC (m^{-1})
AMC Construction Monitoring (Oceanica, 2008 report- data sourced from SKM, 2009)	Reclamation area discharge (W0 site) [1] (max)	29	50	-
	Approx. 100 m from discharge FP1 surface (mean)	6.9[1]	-	-
	Approx. 100 m from discharge FP1 bottom (mean)	15[1]	-	-
	Approx. 600 m from discharge (JB16) (mean)	2.2[1]	1.3	Estimated <0.4
	FP2, FP3, FP4 (range of site surface means)	3.2–4.8[1]	-	-
	FP2, FP3, FP4 (range of site bottom means)	2.5–5.3	-	-
	All other monitoring sites during dredging (mean)	1.5–2.5[1]	0.6-1.2	Estimated <0.1
	Water Quality Criteria	<30	<30	(Z_{sd} > 4.3m)
AMC Plume Survey (Oceanica, 2008 report- data sourced from SKM, 2009)	Vicinity of cutter head surface (range)	4-43[1]	-	-
	Vicinity of cutter head bottom (range)	10-140[1]	-	-
Fremantle Ports Inner Harbour Maintenance Dredging in 2003 by TSHD (SKM 2003)	Inside containment pond (median)	-	94	-
	Outside secondary silt curtain (median)	-	4	-
	200 m from discharge area (median)	-	1.3	-
Fremantle Ports Success and Parmelia Long Term Maintenance Dredging in 2007 by TSHD (SKM 2007)	Transect 150-200 m from dredge (range)	-	0-24	-
	Transect 50-80 m from dredge (range)	-	0-18	-
	Disposal site	-	5-58	-

[1]analysed using MAFRL filtration and gravimetric analysis method.

4.2 Light considerations for EIA and Project 2.2

It is important to note that light intensity is generally the factor measured *in situ* to assess seagrass impacts at an experimental level, however modelling for EIA of dredging usually assesses suspended sediment concentration/turbidity. For EIA modelling '≥2mg/L TSS' which indicates a visible plume is generally used as a conservative proxy for light reduction (Strategen Environmental, 2016), however if there are models available to convert TSS into light, this is the preferrable method for predicting and assessing light reduction impacts. The Kwinana Quay Dredge Modelling Document (Asia-Pacific asa 2009) sets out TSS to LAC conversions for Cockburn Sound. These equations were produced through experiments using suspended material from locally sourced limestone which was ground to mimic post-dredging particle size distribution (PSD) curves. Equations can be used for Project 2.2 light data to convert LAC values to relevant TSS values. The recommended relationships from Partridge & Michael (2009) for deriving LAC from modelled TSS for Cockburn Sound are as follows:

TSS: 0 mg/L to 20 mg/L: $LAC = 0.0079xTSS + 0.0197$

TSS: >20 mg/L: $LAC = 0.0424 - 0.0777\ln(TSS) + 0.0451(\ln(TSS))^2$

4.3 Sediment considerations for EIA and Project 2.2

Sediment dynamics are naturally variable in the Owen Anchorage area (north of Cockburn Sound) over short (hourly to daily) and longer (monthly) timescales and the variability in sediment depth can range by up to 25 cm (Paling et al., 1998). Data on sediment burial was not available from the dredging monitoring projects assessed in this review. Sedimentation rates have been quantified from various case-study dredging projects in tropical Western Australia and if selected values were held constant over a 30-day period would result in burial depths ranging from a few mm up to 4 cm (McMahon et al., 2017). Therefore, from an experimental perspective to develop burial thresholds for seagrass, a broad range of burial depths should be selected that can simulate what might be expected based on natural variability and in a range of dredging scenarios. Further, from an EIA perspective, it is important to characterise species-specific burial thresholds that consider both impact and recovery as the timeframe over which an impact manifests or recovery occurs will depend on the seagrass species and the life history strategy (colonising, opportunistic, persistent).

5 Knowledge Sharing: Industry Consultation

The EIA&M process is generally undertaken by environmental consultants therefore knowledge sharing between researchers and industry experts that have relevant expertise allows for greater confidence in experimental design to ensure applicable management outputs. Knowledge sharing was undertaken through independent facilitated workshops in March to April 2022 with multiple industry partners, especially those with experience and knowledge of dredging pressures impacting temperate seagrasses. This information has been summarised in Table A1 and contributed to Project 2.2 research design and outputs (Figure 4).

The experts involved in the consultation process were from five different consulting firms who have operated in Western Australia and more broadly at the national and international level. Additionally, two Westport technical advisory members who have worked in industry (Dr Paul Erftemeijer) and government (Dr Ray Masini), and one researcher who has extensive experience in designing and carrying out experiments to develop thresholds for seagrass to environmental pressures to inform management (Dr Catherine Collier) were consulted. Most of the experts highlighted the knowledge gaps associated with burial of seagrass by sediments generated from dredging, including how much burial seagrasses could tolerate and for how long, and whether the biogeochemistry of the sediments (particle size distribution and organic carbon content) influenced these tolerance levels, as well as the cumulative impacts of pressures. The uncertainty about how a heatwave would influence the tolerance to light reduction was also noted by several experts. Other potential pressures that were raised by one or two experts was the limited knowledge available on the effect of contaminants and the change in hydrodynamics associated with new channels which may potentially increase the wave energy experienced by seagrasses, or resuspension of sediments by ships in the shipping channel or that epiphyte load may impact the tolerance to light reduction. Additional gaps that were raised included limited knowledge on recovery timeframes and the role of seed banks in facilitating recovery of colonising and opportunistic species.

All experts consulted agreed that the overall experimental approach proposed in the Project 2.2 Plan was sound, especially the burial treatments of intensity (burial depth) by duration and exploring the effects of heatwaves and synergistic impacts on seagrass. Several valuable suggestions were provided and subsequently incorporated into both field and mesocosm experiments. As most monitoring plans incorporate measures of seagrass shoot density and/or cover, these variables were included in Project 2.2. experiments where applicable, to enable transferable interpretation of results to EIA&M. Most EIA&M work to date in temperate WA has focused on the *Posidonia*, *Amphibolis, Zostera* (*Heterozostera*) and *Halophila* genera highlighting the priority to develop thresholds for these taxa.

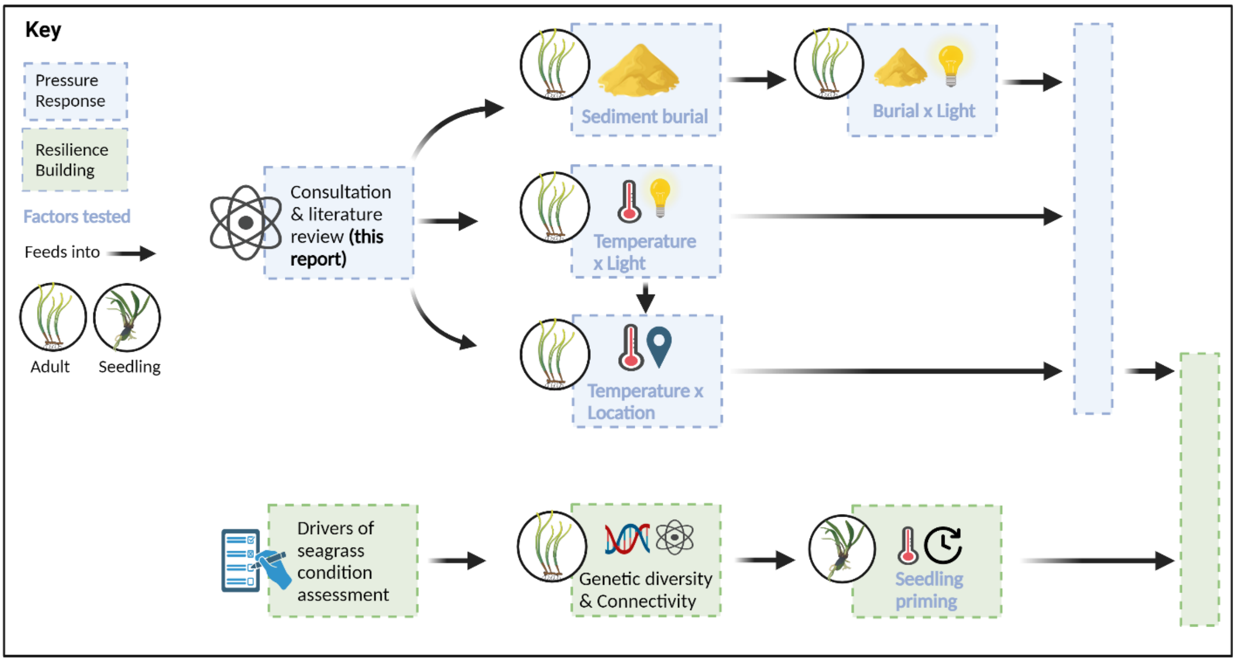

Figure 4. Flowchart indicating how industry consultation and literature review will inform sub-projects for Theme 2.2 seagrass-pressure response relationships and building seagrass resilience.

6 Seagrass Thresholds for Environmental Impact Assessment

The EPA (2021) dredging guidance document provides direction on how to set pressure and ecological thresholds for a dredging project. This guidance document uses specific terminology to define the range of thresholds and how they can be implemented. In this section we have adopted the EPA dredging guidance terminology (EPA 2021) to improve clarity of interpretation. The EIA phase requires an understanding of the spatial extent, severity and duration of the dredging pressure and the predicted impacts to the sensitive receptor, in this case seagrass from both a degradation (i.e. decline in the sensitive receptor) and recovery perspective (EPA 2021). The premise for this spatial consideration is that the severity of the impact is likely to reduce as you move away from the pressure source (i.e. the dredge). Three spatial zones are identified where biological effects guidelines or thresholds are applied (Figure 5):

- Zone of Influence (ZoI): no detectable impact on sensitive receptor (in this case seagrass);
- Zone of Moderate Impact (ZoMI): impact on seagrass, but seagrass *is* recoverable within 5 years;
- Zone of High Influence (ZoHI): impact on seagrass, but seagrass *is not* recoverable within 5 years.

The EPA (2021) dredging guidance document acknowledges that when applying thresholds in each zone (ZoI, ZoMI and ZoHI) there is uncertainty in all predictions which arises from an array of sources. In order to take account of this uncertainty in the EIA process, the final set of predictions may describe the lower and upper ends of the likely range of impacts associated with the proposal (i.e. the likely 'best-case', also equivalent to 'Management target' or 'probable effects guideline'; and, the likely 'worst-case', which is equivalent to 'Environmental Protection outcome' or 'possible effects guideline' within the EPA 2021 document). There are multiple ways to address this uncertainty. The EPA (2021) guidance document, Section 3.5, provides advice on how to use experimental data presented in this report to take uncertainty of impacts into consideration.

The following sections synthesise the data on seagrass responses to light reduction, sediment burial and ocean warming or heatwaves presented in this literature review to align with the 2021 EPA dredging guidance document. Where possible we indicate the duration over which a particular level of light, sediment burial or temperature has no observable effects (including sublethal effects e.g. physiology parameters, carbohydrate stores), where this information is relevant to define the ZoI. This information can further be used to set the outer ZoMI boundary. Lethal effects (e.g. shoot loss) of seagrass in conjunction with timescales of recovery are relevant to define the ZoMI or ZoHI. Where there was information on the timing of pressure, this has also been incorporated.

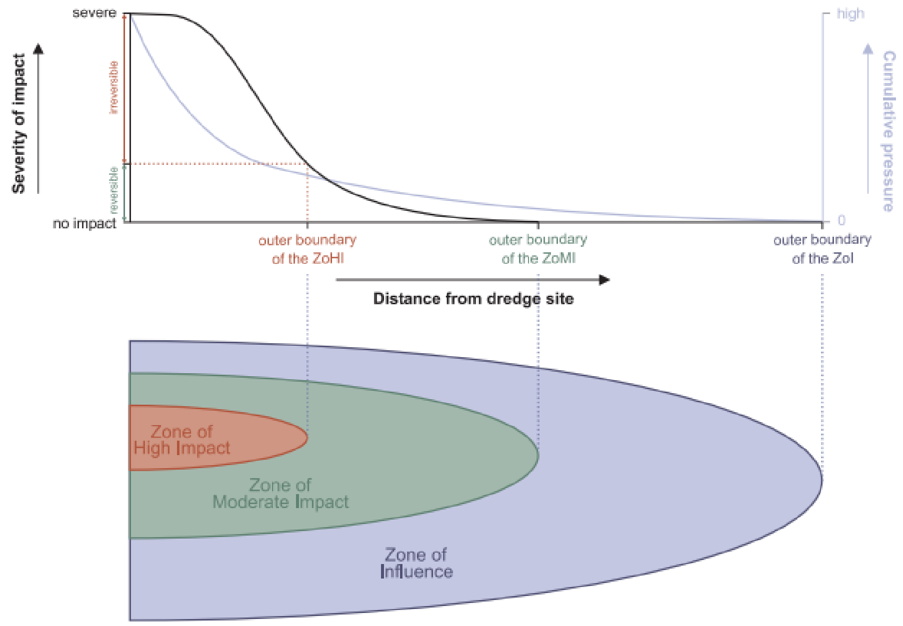

Figure 5. A schematic representation of the degree of change in environmental quality associated with dredging (grey line) and level of resultant impact to benthic communities (black line) along a transect extending away from the dredging site to the outer extremity of the Zone of Influence. The location of the outer boundaries of the Zone of High Impact (ZoHI), Zone of Moderate Impact (ZoMI) and Zone of Influence (ZoI) are shown relative to these predicted changes in environmental quality and impacts on biota. Source EPA (2021).

6.1 Light

6.1.1 Translating light data from literature review into biological effects guidelines (or thresholds)

Six out of 10 species had data available to develop thresholds for impact (5 species for ZoI), and only 3 of these had recovery data making it challenging to predict recovery timescales and develop guidance for the ZoMI and ZoHI (Table 9). The recovery data was only available for persistent species (*Posidonia*, *Amphibolis*) not opportunistic or colonising species (*Zostera*, *Halophila*), but in only two cases was recovery within 5 years observed. In the cases where the timing was assessed, seagrasses were more resilient to the pressure applied in autumn or winter compared to summer, as it took longer for both sublethal and lethal impacts to be realised (Table 9 and Table 10). When using the summary tables below (Table 9 and Table 10) to apply thresholds it is important to recognise that there are species specific differences, and that thresholds can vary with water depth and time of year, and the experiments from which the data was generated had set levels and durations over which impacts were measured. Despite this, there are some generalisable trends that can be applied from an EIA perspective. Where possible, locally derived thresholds should be utilised, but in the absence of this the most conservative available data is recommended (location of studies is stated in Table 1).

Zone of Influence (ZoI)

Thresholds associated with the ZoI can be derived for light levels and durations where there are no sublethal or lethal impacts. Sublethal impacts are physiological and plant-scale responses to the pressure, where no loss of leaves/shoots has occurred. These sublethal impacts can reduce seagrass resilience to further pressures (e.g. reduce carbohydrates stores, affect reproduction). The green squares in Table 9 represent no sublethal impacts. For example, for *P. sinuosa,* if a moderate light reduction (2 mol m^{-2} d^{-1}) is applied in the shallow site there are no sublethal impacts based on the maximum electron transport rate (ETR_{max}), however, for the sublethal measure of carbohydrate reserves there was an impact at 3 months. Therefore, when defining the ZoI <3-months at 2 mol m^{-2}

d^{-1} needs to be utilised. At the deep site which received 3.8 mol m^{-2} d^{-1}, there were no sublethal impacts after 3-months for any measure, therefore a 3-month duration at this light level can be utilised for the ZoI. If a lethal impact was identified at a particular level of light and time, e.g. at 3 months, but no measurements were taken prior to 3 months then there is uncertainty in the duration. An important point to note when developing ZoI thresholds is the frequency of sampling in the experiments. Yellow squares indicate uncertainty in Table 9. In Table 9 a sublethal impact is represented through the orange squares, these values are recommended to be used for the outer boundary of the ZoMI.

Zones of Moderate and High Impact (ZoMI, ZoHI)

Applying appropriate thresholds to the ZoMI and ZoHI is more complex than the ZoI. The ZoMI and ZoHI takes the level of light over duration into consideration for impact, as well as the recovery time of seagrasses following the impact. Table 9 and Table 10 can be used in conjunction with each other to define the ZoMI and Table 10 can be used alone for the ZoHI. It is recommended that the outer boundary of the ZoMI uses sublethal impacts to build in a layer of conservatism (See Section 3.5 in EPA 2021). A sublethal impact is represented through the orange squares in Table 9. For example for *Posidonia sinuosa* if the average daily light is reduced to 1.1 mol m^{-2} d^{-1} (high reduction) in both shallow and deep sites a sublethal impact will be seen after 3 weeks. But as described above, if the light is reduced to 2-6.9 mol m^{-2} d^{-1}, <3 months should be utilised (Table 9). In the absence of this data the green squares within Table 10 can be utilised for the lower boundary of the ZoMI, where no observable lethal impacts were observed. For example, for *P. sinuosa* growing in shallow meadows there is unlikely to be an impact, if average daily light is maintained at 6.9 mol m^{-2} d^{-1} for 6 months. For the observed lethal-impact component, the light and dark orange colours at a set daily light and duration indicate when a lethal impact occurs and can be considered as representative of the upper boundary of the ZoMI and the ZoHI (Table 10). If recovery data is available then if recovery occurred in less than 5 years this would be indicative of the upper boundary of the ZoMI but if it was greater than 5 years, this would be aligned to the ZoHI. For *A. griffithii* if average daily light is between 2.7-4.7 m^{-2} d^{-1} for 3 months there will be an impact, but recovery is predicted within 10 months, therefore this data could be used to assign the upper boundary of the ZoMI. Another example is *P. sinuosa* if average daily light is 2 mol m^{-2} d^{-1} there will be a lethal impact by three months, and if the light conditions return to ambient in shallow sites recovery will occur in less than 5 years but if it is a deeper site, recovery will take greater than 5 years. Therefore, in this case the assignment of upper boundary of the ZoMI or ZoHI depends on the depth of the meadow that is likely to be impacted by the dredging.

Table 9. Seagrass light review summary for sublethal impacts of available data for Environmental Impact Assessment for the Zone of Influence (ZoI). Average Daily light which is representative of different scales of light reduction impacts (Low, Moderate, High) for seagrass thresholds. Light threshold varies across durations/seasons which is represented in the key and coloured cells within the table. Table 1 in this report contains further literature as well as study context.

Key: Sublethal impact unlikely | Impact not known | Sublethal impact: max allowable pressure duration

Seagrass species	Average Daily Light (mol m^{-2} d^{-1}) or %ambient*	Indicator	Duration Impact time (months)														Ref
			Spring/Summer							Autumn/Winter							
			0.25	0.5	0.75	1	1.5	2	3	0.25	0.5	0.75	1	1.5	2	3	
P. sinuosa	2-6.9 (shallow site)	ETR_{max}															1
		Carbohydrates															
	3.8 (deep site)	Carbohydrates, E_k, areal growth															
	0.6-1.1 (deep & shallow)	ETR_{max}, E_k, areal growth															
P. australis	~1.7 (1-10%)*	Growth rates															2
*P. angustifolia**																	
*P. coriacea**																	
*A. antarctica**																	
A. griffithii	2.7-4.7	Carbohydrates, Leaf extension															3
S. isoetifolium	5-50% control	Shoot productivity															4
H. ovalis	13.1	Leaf $\delta_{13}C$															5
	0.9-2.3	ETR_{max}															
	0-3.3	Growth rates															6
	~0 (0.1%*)	Growth rates															7
*Z. nigricaulis**																	
Zostera tasmanica complex*																	

References: 1. Collier et al. 2009; 2. Fitzpatrick & Kirkman 1995; 3. McMahon et al. 2011; 4. Grice et al. 1996; 5. Statton et al. 2018; 6. Collier et al. 2016a&b; 7. Longstaff et al.1999
*No known appropriate available data for these species.

Table 10. Seagrass light review summary for lethal impacts of available data for Environmental Impact Assessment for Zone of Moderate and High Impacts (ZoMI and ZoHI). Average Daily light which is representative of different scales of light reduction impacts (Low, Moderate, High) for seagrass thresholds. Light threshold varies across durations/seasons which is represented in the key and coloured cells within the table. Recovery time is included where data was available. Table 1 in this report contains further literature as well as study context. NA = lethal impact, but recovery not assessed.

Key: Lethal impact unlikely | Impact not known | Lethal impact: max allowable pressure duration | Lethal impact known but pressure continuation

Seagrass species	Average Daily Light ($mol\ m^{-2}\ d^{-1}$) or %ambient*	Duration Impact time (months)																Recovery			Ref
		Spring/Summer								Autumn/Winter								<5 years	>5 years	Unknown	
		0.5	0.75	1	2	3	4	5	6	0.5	0.75	1	2	3	4	5	6				
P. sinuosa	6.9 (shallow site)																				1
	3.8 (deep site)																				
	0.6-2																	≤4m deep	≥7m deep		
P. australis	~1.7 (1-10%)*																			>17months	2
																				NA	
*P. angustifolia**																					
*P. coriacea**																					
*A. antarctica**																					
A. griffithii	4.3-7.4																	10 months for summer only			3
	2.7-4.7																	10 months			
	2.7-7.4																			>2yrs	
*S. isoetifolium**																					
H. ovalis	13.1																				4
	0.9-5																				
	9-10																				5
	5.3-5.8																			NA	
	0																				
	0.1																			NA	6
	~0 (0.1%*)																			NA	7
Z. nigricaulis	30%*																			NA	8
Zostera tasmanica complex	25-35%*																				9
	9%*																			NA	
	2%*																				

References: 1. Collier et al. 2009; 2. Fitzpatrick & Kirkman 1995; 3. McMahon et al. 2011; 4. Statton et al. 2018; 5. Collier et al. 2016a&b; 6. Longstaff and Dennison 1999; 7. Longstaff et al.1993; 8. Kirkman et al. 2012; 9. Bulthius 1983. *No known appropriate available data for these species.

6.1.2 Considerations in applying light data

While the recommended light thresholds were derived from the best available scientific knowledge, below are some considerations when using data for specific dredging projects:

- a potential disturbance should be managed for the most sensitive species present;
- locally derived thresholds if available are recommended where local site conditions (e.g. water depth, background water conditions) could affect seagrass light thresholds;
- there may be a need for seasonally varying light thresholds;
- cumulative impacts on thresholds are largely unquantified (*in situ* experiments capture naturally changing site conditions), and where cumulative impacts are unknown, then conservative thresholds should be applied;
- measurement of light as an approval condition or for compliance needs to be performed at the seagrass canopy (i.e. benthic light) of the meadow. Monitoring light at a shallower or deeper depth will not be an accurate application of the management threshold;
- thresholds are based on total photosynthetically active radiation (400 – 700nm), and do not account for spectral quality, which could affect light thresholds; and
- thresholds are average values, while light levels are naturally variable, peaks in light well above guidelines are likely to be important for some biological processes such as reproduction.

6.2 Sedimentation and burial

6.2.1 Translating burial data from literature review into biological effects guidelines (or thresholds)

The number of studies on the impacts of sediment burial on seagrasses are considerably less compared to the impacts of light reduction. Eight out of ten species had experimental data on the impacts of burial with seven species having data to develop guidance for the ZoI (Table 11). Impacts to burial are reasonably well documented but only two species had information on recovery making it very difficult to assign ZoMI or ZoHI with confidence (Table 11). Most of the experiments assessed multiple burial levels ranging from 1-60 cm depending on the species providing appropriate data to align with the ZoI. Smaller species (e.g. *Halophila* and *Zostera*) were impacted at lower levels, 2-10 cm of burial compared to larger species (e.g. *Amphibolis* and *Posidonia*). For available data to align with the ZoMI and ZoHI, most studies assessed the burial impact over duration, however only two studies (*Z. nigricaulis* and *H. ovalis)* assessed recovery. For all other species there is no recovery data, but where ≤4 cm of burial was tested there were no impacts, and therefore this value could be applied conservatively for the ZoMI and ZoHI for all species assessed here (except *Z. nigricaulis* and *H. ovalis*). It is important to note that sediment quality can impact the response to burial and reduce tolerance. For example Statton et al. (2017a; 2017b) found no sublethal impacts on *H. uninervis* for burial rates up to 7 cm over 14 weeks, however when the sediment was enriched with organic matter (>4%) there were sublethal effects of burial at 4 cm at 6 weeks. No studies that we identified for temperate species incorporated sediment quality.

Table 11. Seagrass sediment burial review summary of available data for Environmental Impact Assessment based on impact, duration and recovery data. Note it is not possible to develop a table similar to Table 9 and 10 for burial as the data does not exist to enable it.

Species	Data available to align with ZoI (no impact)	Data available to align with ZoMI/ZoHI			Assign a ZoMI/ZoHI threshold with confidence?
		Impact	Duration	Recovery	
P. sinuosa	✓	✓	✓	✗	✗
P. australis	✓	✓	✓	✗	✗
P. angustifolia	✗	✓	✓	✗	✗
*P. coriacea**					
A. antarctica	✓	✗	✗	✗	✗
A. griffithii	✓	✓	✓	✗	✗
S. isoetifolium	✓	✓	✓	✗	✗
H. ovalis	✓	✓	✓	✓	✓
Z. nigricaulis	✓	✓	✓	✓	✓
Zostera tasmanica complex*					

*There was no known data available for these species

6.2.2 Considerations in applying sediment burial data

While the recommended sediment burial thresholds were derived from the best available scientific knowledge, below are some considerations when using data for specific dredging projects:

- a potential disturbance should be managed for the most sensitive species present;
- locally-specific guidelines are highly recommended where available as these capture inherent site conditions;
- effects of interactive factors on thresholds are largely unquantified (*in situ* experiments capture naturally changing site conditions); and
- Influence of sediment biogeochemical characteristics on seagrasses may vary thresholds (e.g., organic matter).

6.3 Temperature

Within the context of EIA, it is relevant to focus on the cumulative impact of dredging pressures and temperature as dredging could occur during a marine heatwave event. As temperature and light interact to influence seagrass metabolism, increased water temperatures during dredging operations could require different light thresholds. As previously discussed, some experimental studies have assessed the cumulative impacts of light and temperature on seagrasses and found that when water temperature is outside of optimum range, there is a negative impact of increased temperature and this could be more severe under reduced light conditions or not (Collier et al., 2011; York et al. 2013). Further, in 2010/11 there was a heatwave event that increased temperatures by up to 5°C for 8 weeks in Shark Bay (Fraser et al. 2014). This resulted in seagrass loss, but in areas where the marine heatwave event overlapped with turbid floodwaters, reducing light, there was a more extreme impact to seagrass. Collier & Waycott (2014) also found that interactive light effects were most relevant to shallow water seagrass communities, with variable water quality, and therefore concluded that seagrasses in turbid water (with lower light) will likely be more impacted by high temperatures than those in clear water with high light. This highlights that dredging operations should consider if temperatures are outside of seagrass species thermal optimum (T_{opt}; Table 5) to avoid potential compounding effects of reduced light and temperature. When undertaking EIA for dredging we recommend applying more conservative light thresholds during a marine heatwave. Project 2.2 will undertake a cumulative impact study for heatwaves and light over duration to give greater confidence in recommendations for *P. sinuosa* in Cockburn Sound.

7 Knowledge Gaps and Recommendations

7.1 Knowledge Gaps

Through interrogation of available data in this review, a number of important knowledge gaps have emerged. Further investment in these areas will improve certainty around the recommended management thresholds and guidelines.

Light

- The influence of timing of pressure has only been investigated for a few species. EIA would benefit from seagrass light thresholds being generated at multiple times of year for the majority of species*;*
- There is limited data on the recovery times following impact, especially for opportunistic and colonising seagrass species so further work in this area would be beneficial; and
- The cumulative impacts of other environmental conditions or pressures on light thresholds and recovery from these cumulative impacts has not been assessed (e.g. sediment burial, temperature, salinity) so further research in this area is justified.

Sedimentation and Burial

- Limited studies have assessed recovery time from the impact of sediment burial;
- No studies on temperate species have looked at the effect of sediment quality (e.g. organic matter) on burial thresholds; and
- Field data from dredging operations that accurately characterise the burial pressure field for seagrasses is lacking.

Temperature

- No studies have assessed thermal optima for seagrasses in WA; and
- There is limited understanding of how marine heatwaves may impact on light and/or burial thresholds for dredging.

7.2 Recommendations for prioritising research experiments relevant for WAMSI Westport

Impact prediction and management of seagrasses for the Westport project would be improved by (order of suggestion is not reflective of priority):

- Investigating direct measurements of burial level, duration and recovery associated with dredging, including sediment quality (only one species has been assessed locally);
- Temperature threshold studies under treatments that simulate temperatures that could emerge under future climate warming and marine heatwaves incorporating multiple species; and,
- Threshold studies that incorporate multiple pressures and more accurately reflect the current context of local and global stressors (i.e. burial, light and temperature).

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9 Appendices

9.1 Appendix 1

Table A1 Summary of consultation with experts in dredging (see Section 5), EIA&M and seagrass responses to dredging pressures including representatives from industry including environmental consultants, government and scientists. This consultation was to help identify knowledge gaps in EIA&M, inform the direction and design of experiments in Project 2.2 and to ensure the outcomes were relevant to end-users.

Le Provost Environmental	O_2 Marine	BMT	Catherine Collier	Ray Masini	RPS	Ade Lambo	Paul Erftemeijer
Experience of experts who were consulted							
Significant experience with EIA for dredging. Worked on Geraldton Port project in 2000's, monitoring of effects of lime sand dredging on Success bank seagrasses. He has also been a member of the EPA's Stakeholder Advisory Panel for the current EPA Technical Guidance for Environmental Impact Assessment of Dredging Proposals. with EIA for dredging and seagrass.	Significant experience with EIA for dredging and seagrass. More experience in tropical ecosystems in the past 5 years. Contributed to synthesising outcomes of WAMSI Dredging Science node into policy and management guidance.	Extensive experience with EIA and management plans for dredging and coastal development projects where seagrasses are a sensitive receptor in both tropical and temperate systems. Long history of working in Perth Waters.	Scientist at JCU who conducts research to understand thresholds and resilience of seagrasses to anthropogenic pressures and translates this into management guidance. Conducted PhD research on light thresholds for *Posidonia sinuosa* in Cockburn Sound and is an expert in experimental and ecophysiological research.	Retired Lead of the Marine Branch from the EPA. Led development of existing WA State Government policy on Dredging Management and was the Policy Lead for the WAMSI Dredging Science node. Extensive experience at the nexus of government, industry, and research.	Experience with EIA and management plans for dredging and coastal development projects where seagrasses are a sensitive receptor, most recently in the Southwest temperate region and NT.	Involved in Geraldton Port project and other EIA's looking at dredging related pressures on seagrasses, generally in the tropical region.	Global expertise in dredging management and seagrass. Industry and academic background, with expertise in seagrasses and dredging impacts.
Knowledge gaps: from the work that you have done in the last 5-10 years have you found any knowledge gaps that have limited your confidence in making predictions on the potential impacts from dredging or in developing EIA&M plans, particularly in temperate waters?							
	• Good understanding of light thresholds for temperate seagrasses especially *Posidonia* and *Amphibolis.* • Key gap are thresholds for burial by sediment.	• Sediment type – specifically the particle size distribution (PSD) & the % of biologically available carbon. • Heat waves, specifically how they may affect the light requirements and response to burial.	• An understanding of biogeochemical processes in sediments being deposited and how light reduction affects the biochemical effects and feedbacks. *P. sinuosa* has a huge dependency on below ground structure.	• Original primary loss of seagrass in Cockburn Sound not just light also epiphytes. A key knowledge gap is epiphytic loads. • Focus on getting data outcomes for both construction and	• Seedbanks: underpins assessment of recovery potential of ephemeral species. Would be good to have knowledge surrounding	• From an industry perspective, understanding the actual pressure (behaviour of the plume) is important. • Incorporating ecological windows (opportunities for	• Duration of dredging plume is not necessarily a permanent stress, and therefore duration is a knowledge gap. • Cumulative light statistics. • How quickly can seagrasses replenish

	• Uncertainty about predictions with an added pressure of warming and heat wave events, and it would be very beneficial to be able to predict and manage with more confidence under these multiple potential pressures.	• What is really needed for these pressures is an understanding of the Duration and Intensity or Magnitude of the pressure (D x I) and if this varies at different times of the year (D x I x T). • Responses to dredging pressures may vary over a depth gradient, and if different thresholds are needed at different depths. • For light reduction there is a good understanding of D x I for *Amphibolis* and *Posidonia* informed by experiments • For burial the key gap is in understanding the effect of duration. For example, how long does it take for a response to occur with burial, does this response magnify or increase the longer the plant is buried for. • Does the burial response vary at different times of year? • It is not well known in a dredge development setting how long the sediments that are deposited on the seagrass habitat actually stay there for. It is an assumption that once they are there, they stay there.	• There is limited understanding surrounding low-end tipping point of seagrasses. Measure biomass/shoot counts more regularly at an earlier stage. (i.e., at what point do the plants start shedding leaves).	operation phased of the dredging project. For the operational phase seagrasses in 5-6m water depths are most relevant (Kwinana Shelf).	persistence of seedbanks. • Different burial rates depending on sediment particle types. Common assumption that at low sedimentation rate seagrasses will be able to cope with loading, but important to understand relationship between sedimentation rate, particle types, and survival. • Depending on how deep you dredge you can make changes to the wave climates. Look into hydrodynamics (change in sediment etc) and flushing rates.	respite) provides a level of resilience. Models do not take this into consideration and the thresholds generally do not either. • Sediment quality and affecting contaminants (hard to build into model but needs to be assessed).	their reserves? Dredging can occur over multiple years over periods of differing conditions. • Synergistic pressures. • Recruitment/young seedlings, do they respond the same as mature seagrass plants.

Current experimental approach: do you think the broad experimental approach presented in the 2.2 plan is appropriate or is there a different approach you would consider or suggest?							
• Good approach. *Posidonia* is the major habitat species closest to where the dredging is going to be taking place (cost effective research). • Prolonged light attenuation of ~ 100% shading was the main cause of Amphibolis seagrass biomass loss from the Geraldton Port Enhancement project 2001-2003. Recommended we do a 100% shading treatment over various time periods, and monitor recovery period post shading, for Posidonia sp.		• Overall, we see burial intensity (depth) and duration as a priority including the link with sediment quality and the interactions of burial and light reduction with heat waves. • The heat wave component will be valuable for developments into the future as heat waves and warming is increasing on the WA coast.	• For Posidonia invest time into what is happening below ground. • Chemical processes in the sediment effects redox potential / changes in organic matter/nutrients. In ignoring these aspects there is a risk of misinterpretation of how treatments will affect the seagrass. Mesocosm bias: could be worse in mesocosm (missing ecological processes- bioturbation etc.), Potentially can clean site sand. • Increasing the range (amount) of physiology curves would be beneficial for modelling. Push out to 5 temperatures/points rath then 3 points. • Doing quite a lot of different experiments- with a lot of combinations/treatments. Might be better to scale it back and focus on the key points to get more replication.	• When in the field opportunistically look at other things (e.g., bivalves growing and survival) • Measure the settling of epiphytes on the shade cloth for field experiment. • For field experiment have a plot where epiphytes are cleaned off the leaves to mimic water quality/nutrient loading. • Use dredging sediment for mesocosm burial application.	• In-depth approach • Could consider other seagrass species depending on time	• In-depth experiments	• Collect pre carbohydrate measure before experiments start. • Reproductive output per unit area. What happens when you subject that unit of area to dredging, how does that affect sexual reproduction? This could be answered in part by the field experiment.
Biological response variables: what are the biological response variables that you incorporate into management plans?							
• There were seagrass plots that were monitored ~ every two months for shoot density & biomass (Geraldton Port 2002).		• For assessing permanent loss generally use spatial extent. • For assessing response to dredging the sublethal measures, generally shoot or cluster density depending on the			• Seagrass shoot counts • Epiphyte load • Recovery time	• Shoot density • Percent Cover	• Work by peers in Monaco used seagrass percent cover and shoot density.

		species is utilised. For *Posidonia* it is usually shoot density with leaf length and epiphyte loading that is often also recorded. For *Amphibolis* it is leaves per shoot or clusters per stem. • Other more detailed sublethal measures likes chlorophyll, carbohydrates and growth are generally not used because they are expensive and time consuming.					
Seagrass species: what are the main species you have used for setting thresholds?							
Posidonia and *Amphibolis* (Geraldton Port 2002).		• *Posidonia sinuosa*, *Posidonia australis* and *Amphibolis antarctica*. • There is limited information on *Posidonia angustifolia* and this is more common as you move south of Perth. So would be good to get some relevant information on this species. Other common species with limited information are *Zostera/Heterozostera*.			• Depends on location. • *Posidonia* has generally been the key species of concern. • *Amphibolis* • *Heterozostera* & *Halophila*	Augusta WA: *Posidonia spp*	All temperate species-work in Adelaide Coastal (SA Waters).
Environmental response variable: what are the environmental pressure variables that you incorporate into EIA & management plans?							
• In 2002 there was not a lot of information. Used turbidity/NTU. • There were not light irradiation/saturation thresholds to use.		• Varies depending on the project. • The environmental pressure values for light can be based on the light attenuation coefficient (LAC), total suspended solids (TSS mg/L), turbidity (NTU) or benthic light (mol m^{-2} d^{-1},			• Typically measure PAR, NTU, TSS in the field. • Threshold for TSS is generally mg/L for the modelling (models don't use PAR).	• Almost been entirely TSS and NTU (benthic light availability). • Light availability at the seabed through PAR sensors (coupling that with understanding with NTU and TSS).	• Habitat suitability as a proxy for light (uses a suite of conditions to determine if a location is suitable for seagrasses). • Light availability; Light attenuation by epiphytes, %SI, PAR. • Temperature

		hours of saturating irradiance). • Conversions between the different variables, especially NTU, TSS and LAC are based on site-specific details such as PSD of dredged material. • It is important in the experiment to measure light as mol m^{-2} d^{-1} as this is what the habitat is responding to. Then conversions can be made to include in the hydrodynamic and particle transport models.			• Get relationship between turbidity and light reduction. • Relationship between particle size to relate to TSS because modelling is TSS, but measurements in the field and thresholds are generally PAR. • Sedimentation rates.	• Sediment in the area to get the relationship between sediment, NTU and TSS. • Light is easier to measure and proxy or sometimes as baseline studies TSS and NTU are measured. • Sedimentation (sediment traps) quite heavily measured in NW region (although mostly driven by coral communities).	• Salinity • Substrate • Bottom orbital velocity • Wave exposure • NTU meter • TSS (but not for seagrasses, generally for corals and epiphytes).
Predicted modelling: what were the outcomes of the modelling for burial/light reduction?							
Model predicted sediment transport in TSS using fine sand as the anticipated dredged sediment size, and two years met-ocean data. Dredged sediment data proved to be too coarse because cutting into limestone produced fine silt. In addition**,** Champion Bay experienced a prolonged period of calm weather during the project which reduced flushing rate in the bay. Hence silt accumulated like a blanket over the seafloor in the basin of the bay causing 3-5 months of moderate to high light attenuation.					• Burial: generally only mortality impact in the dredging spoil ground. • Light attenuation/ TSS generally the issue at sublethal levels. • Model validity limited to the strength of the input data.		• Generally speaking, dependent on the quality of the data input (bathymetry, geotechnical information). Clarity surrounding scenario of what the model should replicate, formulation of the thresholds based on scientific literature and how the model uses these thresholds.

Management: did you have a management plan in place?							
• Based on turbidity levels. There were seagrass plots that were monitored ~every two months for shoot density & biomass. • Because a lot of the light meters were not on the sea floor (light sensors were placed mid-water column on channel markers), and therefore did not pick up high turbidity levels at the seafloor.					• Dredge and spoil disposal management plans. • Planning around period of natural high turbidity (based on baseline data).	• WQ in dredge area as well as reference sites. • Plume tracking via satellite imagery. • Adaptive management form WQ data and satellite imagery, where there is an exceedance monitoring elevates to next level: monitor benthic habitat. • Benthic habitat (depending on pressures). • Modifications to design of infrastructure can occur. • Teered approach. Monitor activity, and if there was a trigger then an adaptive management program would be adhered to (dredge can change overflow and area etc).	• Adelaide work for temperate species: Low light during winter season- seagrass protection by limiting dredging during storms (cause of high turbidity).
Recovery							
• After completion of the project, Seagrasses were monitored by CSIRO and shown to have recovered within 5 years (which is within the ZoMI).					Rarely monitored effectively (for long enough).		• Adelaide work: lag time between conditions improving and seagrass recovery large enough to be caught in remote sensing data. • Map survey showed large scale recovery once environmental

							conditions improve ~5 years.
Recommendations							
	• WAMSI Westport program to follow the terminology and structure used in the Dredging Guidance document (E.g., biological or environmental thresholds at the different zones; ZoI, ZoMI, ZoHI). • Ideally the Westport project will deliver similar outcomes to the tropical WAMSI dredging node.	• Identified a number of large-scale programs that assessed dredging related pressures in temperate seagrasses, specifically in Cockburn Sound and Owen Anchorage and nearby waters. The programs developed a range of pressure and biological response thresholds for temperate seagrasses and would be worth getting copies of the EIA documents and Management plans to ensure that the design of the WAMSI Westport 2.2 experiments create realistic and relevant treatments. • EIA process requires delineating zones of High, Moderate, Influence and No impact. Therefore, any research outputs need to inform in this structure. Boundaries of these zones need thresholds for the environmental pressures and biological response thresholds.			Recommend drafting threshold values, recovery times that can be peer-reviewed and used to update regulatory guidance.	Recommend that the data from the Westport project are put into tables that are relevant to EIA processes.	• Undertake a literature review and consider differences in locations, species (genus), durations over which seagrasses can tolerate sub-optimal conditions. • Data to be useful for the end-user, intended to be applied for dredging campaign. • Recommend - Seagrass Watch approach: canopy height, community composition, few biomass samples, epiphyte cover. • Early warning indicator, can you attribute it to the dredging? Intensive research effort for this. Also is it just a physiological adjustment.
Other/comments							
• If cutter suction dredge needs to be used in Cockburn sound it will produce large amounts of silt				• Owen anchorage is not a key issue, key issue is around Westport/Kwinana shelf.	• Over the period of dredging do you change the nature of the sediment (oxygen transfer	• There was extensive *H. ovalis* (ephemeral species) meadows during Inpex	

like at Geraldton. Trailer hopper dredge like the one used by Cockburn Cement to dredge lime sands do not produce large or persistent plumes. • Geraldton Port dredging project saw Amphibolis suffer loss of biomass but has since recovered within 5 years. Posidonia did not seem to be affected.				• SLIP locate has detailed imager for Kwinana Shelf. • Look for synergies with other Westport themes. • Generally, in agreeance with BMT comments.	through sediment, redox continuity), which can have an effect on seagrass health as well as prevent/ or prolong recovery potential and result in changes in seagrass habitat.	monitoring that had seasonal changes in cover. Confounding from an impact assessment perspective.	

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