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Current state of knowledge regarding the effects of dredging-related ‘pressure’ on seagrasses: Report of Theme 5 - Project 5.1.1 prepared for the Dredging Science Node

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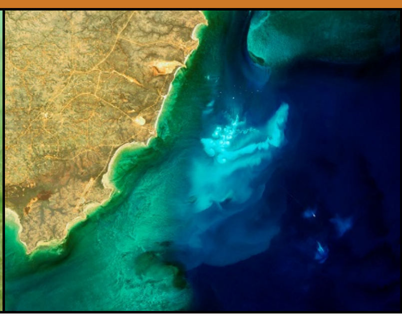


WAMSI Dredging Science Node

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

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

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

Funding and critical data **Critical data**

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Front cover images (L-R)

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

Image 2: Many filter feeders are associated with seagrass beds like this ascidian feeding on the plankton in surrounding waters. (Source: Kathryn McMahon)

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

Image 4: Tropical seagrasses are important habitats for marine turtles including the loggerhead turtle that feeds on fauna associated with seagrass beds such as ascidians, clams, mussels and other invertebrates. (Source: Kevin Crane)

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Executive Summary

This review summarises our understanding, from a north west of Western Australia (NWWA) and global perspective, the pressures seagrasses are exposed to from dredging, their tolerance thresholds and responses to dredging related stressors, and the bioindicators of dredging related stressors. From this information, we also identified gaps in our knowledge and areas where environmental management and monitoring approaches could be improved.

For this review we used information compiled by the WAMSI Dredging Science Node, which included unpublished data from industry, as well as published reports, articles and books.

Dredging related pressures to seagrass

We identified five dredging related stressors that are likely to directly impact seagrass habitat and of these we prioritise three (the top 3 in the following list) that are of most interest for impact prediction and management of dredging events, as they are likely to affect the greatest number of life-history stages and processes of seagrass:

- reduced benthic light quantity;
- burial by sediment;
- sediment anoxia and increased hydrogen sulfide production;
- altered benthic light quality (i.e. spectral characteristics); and
- increased suspended sediment.

Light reduction

The effects of dredging on light quantity were assessed using the Gorgon dredging project as a case-study. Around Barrow Island, a site known to support seagrass, total daily light ranged from around 3 mols m^{-2} d^{-1} in June and July to a maximum of 11 mols m^{-2} d^{-1} in December. The light climate, particularly from August to December, and April, would support tropical seagrass species. The potential drivers of natural variation in benthic light intensity are numerous, and include water depth, day length, tidal range, wind speed and direction and cloud cover. For sites around Barrow Island the best predictor of total daily light were day length, wind speed, the interaction between wind speed and direction, and the interaction between day length and direction.

Dredging associated with the Gorgon Project significantly reduced the quantity of benthic light. Around Barrow Island, background levels showed intra-annual variation, with maxima recorded from September to December and minima from June to August. During periods of dredging, there was a reduction of up to 65% relative to pre-dredging conditions at comparable times of year. The greatest reductions occurred from October to December where the deficit in benthic light relative to background conditions at a similar time of year were up to 6 mol m^{-2} d^{-1}. The magnitude of light reductions decreased with distance from the dredge; a reduction of 29% was apparent up to 9 km from the dredge. The duration of reduced light conditions ranged between one and six months, depending on the distance from the dredge. The magnitude of light reductions were not consistent throughout the year.

Burial by sediment

The effects of dredging on burial were assessed through three case studies: Rio Tinto Cape Lambert, Woodside Pluto and Chevron Gorgon Projects. The first two case studies had pre- and during-dredging data, whilst the last only had during dredging data. There are no direct measurements of the processes of sediment deposition and resuspension on the sea floor, which lead to burial. In the absence of direct measurements, we estimated burial rates from sediment trap data. We acknowledge that this approach, and the data, have significant limitations, but it is a common approach in the absence of direct measurements. The burial rates presented here need to be interpreted with caution and probably represent the gross sediment burial depth rather than the net depth, which would be the sum of deposition and removal through resuspension (which does not occur in sediment traps). Similarly, it is not clear if sediment deposited in the traps arrived at a constant rate over the deployment period or in discreet events. The burial rates reported would require prolonged periods with no resuspension of sediments. The data prior to dredging showed large variations among sites in the burial rates, with average burial rates at the sites ranging from 0.03 mm d^{-1} to 3.6 mm d^{-1}. The estimated burial rates increased at most sites during dredging, by 2.3–13 fold depending on the site. During dredging, the estimated average burial rates at sites within the predicted Zones of High or Moderate Impact were 0.07–2.79 mm d^{-1}, with maxima of 0.42–18.5 mm d^{-1}. Burial rates were much higher at Cape Lambert compared to Pluto and Gorgon.

Information gaps

The biggest gaps in our knowledge for understanding changes in the environmental variables relevant to seagrasses with dredging is the lack of understanding on burial depths, and the temporal dynamics of sediment deposition and resuspension. In addition, a good understanding of background conditions for both light and sediment burial is important to understand the significance of dredging induced changes, particularly considering the large variability in background light and sediment burial rates.

Seagrass tolerance thresholds to dredging-related stressors

Our understanding of thresholds for dredging related stressors is poor. Only 4 of the 11 seagrass species from NWWA have had light thresholds developed for adult plants, and 7 out of 11 have sediment burial thresholds. These were all developed from studies outside of WA. Even fewer species have had these thresholds developed for juvenile plants (seedlings) and other key life-history processes such as flowering.

There is a range in the threshold for dredging related stressors for a single species, potentially due to location and the environmental conditions they are growing under. For this reason, locally-derived thresholds for NWWA are needed to improve our confidence in the thresholds which should be applied. In addition, due to the lack of local-derived thresholds for adult plants and for different life-history stages and processes, very little is known of how threshold may change when seagrasses are exposed to multiple stressors, such as light reduction and sediment burial.

Will dredging-generated pressure fields in NWWA impact seagrass?

Using the known seagrass thresholds of tolerance for light reduction and sediment burial together with the light reductions and sediment burial stresses measured or estimated during dredging projects, we assessed whether dredging is likely to significantly affect seagrasses in NWWA.

Data for a site 10 km distant from the Gorgon dredging project were compared against light thresholds for two local seagrass species, *Halodule uninervis* and *Halophila ovalis*. This site was used as seagrass habitat has been observed at this site, so it is a relevant comparison and there were dredging related impacts to benthic light. During periods of dredging, the thresholds were exceeded at this site for both species. However, the same thresholds were exceeded in non-dredging periods but the frequency of exceedances was 2–3 fold higher during dredging periods. Therefore, if Halophila or Halodule seagrass were present, they would likely have been impacted.

For burial stress we estimated how many days it would take to result in a 50% mortality rate. Based on the range of averages across sites for the estimated burial rates at the Cape Lambert dredging project, we estimated that it would take 7–71 days to exceed a burial threshold of 2 cm at average sediment burial rates; or 1-14 days with the maximum estimated burial rate. This is within the range of the duration of dredging programs and so it appears feasible that impacts to seagrasses could occur. However, at other locations 2 cm of burial would require 34–105 days to manifest at average sediment burial rates, or 16–18 days based on the maximum rates. Although these periods fit within the duration of dredging programs, it less clear if these average rates would persist those periods of time.

Therefore based on the burial rate estimates from NWWA industry data, impacts to seagrass from burial are theoretically possible but due to the uncertainties associated with the estimate burial rates and the absence of information on *in situ* sediment deposition rates, there is a significant level of uncertainty regarding burial rates.

Bioindicators for monitoring

Bioindicators for light stress are reasonably well-understood, but our understanding of bioindicators for sediment burial is limited. Despite this, there are a few variables that respond in a similar manner for both stressors (leaf growth, shoot mortality, shoot density) and others that are specific to particular stressors e.g. vertical internode length for burial stress or photosynthetic variables such as maximum electron transport rate for light reduction stress. More research is required to understand the effect of combined stressors on seagrass responses and bioindicators.

Considerations for predicting and managing the impacts of dredging

Assessing seagrass habitat

- Impact prediction would be assisted by the development of guidance on what constitutes significant seagrass habitat and the most appropriate methods, including timing, for detecting seagrass habitat, particularly in turbid waters where seagrass species are very small and temporally variable.
- Some areas of seagrass habitat have been mapped multiple times but because this was done by different proponents these valuable time-series data are not available. Where the same areas have been mapped multiple times there would be benefits in collating the different data sets to create a time-series, which could provide an indication of potential seagrass habitat, particularly for annual or transitory communities.

Predicting dredging impacts in seagrass habitat

- There are limited data on the light conditions required for seagrass growth and even more limited data on likely sedimentation rates and sediment burial depths. Without understanding the natural dynamics and changes due to events such as cyclones it is difficult to predict the added potential stressors from dredging. Thorough analysis of consistently collected, continuous long-term data is essential to improve our confidence in these patterns.
- The intra-annual patterns in benthic light do not appear to be consistent across NWWA, so predictions in one area will not necessarily hold in another. The amount of, and variation in, benthic light appears to be determined by multiple factors which can vary among locations. It is important to collect local data to confirm the background conditions.
- Timing of dredging related stress is an important consideration, as there are particular times of year when dredging impact on seagrasses and seagrass habitat could be minimal, though these times may vary among locations (see previous point).

Threshold development

- Few dredging projects have developed thresholds specifically for seagrasses. Those that have, tend to focus on turbidity and TSS, which are not the most relevant stressors when predicting impacts on seagrass. Impact prediction would benefit from the provision of guidance on threshold development, focusing on relevant stressors for monitoring and managing seagrass habitat, such as total daily light (mol m^{-2} d^{-1}), light attenuation coefficient (LAC m^{-1}) with water depth, and sediment fluxes (re-suspension and deposition) including net depth of burial over time.
- For populations or species where sexual reproduction is important for the maintenance of the population, thresholds relevant to sexual reproduction and seedling establishment should be considered. For areas of very high impact (e.g. Zone of High Impact (EPA 2016)) criteria could be developed where there is mortality and recovery in 5 years versus mortality and no recovery.

Impacts of dredging on light quantity in NWWA

- Based on limited case study data for NWWA, the total daily benthic light (mol m^{-2} d^{-1}) is highly variable at dredging locations. Despite this, the presence of dredging and the distance from the dredge are significant predictors of total daily light, along with the background environmental conditions. Light is reduced with dredging, and the magnitude of this reduction declines with distance from the dredge.
- The effects of dredging on total daily benthic light were observed over 9 km from the dredge, in a site that was designated as a reference site, further confirmed by Evans et al. (2012) whose plume modelling showed dispersal further south from the dredge than predicted and reaching the reference site. Where the thresholds for compliance monitoring are based solely on comparisons against reference conditions at the time of monitoring, serious flaws will occur if the reference site is impacted. It is recommended that compliance monitoring includes assessment of reference sites relative to background conditions, to confirm the validity of the reference sites.
- Total daily benthic light is significantly reduced with dredging, up to 65% (on average), within 1 km of the dredge in one case study. The magnitude of reduction declines with distance from the dredge, but in that same case study there was a 29% reduction up to 9.4 km away. There was also a high frequency of reduced light: within 1 km of the dredge, over 93% of the observations were below the median of the background period; at 9.4 km away 75% of the observations were below the median of the background period. The duration of time light was reduced (i.e. the number of consecutive days that light was below the 20th percentile of the background period) was 185 days within 200 m of the dredge and 78 days 9.4 km from the dredge. These reductions are outside of the known tolerance thresholds of seagrass species found NWWA and impacts are therefore likely, if the known tolerance thresholds apply in this region.
- The impact of dredging varied temporally, due to the interaction of dredging activity and environmental conditions. The decline in benthic light due to dredging, relative to reference conditions, was greatest in October-December at most sites, reduced by up to 6 mol m^{-2} d^{-1}. This is the time that under background conditions the maximum daily light was observed. From the limited data available for NWWA, this appears to be a time of rapid growth and reproduction for seagrasses, so declines at this time are likely to have a large impact on seagrass. Due to lack of data, the patterns from January to March are not known.

Impacts of dredging on sedimentation and burial in NWWA

- The information on burial depth is more limited than light data and due to the method of collection and time-scale of collection should be interpreted with caution.
- Under non-dredging conditions, the estimated burial rates varied among sites from an average of 0.02–0.04 mm d^{-1} up to 1.2–1.7 mm d^{-1}. During dredging they ranged from a site average of 0.35–0.51 mm d^{-1} to 1.3–1.8 mm d^{-1}.
- The maximum estimated burial rate in the commercial operations for which we have data was 5 mm d^{-1}.
- Based on these estimated burial rates, and the known thresholds of tolerance for seagrasses to burial (for NWWA species but derived from other locations), it is theoretically possible that some seagrasses would be impacted (defined by a 50% shoot mortality) within 2–7 days at the estimated maximum and average burial rates, respectively. The more resilient species could theoretically be impacted after about 29 days at the average rate, and about 4 days at the maximum rate. These time periods are within the timeframe of most dredging operations. Whether these theoretical burial pressures would be realised remains uncertain given the absence of field data on net sediment deposition. However, given the considerable concerns regarding estimates based on sediment trap data, they should be treated with caution and viewed as extreme possibilities.

Residual Knowledge Gaps

Dredging effects on environmental conditions that are likely to impact seagrass.

- There is an absence of data on changes in sediment burial depths and the frequency and duration of sediment deposition and resuspension with dredging, in both the near and far-field dredging sediment plumes.
- There is an absence of data on changes in sediment biogeochemistry associated with dredging-induced sediment deposition, especially oxygen concentrations, which can potentially impact seagrasses.
- There is an absence of data on changes to benthic light quality associated with dredging, which may impact seagrasses.
- There are limited data on the background variation in dredging-related stressors, which could help inform the best timing for dredging and better differentiate existing water quality dynamics from dredging-induced changes.

Thresholds for dredging-related stressors

- There is an absence of locally-derived thresholds (light reduction and sediment burial) for NW adult Australian seagrasses.
- There is an absence of thresholds (light reduction and sediment burial) related to other life-history stages such as seedlings.
- The frequency of sediment deposition and removal (through resuspension) may be an important component to incorporate into burial thresholds but there is currently little information on these processes.
- There is no understanding of how thresholds may vary when seagrasses are exposed to multiple stressors such as burial and light reduction, or with changes in other environmental factors such as temperature.

Monitoring during dredging campaigns

- There is a poor understanding of bioindicators for impacts due to sediment burial.
- There is a poor understanding of potential bioindicators for seagrasses exposed to multiple stressors such as light reduction and sediment burial.

1 Introduction

There is a general understanding of how primary producers will respond to the environmental changes produced by dredging (Erftemeijer & Lewis 2006). However, this generalisation is based on a small number of species, and as seagrasses are a biological group with a range of life-history strategies and potentials to resist and recover from disturbance, the magnitude, duration and frequency of stress they can cope with and recover from will vary among species (Kilminster et al. 2015, McMahon et al. 2017). At present, we have almost no knowledge of how species of primary producers in the NW of Australia will respond to the environmental changes produced by dredging. Consequently, it is difficult to predict and then manage the impacts of dredging on these critical habitats with an acceptable level of certainty.

For benthic primary producer habitat (BPPH), the main pressures exerted by dredging are the associated reductions in light availability, and the smothering of benthic primary producers when resuspended sediments settle on the seabed (Erftemeijer & Lewis 2006). The current framework for assessing the impact of proposed infrastructure developments requires proponents to predict the pressure fields their dredging activities will produce and then predict the biological response to these pressure fields (EPA 2016). If a project is approved, then proponents are generally required to implement environmental monitoring programs to inform management of the dredging activities to minimize impacts and determine compliance with legally binding environmental impact limits established through approval conditions. Environmental monitoring should also aim to generate data with which to validate impact predictions made at the assessment stage. To meet these requirements, it is necessary to:

- predict responses (both lethal and sub-lethal): this requires a sound understanding of the thresholds of tolerance of the various habitats to the pressures generated;
- predict the persistence of those effects: requiring an understanding of the ability of the habitat to recover following particular severities and durations of pressure; and
- monitor and manage impacts and validate predictions: requiring a management framework that includes robust monitoring protocols. To develop these monitoring protocols, it is necessary to understand which variables to monitor, and how changes in those variables should be interpreted regarding the current and projected state of the habitat.

Despite the long-term and widespread nature of dredging, there is surprisingly little convincing information in the scientific literature that can be used to meet the information requirements outlined above. For some primary producer habitats and species, some of the above information needs are partially addressed (e.g. Erftemeijer & Lewis 2006), but local case-studies are very rare (WAMSI Project 5.1.2 (McMahon et al. 2017)). Where there is relevant information, this has focused largely on the light-reduction impacts associated with dredging and there is extremely limited information on the effects of sediment burial from a dredging context. For sub-tropical and tropical primary producer habitats in Western Australia, there is no consolidated body of knowledge on either light reduction or burial effects that can be applied in an impact prediction or management framework.

This review summarises the current state of knowledge regarding the nature of the pressures that dredging imposes on seagrasses in NWWA. The review focuses on seagrass species following the recommendations of WAMSI DSN Project 5.1.2 (McMahon et al. 2017). The primary purpose of this review is to determine the levels of stress (light reduction/sediment deposition) that occur under dredging conditions and evaluate the likely effect of these levels of pressure based on the existing seagrass literature, considering the range of variability and environmental quality conditions associated with dredging programs in WA. It sets the baseline on which experimental studies will build.

The review is divided into the following sections:

- dredging-related pressures to seagrass habitat, with case-studies in NWWA;
- thresholds developed for seagrass habitat in relation to dredging-related pressures;
- comparing dredging induced changes from NWWA case-studies with thresholds to assess whether the type of impacts from dredging are likely to impact seagrass habitat;
- bioindicators developed for seagrass habitat in relation to dredging-related pressures; and
- summary of impact prediction, monitoring and management approaches of NWWA seagrass habitat with dredging.

2 Dredging-related pressures for seagrasses

This section provides an overview of the key physical and chemical conditions that are likely to be affected by dredging, and identifies those of most interest for management of seagrass habitat. The focus is on the indirect effects of dredging, specifically the effects of plumes from dredging and dredge material placement, not the direct effects of habitat removal and habitat modification, or the effects due to changes in toxicants. It also presents data on the magnitude, duration and frequency of dredging-related pressures that have been measured in NWWA, from the Chevron Gorgon Project (EPA 2009), the Rio Tinto Cape Lambert Project (EPA 2010) and the Woodside Pluto Project (EPA 2007). Because seagrass habitat was not considered in the monitoring programs of these projects either because it was not identified in the zone of influence or it was considered likely to recover so was not included in the assessment, the data do not necessarily reflect conditions that seagrass habitat has been exposed to, but do reflect the potential water quality effects from dredging.

2.1 Defining pressure fields and stressors

A number of physical and chemical conditions and processes are likely to be affected by dredging (Table 1). These include: increased concentrations of suspended sediments, increased rates of sedimentation, changes in sediment deposition and resuspension dynamics, reductions in light availability and changes in light quality, all of which attenuate with distance from the dredging activity (PIANC 2011). The changes in water quality conditions (i.e. light quantity, quality and sediment deposition) resulting from dredging are dependent on a number of factors, including: dredge type, mode of operation e.g. overflow and depth of water it is operating in; the duration and frequency of dredging; the type of sediment including factors, such as size distribution, concentration and volume; and the hydrodynamic and weather conditions during dredging (PIANC 2011).

Table 1: Key physical and chemical conditions and processes that could change during a dredging operation (Adapted from PIANC 2011). Bold text indicates the physical and chemical conditions which when changed could act as stressors to seagrass habitat.

Conditions	Predicted response	Processes	Predicted response
Light quantity	↓	Hydrodynamics	Alter
Light quality	Alter	Particle transport	Alter
Turbidity	↑	Particle aggregation	Alter
Suspended sediments	↑		
Sedimentation & burial	↑		
Resuspension	↑		
Sediment type	Alter		
Sediment particle size	Alter		
Nutrients	Alter		
Organic matter	Alter		
Toxicants	↑		
Oxygen	↓		
Sediment redox potential	Alter		
pH	Alter		

2.1.1 Stressors to seagrass habitat and life-history stages and processes

Potential impacts to seagrasses from dredging related stressors can manifest at different life-history stages or processes during the life-cycle (McMahon et al. 2013). There are a number of different life-history stages of seagrass (adult plants, pollen, seeds, seedlings) and biological processes (adult plant survival, flowering, pollination, fruit and seed development, seed germination, seedling survival) essential to the maintenance of seagrasses (Ralph et al. 2006). Dredging-induced changes in physical and chemical conditions are not likely to affect these different life-history stages and processes in the same way (Rollon et al. 2003). We identify five environmental conditions that can alter with dredging (PIANC 2011), and assess whether: 1) the stressors are known to impact seagrasses (i.e. we have direct evidence of this); 2) there is no evidence of impact to seagrasses but it is biologically plausible; and 3) there is no evidence of impact and no evidence to support a biologically plausible cause-effect pathway (Table 2). The five stressors are:

- reduced benthic light quantity, which is influenced by the turbidity, suspended sediments, resuspension of deposited sediment plumes and the nature of the sediment particles;
- altered benthic light quality (i.e. spectral characteristics), which is influenced by the turbidity, suspended sediments, resuspension of deposited sediment plumes and the nature of the sediment particles;
- sediment burial, which is influenced by the sediment released by dredging that settles to the bottom and is then mobilised through sediment resuspension and deposition processes. The sediment deposition footprint is dependent on the interaction between the sediment type and particle size, the local hydrodynamics and the trapping capacity of the seagrass bed;
- increased suspended sediment; and
- sediment anoxia and increased hydrogen sulphide production, which is influenced by the sediment type, particle size and organic matter content.

Reduced Benthic Light

This is the most documented and well understood pathway of impact to seagrass. As seagrasses require light to photosynthesise, a reduction in light beyond the minimum light requirement leads to loss in seagrass condition and if this reduction persists over time, eventually mortality (Ralph et al. 2007). But seagrasses do not all respond in the same way, as their light requirements and duration that they can persist with reduced light varies among species (Ralph et al. 2007, McMahon et al. 2013, Kilminster et al. 2015, McMahon et al. 2017). Consequently, from a dredging management perspective, species-specific light criteria are required. There is a well-supported cause-effect pathway for reduced light impacting adult and juvenile plants (seedlings), as well as critical life history processes such as flowering (Ralph et al. 2007, Ochieng et al. 2010, McMahon et al. 2013).

To our knowledge, there is no evidence that reduced light impacts seagrass seed germination, however, it is biologically plausible that reduced light could hinder germination, as light has been identified as a potential cue for germination in some species (McMillan 1988). Finally, we have no evidence, nor consider it biologically plausible that reduced light will impact pollination.

Altered spectral quality

The effects of changes in light quality on seagrasses are poorly understood, highlighting a significant knowledge gap. Only five published studies having investigated the effects of changes in light quality, revealing alterations to branching patterns and internode length in response to shifts in the red:far red ratio (Tomasko 1992, Rose & Durako 1994), no known effects of a green-shift (Mvungi et al. 2012), enhanced germination of seeds under blue light (Soong et al. 2013), and the capacity for seagrasses to acclimate to different light quality conditions (Kahn & Durako 2009). Biologically, it is plausible that altered light quality could be a stressor to seagrasses as different wavelengths have been shown to be important in regulating growth and key life-history processes such as flowering and seedling germination and survival (Cerdán & Chory 2003, Goggin & Steadman 2012). If dredging results in the loss of important spectral wavebands and these processes are impacted it could disrupt the life-cycle of seagrasses. Further, certain wavebands of light are more efficient at stimulating photosynthesis as they are absorbed directly by chlorophyll, particularly between 400–500 nm and 600–700 nm (Lambers et al. 2008). If dredging reduces the most effective wavebands for photosynthesis, growth and survival could be impacted, particularly if the quantity of light is also reduced. Therefore, we predict that it is biologically plausible that alteration of light quality, particularly a loss of wavebands from 400–500 nm and 600–700 nm could impact adult plant survival, flowering, fruit and seed development and seedling germination and survival. In fact, one study has shown that light quality does effect the survival of Thalassia seagrass seeds (Soong et al. 2013). Finally, we have no evidence nor consider it biologically plausible that altered light quality will impact pollination.

Sediment burial

Burial of seagrasses can occur following release of dredged sediment into the water column. Over time, depending on the density and size of the sediment particle and the local hydrodynamics, these suspended particles settle and can potentially bury seagrass. However, under natural conditions there is a regular movement of the sediment bed with sediments resuspending and depositing, and the rate of this movement is dependent on the sediment particle size and density and the bottom velocity and shear stress (Middleton & Southard 1984). Seagrasses are very effective at trapping sediments (Madsen et al. 2001), specifically through reducing resuspension once the particles are within the canopy (Gacia & Duarte 2001). Therefore burial effects can manifest either through the direct settling of sediment particles, or through the secondary resuspension and deposition processes, that over time result in the accumulation of sediment in the seagrass meadow. Exposure of seagrasses to burial stress is a combination of the amount of additional sediment added into the system, the sediment resuspension and deposition rates and the trapping capacity of seagrasses. There is direct evidence that sediment burial can negatively affect seagrass adult plant survival (Cabaco et al. 2008), seed germination (Dagapioso & Uy 2011, Valdemarsen et al. 2011) and seedling survival (Rollon et al. 2003, Dagapioso & Uy 2011, Valdemarsen et al. 2011). These impacts are dependent on the extent (depth) of burial but also the spatial extent of the burial, because buried individuals may be supported by unaffected parts of the plants if they are connected over space (Cabaco et al. 2008, Ooi et al. 2011). It is biologically plausible that burial could also directly affect pollination if the plants are covered by sediment above the level of the flowers, as pollen would not be able to be released into the water column to reach receptive flowers. It is similarly plausible that sediment burial could reduce flowering and seed set, as occurs with when seagrasses are exposed to other stressors such as overgrazing, plants may trade-off investment in sexual reproduction for survival of adult plants and vegetative growth (Lal et al. 2010).

Suspended sediment loads

The direct effects of increased suspended sediment loads on seagrasses is poorly understood, although the negative effects on the light climate which, in turn, impacts seagrasses is clear (Sofonia & Unsworth 2010). To our knowledge there is no evidence of direct impact to seagrasses from increased suspended sediments. However, it is biologically plausible that increased suspended sediments could impact pollination, by smothering the pollen, affecting the stickiness of the receptive flowers or interfering with pollen movement. Pollen grains can regulate buoyancy to maximise pollination and in some species are covered with a mucilaginous slime to assist with attachment to the receptive flower (Verduin & Backhaus 2000, Ackerman 2006). Therefore if suspended sediments attach to the pollen, it may interfere with its movement and ability to attach to receptive female flowers. Furthermore, for small delicate plants such as Halophila, or the delicate flowers and seedlings of most species, an increase in suspended sediments may abrade the surface of the leaf or flowers and reduce function such as seed set, or increase mortality, negatively impacting seedling and adult plant survival or successful flowering and seed set.

Sediment anoxia and hydrogen sulphide production

The sediment matrix that seagrasses grow in can vary with respect to its particle size distribution, type of sediment and amount of organic matter. Seagrasses interact with this matrix, modifying the geochemistry including the oxygen concentration, redox and nutrient cycling (Marba et al. 2006). Usually only the top few millimetres of seagrass sediments are oxygenated, but many seagrass species exude oxygen from their root tips (Penhale & Wetzel 1983, Borum et al. 2006), as an adaptation to survive the toxicants within the deeper anoxic sediments. Dredging can affect the biogeochemistry of sediments by placing an additional layer of sediments on the surface of existing sediments, possibly affecting fluxes of fluids and gases across the sediment-water interface, and hence reducing oxygen concentrations in the sediment. It is not only the amount (Dooley et al. 2013) of sediment but the type of sediment, that can influence the oxygen dynamics, particularly the amount of organic carbon. Higher amounts of organic carbon can deplete oxygen and create more anoxia, through bacterial respiration (Borum et al. 2005). Hydrogen sulphide is commonly produced in the deeper anoxic conditions and highly reducing sediments of seagrass meadows (Borum et al. 2005, Marba et al. 2006). Hydrogen sulphide is toxic to seagrasses and can permeate into underground seagrass roots, and up into shoot meristems causing mortality, particularly when oxygen release from root tips is reduced or stopped. There is evidence that sediment anoxia and increased hydrogen sulphide production can directly impact the survival of adult plants (Borum et al. 2005, Raun & Borum 2013) and seedlings (Dooley et al. 2013). It is biologically plausible that increased rates of hydrogen sulphide production could impact seed germination, as hydrogen sulphide is a phytotoxin but there is no biologically plausible pathway for hydrogen sulphide to directly impact flowering, pollination and seed set.

When comparing all the dredging related stressors, the stressor that impacts the most life-history stages and processes is reduction in light, we have evidence of negative impacts to 4 of the 6 life-history processes, with an additional one which is biologically plausible (Table 2). The second stressor is burial, where we have evidence that it impacts 3 of the 6 life-history processes, but the remaining three are biologically plausible. The third most significant stressor is anoxia and hydrogen sulphide production where we have evidence that it can affect 2 of the 6 life-history processes and it is biologically plausible to impact one other. For the two remaining dredging related stressors, altered light quality and increased suspended sediments, we have no direct evidence that changes induced by dredging will impact seagrasses, but for 4–5 of the life-history processes, it is biologically plausible.

Based on the environmental variables that are likely to change with dredging and directly impact the most life-history stages and processes of seagrasses we recommend prioritising the following variables for understanding the direction, magnitude, frequency and duration of dredging induced changes:

- the benthic light quantity (total daily light);

- sediment burial depths; and
- sediment anoxia and hydrogen sulfide production.

Focussing on how seagrasses respond to dredging-induced changes in these environmental variables will provide the greatest benefit for predicting or improving our understanding of dredging impacts to seagrass. Due to the poor understanding of the changes in benthic light quality that occur with dredging, we cannot reliably prioritise this as an environmental variable that should be measured. However, we can identify it as a priority for research, to assess if changes in light quality impact the population dynamics of seagrasses.

Table 2: Our understanding of how dredging related stressors affect the key life-history stages and processes of seagrasses. Red squares indicate that there is evidence of a negative impact from the stressor, yellow indicates that it is biologically plausible but to our best knowledge has not been demonstrated and black indicates no expected or biologically plausible explanation for an impact.

Dredging related stressor	**Key life-history stages and processes**					
	Adult plant survival	Flowering	Pollination	Fruit & seed development	Seed germination	Seedling survival
Reduced benthic light						
Altered light quality						
Increased sediment burial						
Increased suspended sediments						
Anoxia & increased hydrogen sulfide production						

Key Points

We identified five dredging related stressors that are likely to directly impact seagrass habitat, and of these we prioritise three that are of most interest for impact prediction and management of dredging events, as they are likely to affect the most life-history stages and processes of seagrass:

- benthic light quantity (Total daily benthic light: PPFD, mol m^{-2} d^{-1});
- sediment burial depths including the frequency and duration of sediment deposition and resuspension; and
- sediment anoxia and hydrogen sulfide production rates.

2.1.2 Available data on dredging-related changes to key environmental variables

From the data made available through the WAMSI Dredging Science Node from industry (Jones et al. 2015), it was clear that not all of the important dredging-related stressors for predicting direct impacts to seagrasses have been monitored in past commercial dredging operations or post-dredging compliance monitoring programmes. Therefore it is difficult to summarise the magnitude, duration and frequency of these stressors from dredging operations in NWWA. We summarise below the information we could analyse.

Reduced benthic light

To characterise the impacts from dredging to benthic light quantity the Chevron Gorgon Project (EPA 2009) data was used as this had the most comprehensive pre and during dredging data. Previously, light availability was inferred from turbidity or total suspended solids measurements, which introduces a level of error in the estimation (Sofonia & Unsworth 2010), and a challenge in linking the biological response to the stress field. From a seagrass perspective, it is the total amount of photosynthetically active light (PPFD) that directly affects their growth and survival, and should be an environmental variable of choice for predicting and monitoring impacts to seagrass. We examine the impacts of dredging on benthic light below.

Sediment burial

Sediment deposition rates, estimated from sediment traps were also available to summarise this dredging-related stress from the Chevron Gorgon Project (EPA 2009), the Rio Tinto Cape Lambert Project (EPA 2010) and the Woodside Pluto Project (EPA 2007). However, there were no available data on sediment burial depth, so it had to be estimated from the sediment trap data. Using sediment trap data to estimate sediment deposition rates is not ideal and the shortcoming of traps has been extensively described (Storlazzi et al. 2011, Ridd et al. 2001, Buesseler et al. 2007, Gardner et al. 1983, Gardner, 1980). Benthic sediment traps overestimate the burial depth or rates, as sediment traps capture the settled sediment and it is not allowed to resuspend, and they may also cause more sediment to deposit due to the reduction in water flow created by the trap (Browne et al. 2012). For this reason Storlazzi et al. (2011) suggest that traps, at best, only approximate the amount of sediment that deposits, while others (Buesseler et al., 2007; Gardner, 1980; Gardner et al., 1983) feel they are more useful for describing sediment dynamics than quantifying deposition rates. However, as seagrasses also limit resuspension of sediments due to their sediment trapping capacity (Gacia & Duarte 2001, Madsen et al. 2001), sediment traps may be more appropriate for estimating burial depths for seagrasses, compared to coral habitat which has limited sediment trapping capacity and may include species with the ability to remove sediment (Fabricius 2005). This is of particular relevance when considering not just the direct deposition or settling from plumes, but the resuspension and deposition of these dredging sediments over time (Browne et al. 2012).

Sediment traps usually estimate deposition as mg sediment cm^{-2} d^{-1} (Storlazzi et al. 2011) but many of the thresholds for burial related to seagrasses are expressed as the height of sediment addition (i.e. mm or mm/t (Cabaco et al. 2008)). This highlights a challenge in linking stress fields from dredging directly to the seagrass habitat. Directly measuring and estimating sediment deposition and resuspension is more complex (Browne et al. 2012) and this was identified as a critical information gap in the Woodside Offsets Workshop Research Priorities document (Lavery & McMahon 2009), although new techniques are emerging that are improving on this (e.g. Browne et al. 2012). Notwithstanding the limitations of sediment trap data, we predict the burial stress from dredging on seagrasses, and acknowledge that it is likely an overestimate of the burial that seagrasses are exposed to. However, further research is required to validate this.

Anoxia and increased hydrogen sulphide production rates

There were no available data on sediment anoxia and hydrogen sulphide production rates associated with dredging. Therefore we have not been able to investigate dredging-induced changes in this environmental variable associated with seagrass habitat. This is an area of study that warrants further research.

Altered benthic light quality

There was no available data on benthic light quality associated with dredging. Therefore we have not been able to investigate dredging-induced changes in this environmental variable associated with seagrass habitat. This is an area of study that warrants further research. Light quality measures are often taken during dredging projects for the calibration of remote sensing products, in order to map and characterise the dredging plume distribution and to derive other variables such as total suspended solids, turbidity and benthic light (Evans et al. 2012). There is an opportunity to interrogate these data from a benthic light quality perspective to improve our understanding of the changes in light quality that seagrass habitat are exposed to from dredging.

2.2 Variation in light quantity due to dredging

Analysing the benthic light data for regions of interest can improve our understanding of the natural patterns in light. Together with an understanding of the temporal variation in seagrass habitat, understanding the light climate can inform the most appropriate time to dredge, with respect to minimising impacts on seagrass. Examining the impacts of dredging on benthic light can improve our understanding of the light reduction caused by dredging, how this varies over space and time and in relation to other environmental conditions e.g. tides and wind. A number of case studies were available to analyse the impacts of dredging on the light environment in specific parts of NWWA. We focused mostly on the Gorgon Dredging Project at Barrow Island (EPA 2009) as it was the most complete dataset. However, the monitoring program was set-up for assessing the impacts to corals, not seagrasses, so it does not necessarily reflect the light conditions that seagrasses grow under. Only one site (DUG) regularly had observations of seagrass in the vicinity (Osborne et al. 2000, RPS 2005).

2.2.1 Understanding natural patterns in benthic light

The aims of this analysis were to:

- examine annual patterns in total daily benthic light, focusing at the site where seagrass has been observed; and
- identify key drivers of total daily benthic light.

Prior to dredging at Barrow Island a number of water quality monitoring and reference sites were established, collecting instantaneous light measurements (over 10 minute intervals) (Jones et al. 2015). From this data set the total daily benthic light (PPFD) was calculated (mol m^{-2} d^{-1}) but only for days with a complete light record. A subset of sites were selected to analyse patterns in benthic light. These were selected to cover a range of distances from the dredge site, 0.2–33 km, a range of dredging management zones and where possible have seagrass present (Table 3). The management zones were defined based on the Western Australian Environmental Protection Authority’s *Technical Guidance: Environmental Impact Assessment of Marine Dredging Proposals* (EPA 2016). This framework for Environmental Impact Assessment requires designation of spatially explicit zones to describe the predicted extent, severity and duration of impacts. The Zone of High Impact is the area where impacts to benthic organisms are predicted to be irreversible. The Zone of Moderate Impact is the area where predicted impacts on organisms are sub-lethal, and/or the impacts are recoverable within five years of the completion of dredging. The Zone of Influence is the area where changes in environmental quality are predicted but these changes would not result in a detectable impact on the benthic biota. Reference sites are outside of the predicted Zone of Influence (EPA 2016). The light record was not complete, and the number of days with light measures varied among sites (Table 3).

Table 3: Sites assessed for natural variation in benthic light over an annual cycle as well as changes in benthic light in the presence of dredging. Coordinates in Easting and Northings based on the grid system GDA94, MGA Zone 50.

Site code	Management zone	Easting	Northing	Depth (m)	Distance from dredge (km)	Before dredging data	During dredging data
AHC	Reference	350243	7731659	8.5	32.8	20/6/2009 – 18/5/2010 (n=213)	19/5/2010 – 31/10/2011 (n=503)
BAT	Reference	340703	7681301	3	15.9	20/6/2009 – 18/5/2010 (n=229)	19/5/2010 – 31/10/2011 (n=454)
DUG	Reference	340099	7687998	5.5	9.4	20/6/2009 – 18/5/2010 (n=224)	19/5/2010 – 31/10/2011 (n=401)
ANT	Zone of influence	342065	7708657	4	8.7	20/6/2009 – 5/5/2010 (n=211)	23/6/2010 – 31/10/2011 (n=361)
LNG2	Zone of influence	344396	7695372	7	1.1	20/6/2009 – 18/5/2010 (n=126)	19/5/2010 – 31/10/2011 (n=407)
LNG1	Moderate impact	344584	7695823	10	0.6	20/6/2009 – 18/5/2010 (n=118)	19/5/2010 – 31/10/2011 (n=443)
LNG0	High impact	344796	7696108	9	0.2	20/6/2009 – 18/5/2010 (n=324)	19/5/2010 – 31/10/2011 (n=427)

2.2.2 Temporal variation in benthic light

As the seven sites selected covered a range of depths (3–10 m), and light declines with depth (Kirk 1994), the relative daily light was range standardised between 0–1 and then plotted to aid visual assessment of the temporal patterns. There was little missing data across sites from June to December 2009, but only one site had data from January to March 2010 (Figure 1). At times, there was striking variability in benthic light intensity from one day to the next (Figure 1), with a 40% change often observed. Despite this and the limitations due to missing data, some general temporal patterns were obvious. There was an increase from minimum daily light in June through to maxima in September to December, depending on the site. Some sites peaked in September (e.g. AHC) then declined, others in October (e.g. LNG0), November (e.g. ANT) or December (e.g. BAT, DUG), all declining thereafter (Figure 1). We are not confident of the general pattern from January to March, due to the very low coverage of data during this time. However, the one site with data present showed a decline over this period.

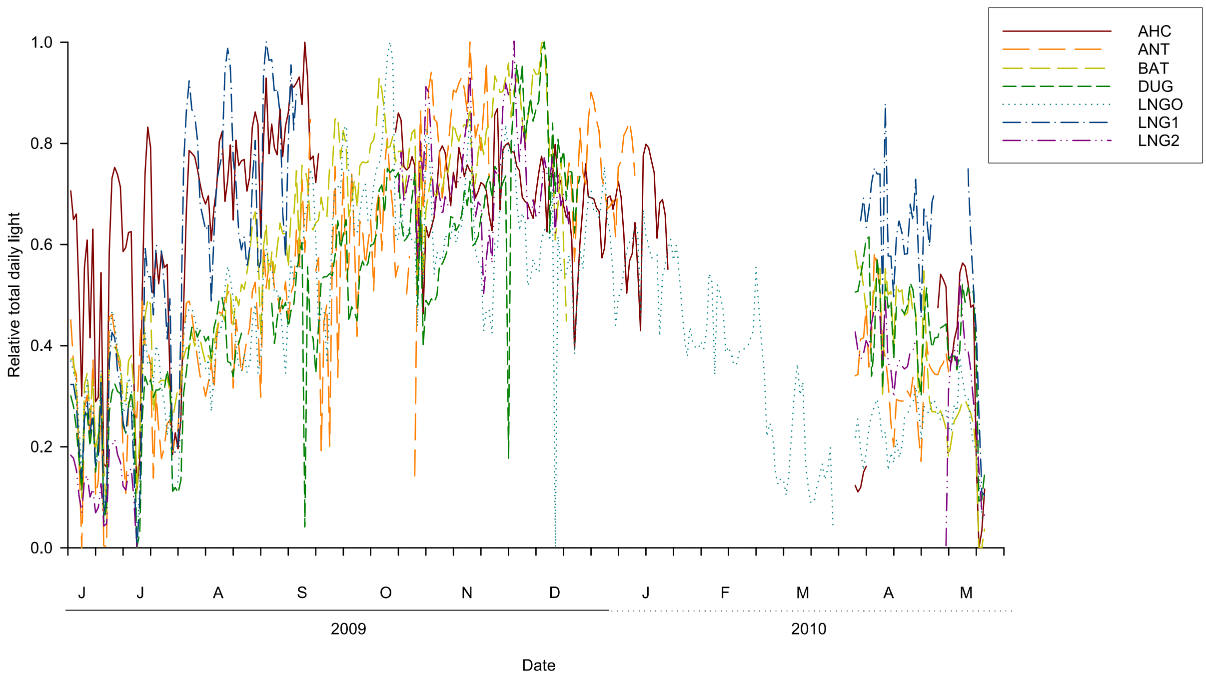

Figure 1: Total daily benthic light, range standardised between 0–1 to show that general patterns over time from 20 June 2009 (day 1) to 18 May 2010 (day 333) at a sub-set of six monitoring sites at a range of distances from the dredging site (AHC, ANT, BAT, DUG, LNG0, LNG1, LNG2) which were part of the Barrow Island water quality monitoring and reference sites for the Gorgon dredging project. These measurements were taken prior to dredging commencing. Dashed lines on x-axis indicate 10 day intervals.

Key Points

- Around Barrow Island, the benthic light is highly variable from day to day. Despite this, there are clear intra-annual patterns with minima in June–August and maxima in September to December. Due to the lack of data from January to March, the patterns in benthic light at this time are not clear.

To focus in more detail on the site where seagrass has been observed on a number of occasions, the total daily benthic light was averaged per month. This data was tested to determine if there were significant intra-annual variations using a PERMANOVA main and pair-wise comparison test on the DUG site. This site, in 5.5 m depth of water, was selected to assess intra-annual patterns as previous reports had indicated that seagrass was present in the near vicinity (Table 3). All days with data within a month were grouped together for the analysis. Despite the large daily variations observed in Figure 1 there were significant differences among months (Pseudo F 73.3, $p<0.001$, $n=223$, Figure 2). The total daily light, averaged by month, ranged from around 3 mols m^{-2} d^{-1} in June and July, increasing to around 5.5 mols m^{-2} d^{-1} in August and May with a maximum of

11 mols m^{-2} d^{-1} in December (Figure 2). The light climate, particularly from August to December, and April, would be able to support tropical seagrass species (Table 11). Due to the missing data we cannot comment on the months of January to March.

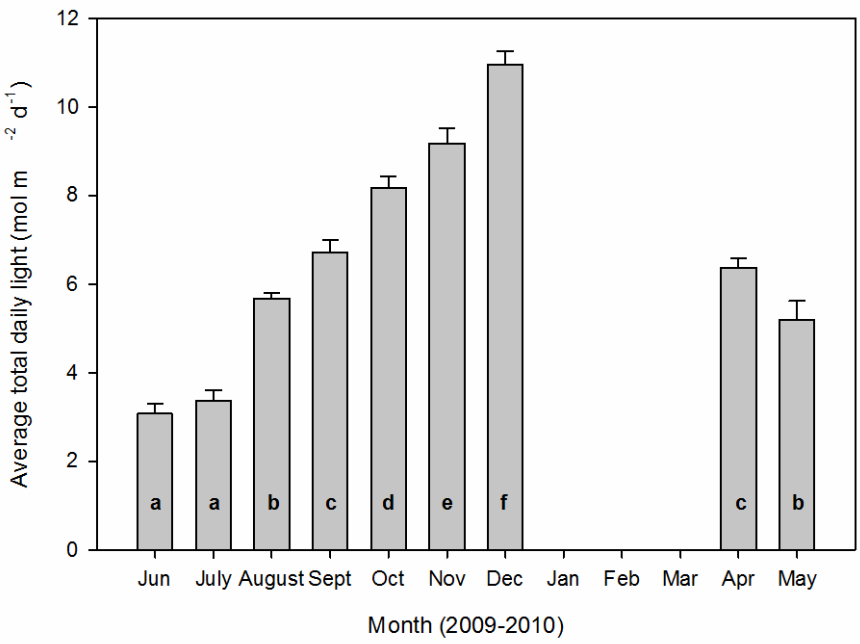

Figure 2: The average total daily light (mol m^{-2} d^{-1}) by month from Jun 2009 to May 2010 at reference site DUG. No data available from Jan–Mar 2010. Lettering on bars indicates where the significant differences lie based on a PERMANOVA pairwise comparison test — shared letters indicate no significant difference. Error bars are standard error (se).

Key Points

- There is significant intra-annual variation in total daily benthic light.
- At this particular site (DUG), light increases from minima in July to maxima in December. It declines from April to May, and is unknown what occurs from January to March due to missing data.
- The benthic daily light at this site (DUG), could support seagrass habitat for part of the year, August to December (unclear for Jan–March).
- Timing of dredging is an important consideration for the management of seagrass habitat, as there are only particular times of year when seagrass could survive with this light climate.

Drivers of variation in light

In NWWA the potential drivers of variation in benthic light intensity are numerous, and include water depth, day length, tidal range and state, wind speed and direction and cloud cover. The Gorgon dataset described above (Jones et al. 2015), provided an opportunity to examine the relationship between daily benthic light and some of the factors that are known to influence this.

We performed a generalised linear model (GLM) with total daily light as the dependent variable, and water depth, day length, tidal range, wind speed and direction as the predictor variables. As water depth is known to affect benthic light, we included this in the null model. Cloud cover is also known to affect instantaneous benthic light intensities (Anthony et al. 2004) however we were unable to include this variable as there were no cloud cover data available for the study region; the nearest data were for sites in the order of 80–100 km from the benthic light sites. We used all the daily data from the seven water quality-monitoring sites before dredging commenced (n=1445 observations). The predictor variables were paired with the individual daily light readings, but water depth was set for a particular site. Table 4 details the sources of the predictor variables. The GLM examined the additive and interactive effects of the predictor variables. The Akaike Information Criterion (AIC, Burnham & Anderson 2002) was used to select the set of models which best predicted the total daily light (Table 5) and, from these, the predictors most important for explaining the variation in light (Figure 3). A more detailed explanation of this approach is presented in Appendix 1.

The best predictors of total daily light across all sites were: day length, longer days tended to have more benthic light; wind speed; the interaction between wind speed and direction; and the interaction between day length and direction (Table 5, Figure 3). There were five models that were well supported. Interestingly, tidal range was not a strong predictor of total daily benthic light, nor was wind direction on its own, only in interaction with other variables. As mentioned above, it was not possible to include cloud cover in the analysis due to an absence of data. Based on previous studies (Anthony et al. 2004) it is possible that cloud cover could also be a predictor of benthic light, though that previous study used instantaneous light intensities and it is unclear whether a similar effect would be observed on total daily light, the variable used in our analysis.

Table 4: The sources of data for the independent variables used in the GLM model to estimate the best predictors of total daily benthic light.

Predictor variable	Source
Depth of site (m)	Gorgon Water Quality Monitoring data, Background and Compliance Monitoring (Jones et al. 2015)
Day length (hours)	http://www.timeanddate.com/sun/australia/ for Karratha, the closest reading
Tidal range	The difference between high and low tide on that day http://www.mobilegeographics.com/iphonetides/ for Barrow Island
Average wind speed (km/hr)	Bureau of Meterology from Barrow Island http://www.bom.gov.au/climate/data/stations/(Station 5094)
Direction of dominant wind	Bureau of Meterology from Barrow Island http://www.bom.gov.au/climate/data/stations/(Station 5094)

Table 5: The significant models derived from the GLM's which best explained the total daily benthic light (mol m^{-2} d^{-1}) across seven sites around Barrow Island, Pilbara WA.

Model	AIC value	Relative support for model based on the Akaike weight (wi)
day length + wind speed + wind direction + wind direction:day length + wind direction:wind speed	6215.384	$6.946930e^{-01}$
day length + tide + wind speed + wind direction: day length + wind direction: wind speed	6217.029	$3.051328e^{-01}$
day length + wind speed + wind direction + wind speed:tide + wind direction: wind speed	6233.284	$9.013510e^{-05}$
day length + tide + wind speed + wind direction + wind direction: wind speed	6236.850	$1.515594e^{-05}$
day length + tide + wind direction + wind speed: day length + wind direction: wind speed	6237.672	$1.004831e^{-05}$

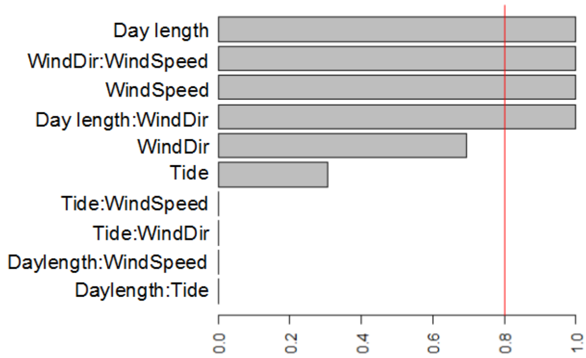

Figure 3: The important terms for predicting daily benthic light. Any predictor value over 0.8 is considered an important contributor to the total daily light (mol m^{-2} d^{-1}).

Due to the complex nature of this model, it is not possible to plot light against the significant predictor variables. However, to demonstrate the main relationships, total daily light is plotted against the two main significant, interacting factors (Figure 4). The contour plots highlight that the amount of benthic light increases with day length, but with some exceptions. Total daily benthic light is lower when the day length is 12.5–13 hours and the wind direction is from ESE to S, and when the day length is from 11.75–12.75 hours and the wind direction from WSW to NW (top panel). For the interaction between wind speed and wind direction, higher light is observed generally when the winds are from a SW to N direction, which makes sense from the location of these sites; they are mostly on the east side of Barrow Island (lower panel). Lower light is observed when the wind comes from a NE to SSW direction, the direction of greatest fetch for these sites.

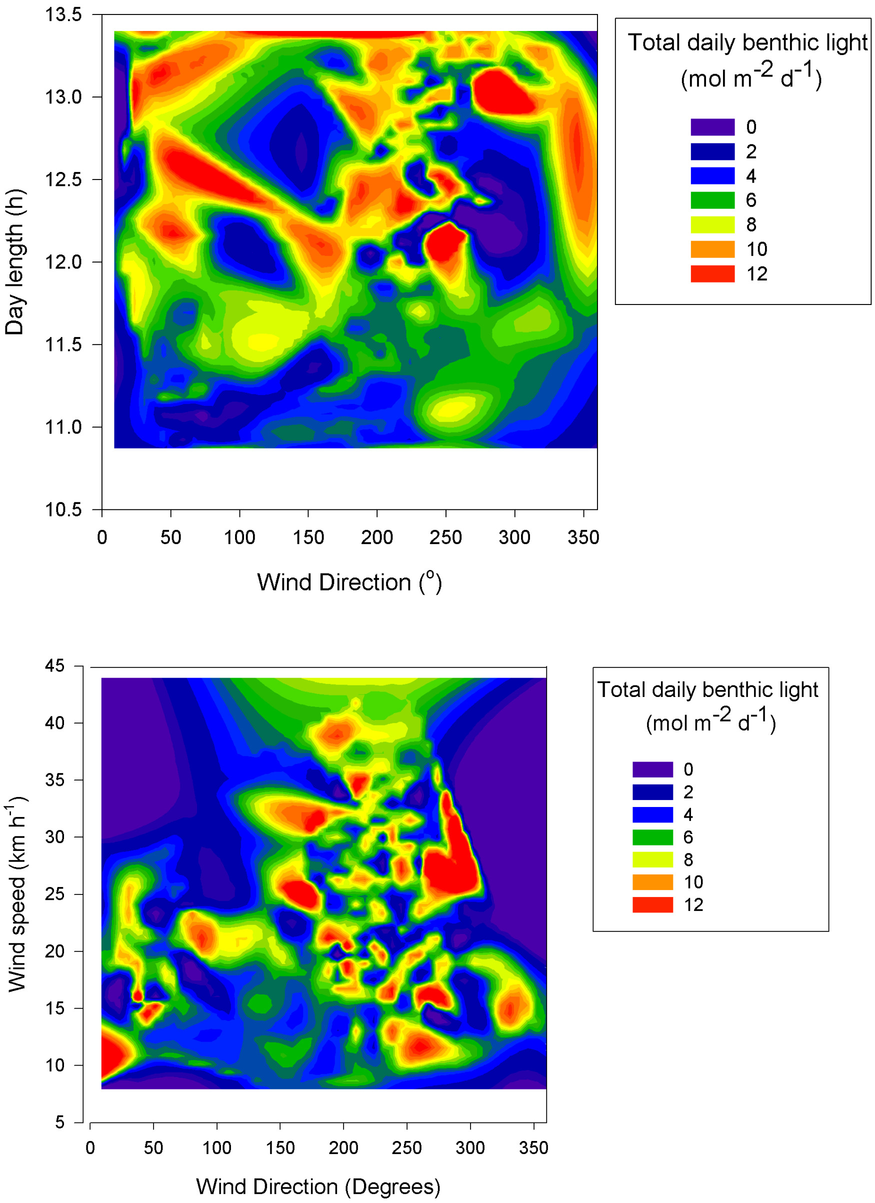

Figure 4: An illustration of how the interaction between wind speed and day length (top) and wind speed and wind direction (bottom) influence the total daily benthic light across all monitoring sites during the background period, prior to dredging. Contours indicate the amount of total daily benthic light (mol m^{-2} d^{-1}).

Key Points

- Based on the Gorgon case study, seagrasses in the NW are likely to experience highly variable amounts of light. This variability can be explained by environmental conditions. The best predictors of benthic light over a year around Barrow Island were day length, wind speed, the interaction between wind direction and speed, and the interaction between day length and wind direction. Despite the large tidal range in this area, the magnitude of the tide is not a strong predictor of daily benthic light. We could not assess the importance of cloud cover for benthic light due to an absence of data.

2.2.3 Dredging-related impacts to benthic light

In this section we examine the benthic light data at the seven sites that were presented in Table 3, comparing pre-dredge (background) data with those collected during dredging. Three different analyses were performed:

- the first was a comparison of pre- and during-dredging data. The data were pooled into two categories, background or dredging period and summary statistics were calculated to estimate the magnitude of dredging-induced change in total daily benthic light, the frequency of the change and the maximum duration of the change. A representative site was selected from each zone (High Impact-LNG0, Moderate Impact-LNG1, Zone of Influence-LNG2 and Reference-DUG);
- the second, data from the background and dredging periods were analysed over a finer temporal resolution, to identify if changes in light were of a greater magnitude or frequency at particular times of the year; and
- the third, a GLM was performed to estimate the best predictors of total benthic daily light over the period prior to and during dredging. All the predictors from the model assessing natural drivers of benthic light (see section 2.2.2) were included, as well as the categorical predictors ‘presence of dredging’ and ‘distance from dredge’. This analysis tested whether the presence of dredging is an important predictor of total daily benthic light, along with other environmental factors tested previously. Again, cloud cover could not be included in the analysis due to an absence of site-specific data.

Dredging impacts to total daily benthic light

At a number of sites from the High Impact Zone, Moderate Impact Zone, Zone of influence and the Reference site (up to 9.7 km away from the dredge site, see previous section for explanation of zones (EPA 2016)), there was lower total daily benthic light during the dredging period compared to background (Table 6). The magnitude of this decline decreased with distance from the dredge. At the High Impact site (LNG0) there was a 65% decline in benthic light, a 56–58% reduction at the Moderate Impact site (LNG1) and in the Zone of Influence (up to 1.1 km from the dredge, LNG2) and a 29% reduction at the Reference site (DUG), 9 km from the dredge. The 1st, 5th, 20th and 50th percentiles of daily light were also reduced under dredging conditions (Table 6).

The frequency of lower benthic light conditions relative to background conditions was assessed by calculating the number of the days that light during the dredging period fell below the 1st, 5th, 20th and 50th percentile of the background data (Table 6). The reduction in light occurred most frequently closer to the dredge, but this was dependent on the percentile considered. For example, the frequency that the total daily benthic light was below the 50th percentile of the background light was similar across the High and Moderate Impact site and Zone of Influence (within 1.1 km of the dredge), for 93–94% of the time. Whereas, for the 1st, 5th and 20th percentiles the frequency declined with distance from dredge: e.g. benthic light during dredging fell below the 20th percentile of background 81% of the time at the High Impact Zone, 69% at the Moderate Impact Zone and 53% at the Zone of Influence. Even at the reference site, 9 km away from the dredge, the total daily light readings were below the 20th percentile of background values 45% of the time and below the 5th percentile 15% of the time. This analysis indicates that the average light conditions were reduced similarly across all sites, but that the more extreme reductions were greater closer to the dredging site.

The duration that light was lower during the dredging period compared to the background period was assessed by calculating the number of continuous days that the total daily light was below the 20th percentile of the background data (Table 6). In the High Impact Zone, the maximum number of consecutive days was 185 (~ 6 months). The duration of lower light declined with distance from the dredge: 99 days (~3 months) in the Zone of Moderate Impact; 38 days in the Zone of Influence; and 78 days at the Reference site (~2.5 months).

Table 6: Summary of total daily light prior to (background) and during dredging at four sites which represent each of the dredging management zones around Barrow Island, and located at increasing distance from the dredging site. The total (average ± standard error) minimum, 1st, 5th, 20th and 50th percentiles of Daily Light were calculated from all data over the background period and in the dredging period. The frequency of light reduction was expressed as the number of days in the dredging period that fell below each of the 1st, 5th, 20th and 50th percentile values from the background period. The duration (*) was expressed as the maximum number of consecutive days that the total daily light in the dredging period was below the 20th percentile of the background period.

			Percentiles					# days falling below background percentile in the dredging period			
Management zone & site	**Period**	**Avg ± se (n)**	**Min**	**1st**	**5th**	**20th**	**50th**	**1st**	**5th**	**20th**	**50th**
High impact											
LNG0	Background	4.01 ± 0.01 (324)	0.05	0.54	1.22	2.40	3.93				
	Dredging	1.40 ± 0.06 (427)	0.001	0.003	0.04	0.31	1.03	124 (29%)	240 (56%)	347 (81%)	403 (94%)
		65% reduction								185 days*	
Moderate impact											
LNG1	Background	3.57 ± 0.14 (118)	0.06	0.49	0.89	1.95	3.78				
	Dredging	1.57 ± 0.06 (443)	<0.001	0.005	0.05	0.39	1.18	106 (26%)	181 (41%)	308 (69%)	411 (93%)
		56% reduction								99 days*	
Zone of influence											
LNG2	Background	5.85 ± 0.28 (126)	0.07	0.21	0.88	2.19	6.07				
	Dredging	2.45 ± 0.09 (407)	0.002	0.04	0.19	0.70	2.04	26 (6%)	91 (22%)	214 (53%)	383 (94%)
		58% reduction								38 days*	
Reference											
DUG	Background	6.75 ± 0.18 (224)	0.08	0.66	1.89	4.42	6.60				
	Dredging	4.80 ± 0.13 (402)	0.001	0.007	0.30	2.52	4.93	30 (7%)	61 (15%)	182 (45%)	300 (75%)
		29% reduction								78 days*	

Key Points

- There are indications that there are effects on the total daily benthic light at a site over 9 km from the dredge, which was considered a reference site. The amount of benthic light was lower during dredging and the frequency and duration of lower light was greater during dredging compared to background levels. Inter-annual variations in light may have contributed some of this difference. However, plume monitoring undertaken by Department of Parks and Wildlife at the time of this dredging campaign found that the plume dispersed further south from the dredge than predicted and reached the reference site (Evans et al. 2012), providing confidence that the reductions in benthic light at the DUG reference site reflect, at least partially, dredging impacts. Further analysis below investigates the effects of dredging and distance from dredge on light.

Seasonal variation in the effect of dredging on light

The previous analysis examined the differences in benthic light averaged over 1–2 years, and did not consider the interaction between the seasonal variation in total daily benthic light and dredging. If particular times of the year are more turbid due to environmental conditions, then it follows that the effects of dredging may vary depending on the time of year. These interactions could be of significance for benthic habitats such as seagrasses, particularly if there are times that are crucial in the life-cycle of seagrasses (i.e. flowering, seed germination, seedling development). In the Western Australian context, these crucial times are considered critical windows of environmental sensitivity and are defined as times of year or particular sites where key species or ecological communities or critical processes may be particularly vulnerable to pressures from dredging (EPA 2011). Therefore, it would be preferable to perform dredging outside of these windows or places. In other places though, environmental windows are considered times when dredging should occur to minimise impact to the receiving environment (NRC 2002).

To assess the interaction between the seasonal variation in total daily benthic light and dredging we plotted the total daily benthic light, averaged over one week in the background period, and then compared the same week of the year in the dredging period. The dredging period was separated into year 1 and 2, ensuring that similar times of year could be compared. Intervals of one week were chosen as they were easy to compare from one year to the next and, due to the extensive missing data, comparing months using a similar number of days was not possible. Clearly this does not take into account variations in light, which may be due to differences in other environmental factors such as wind speed and direction. We address the interaction with environmental factors and dredging in a later section.

At the sites closest to the dredge, which were also the deepest sites, the average total daily light prior to dredging ranged from minima of 1–2 mol m^{-2} d^{-1} in June–August, to maxima of 6–9 mol m^{-2} d^{-1} in September–December (Figure 5). The variation in the timing of these minima and maxima was due to different patterns among sites (Figure 5). Under dredging conditions, the amount of light declined, particularly at the High (LNG0) and Moderate Impact (LNG1) sites and the Zone of Influence (LNG2) within 1.1 km of the dredge site. The average total daily light ranged from <1 to 5 mol m^{-2} d^{-1} and the weekly average during the dredging was consistently below that of the corresponding week in the background period. The reduction relative to background conditions was greatest during October and December at the High Impact site and April and May at the Moderate Impact site. Due to the missing data we cannot be as confident about these temporal patterns as those at LNG0, as in many cases we do not have temporal overlap between the pre-dredging and dredging time.

At sites, further from the dredge, which were also shallower, the total daily light was higher but the seasonal patterns were similar to that described above (Figure 6). Minima were observed in June–August (3–4 mol m^{-2} d^{-1}) and maxima in November (12–14 mol m^{-2} d^{-1}). At the Reference sites BAT and DUG the greatest reduction relative to background occurred during November and December. There were no clear patterns at the other two sites.

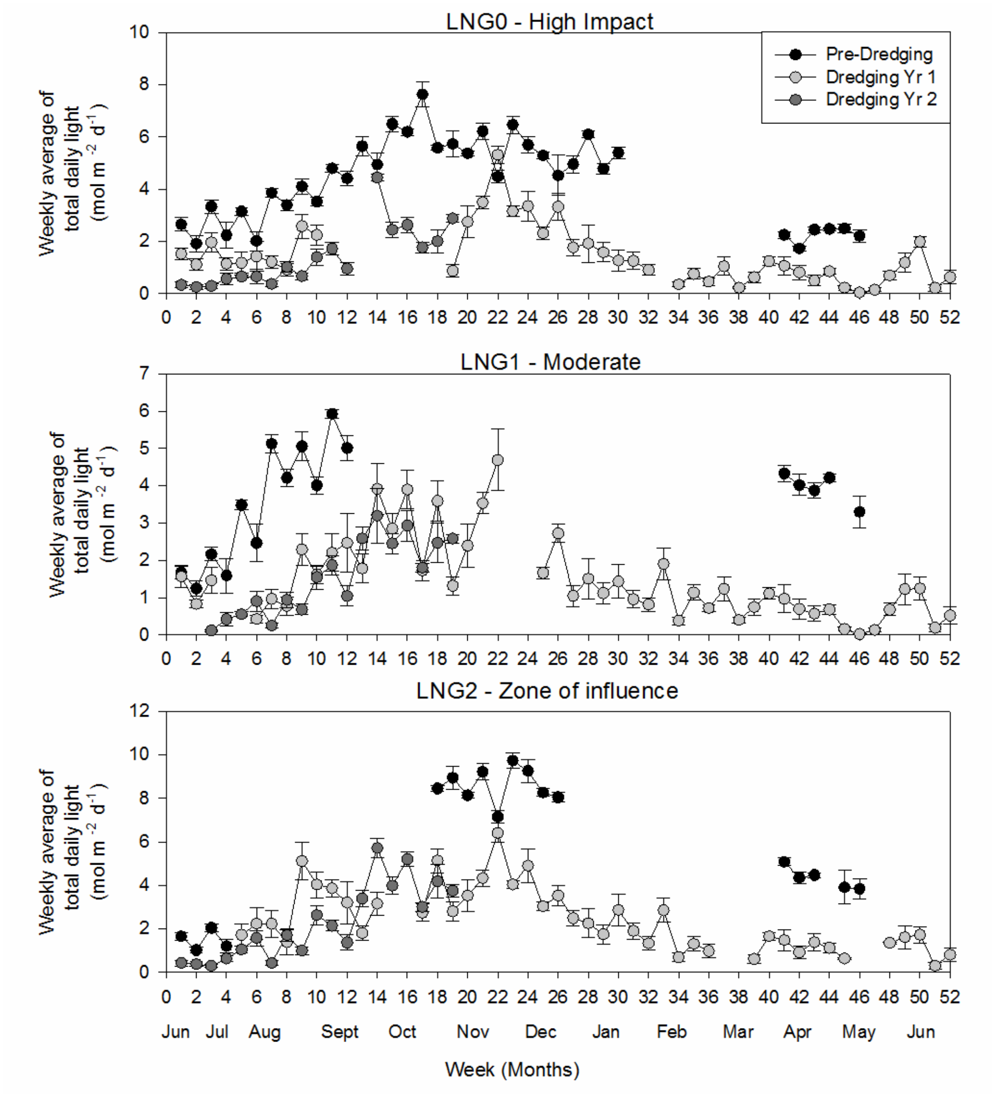

Figure 5: Daily total light (mol m^{-2} d^{-1}) for sites closest to the dredge, averaged over 7 days from 20 June 2009 (week 1) to 18 May 2010 (Week 52) for pre-dredging data, 19 May 2010 to 18 May 2011 for Year 1 dredging data, and then 19 May 2011 to 24 October 2011 for Year 2 dredging data. Only weeks with 6 or more daily readings were included.

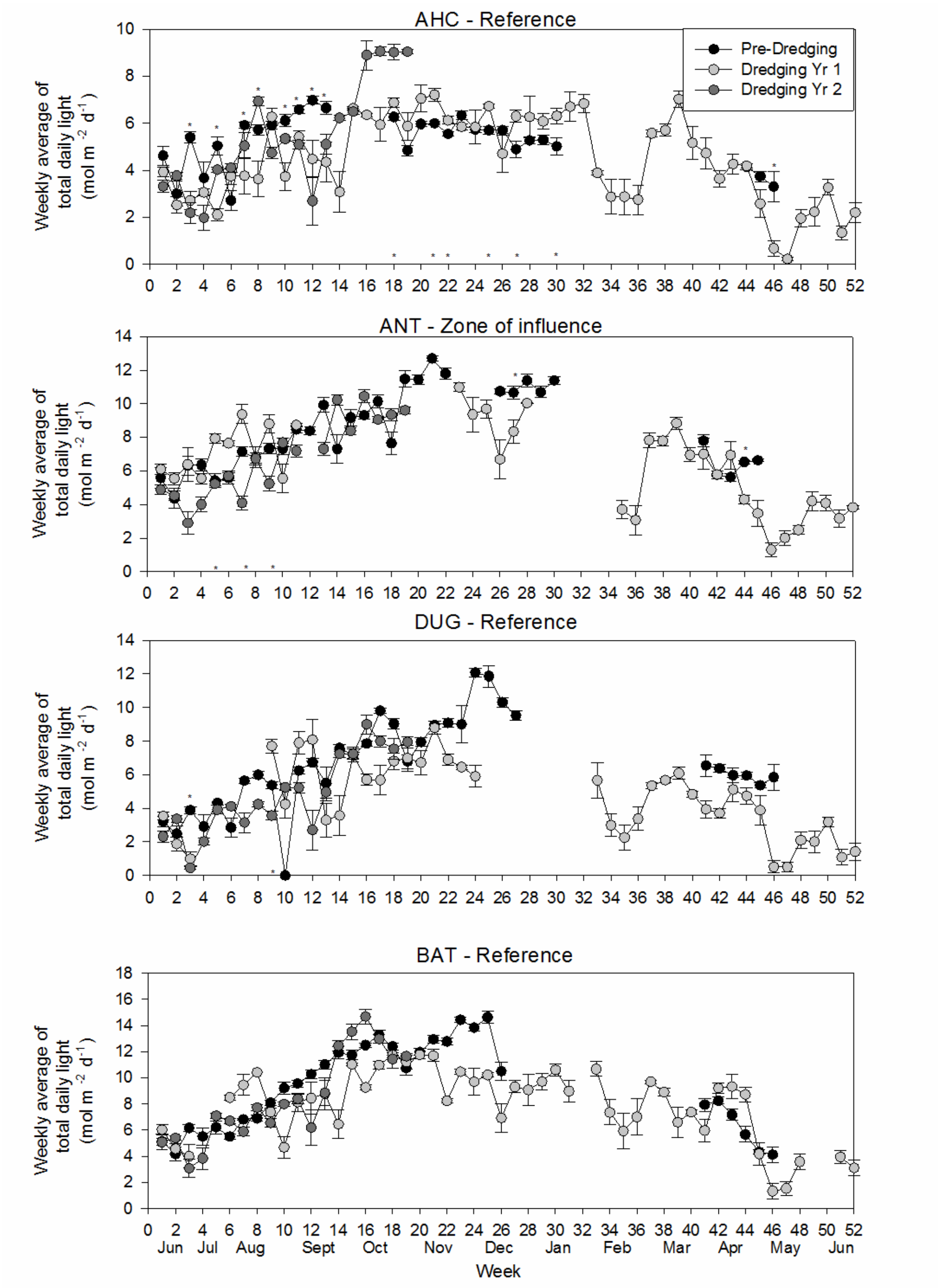

Figure 6: Daily total light (mol m^{-2} d^{-1}) for sites furthest from dredge, averaged over 7 days from 20 June 2009 (week 1) to 18 May 2010 (Week 52) for pre-dredging data, 19 May 2010 to 18 May 2011 for Year 1 dredging data, and then 19 May 2011 to 24 October 2011 for Year 2 dredging data. Only weeks with 6 or more daily readings were included.

Key Points

- For the Gorgon dredging project, the impact of dredging varies temporally, potentially due to the interaction of dredging activity and environmental conditions. The decline in benthic light due to dredging, relative to reference conditions, was greatest in October–December at most sites. From the limited data available for NWWA, this appears to be a time of rapid growth and reproduction for seagrasses (see WAMSI DSN Project 5.1.2 (McMahon et al. 2017)). In addition, based on the light data (Figure 2), this is the time most likely to support seagrass habitat.

- For the Gorgon dredging project, the amount of benthic light was consistently reduced within 1.1 km of the dredge, relative to background conditions.

To highlight the deficit in benthic light from background conditions, the weekly data were replotted as the deviation from background for each week (Background minus Year 1 or Year 2) (Figure 7 and 8). This clearly demonstrates the magnitude of light reduction in mol m^{-2} d^{-1} at the times when there is comparative data, and when the greatest reductions occur. At the High, Moderate and Zone of Influence sites, within 1.1 km of the dredge, almost all comparisons were negative, indicating a deficit in light relative to background conditions (Figure 7, Table 7). The reduction was mostly around 1–4 mol m^{-2} d^{-1} but reached maximums of 6 mol m^{-2} d^{-1}. The deficit consistently increased from June through to August and September at LNG0 and LNG1. A greater magnitude of reduction at this time may be of relevance to seagrass habitat if present, as this is leading to the maximum light period which could correspond with greater productivity and abundance of the seagrass habitat, and also to the period when flowering, fruiting and the development of seed banks occurs. Recent observations have shown flowering, fruiting and seeds banks in November and December across 6 locations in the Pilbara (see WAMSI DSN Project 5.3 (Vanderklift et al. 2017)). The changes in daily PPFD were sufficient to reduce benthic PPFD from levels that elsewhere (Queensland, Chartrand et al. 2012) are considered the minimum required to sustain seagrass (about 6 mol m^{-2} d^{-1}) to well-below those levels.

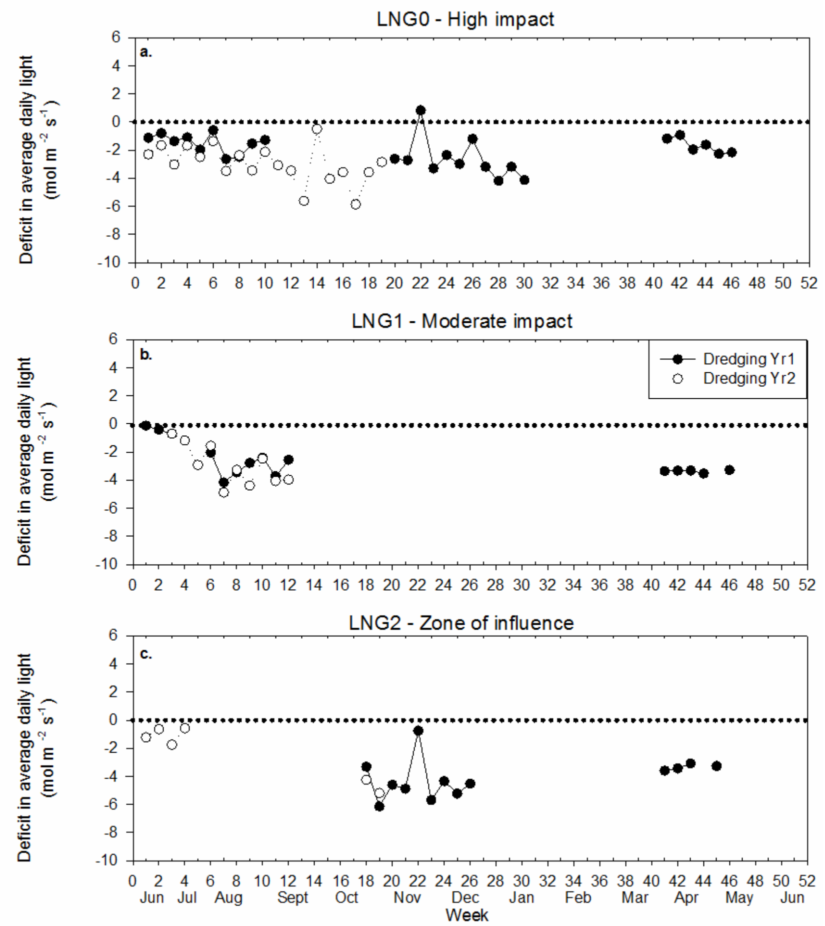

Figure 7: Deficit relative to pre-dredging data at the same time in daily total light (mol m^{-2} d^{-1}) for sites closest to the dredge, averaged over 7 days from 20 June 2009 (week 1) to 18 May 2010 (Week 52) for pre-dredging data, 19 May 2010 to 18 May 2011 for Year 1 dredging data, and then 19 May 2011 to 24th October 2011 for Year 2. Values below the line indicate a deficit. Only weeks with 6 or more daily readings were included.

At the four shallower sites, further from the dredge, the total daily benthic light during the dredging period, was at times higher than during the corresponding background period, generally up to 2 mol m^{-2} d^{-1} but sometime up to 4–5.5 mol m^{-2} d^{-1}, depending on the site (Figure 8). However, across these four sites the majority of the deviations were negative (Table 7), with the deficits in benthic PPFD generally up to 4 mol m^{-2} d^{-1} but, at some times and sites (e.g. DUG and BAT), up to 6 mol m^{-2} d^{-1} (Figure 8).

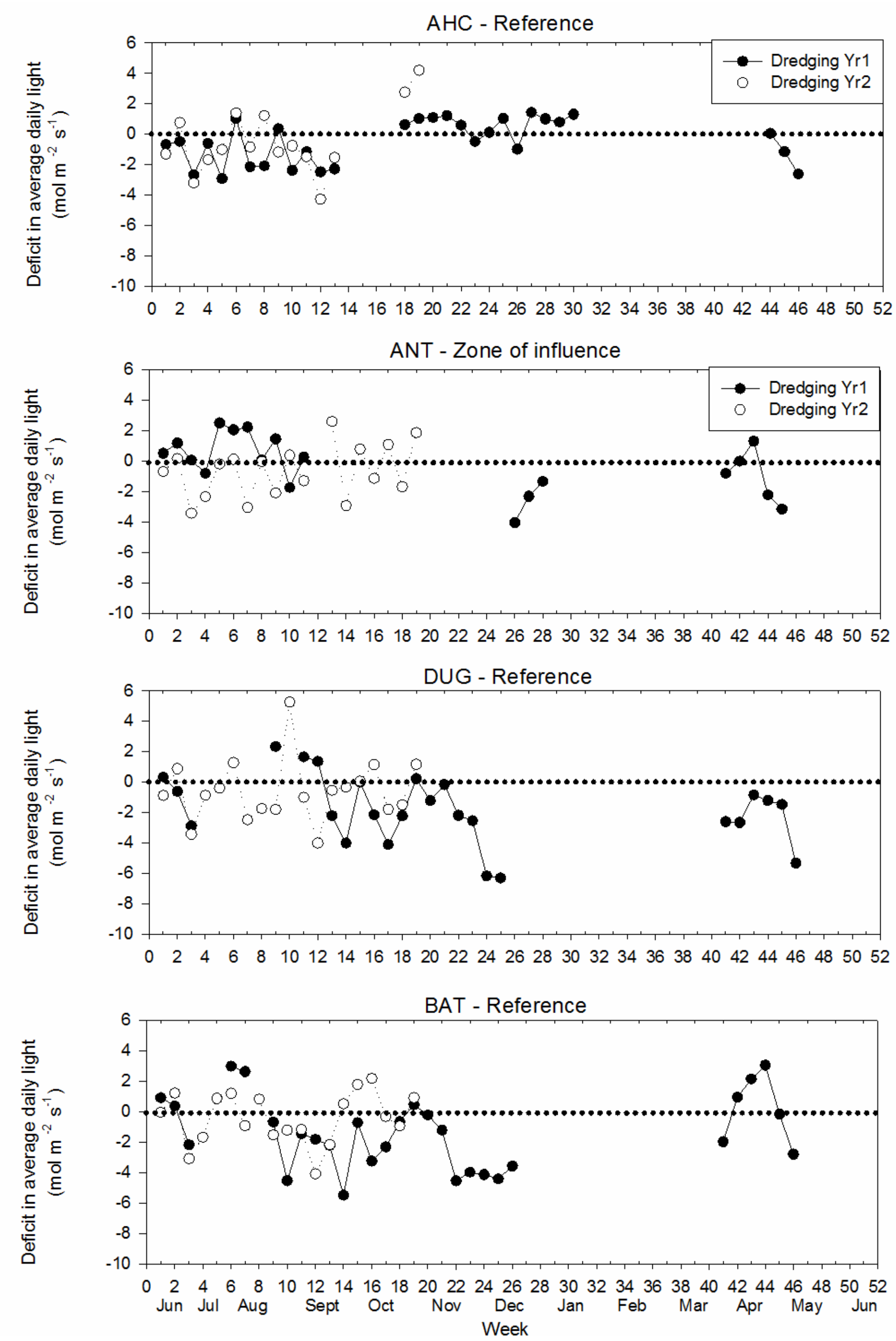

Figure 8: Deficit relative to pre-dredging data at the same time in daily total light (mol m^{-2} d^{-1}) for sites furthest from the dredge, averaged over 7 days from 20 June 2009 (week 1) to 18 May 2010 (Week 52) for pre-dredging data, 19 May 2010 to 18 May 2011 for Year 1 dredging data, and then 19 May 2011 to 24 October 2011 for Year 2. Values below the line indicate a deficit. Only weeks with 6 or more daily readings were included.

The frequency of the deficit from background light was assessed only on those weeks when the deficit was greater than 2 mol m^{-2} d^{-1}. This was a conservative approach, and considered to be of significance to seagrass habitat. At the sites close to the dredge, there were deficits greater than 2 mol m^{-2} d^{-1} in 70% or more of the observations. With greater distance from the dredge this declined, to 24–40% of the observations. The duration of this deviation was 5–7 weeks in the high and moderate impact sites, and from 2–5 weeks in the other sites (Table 7).

Table 7: Frequency and duration of light deficit during the Gorgon Dredging Project relative to background values. Total observations are the number of weeks where there are comparative data (prior to and during dredging). The number of observations with a light deficit includes any weeks where the difference in light was >0 or >2 mol m^{-2} d^{-1}. This is equivalent to the frequency of light reduction, also expressed as the % of observations. The duration that these >2 mol m^{-2} d^{-1} light deficits occurred was estimated by the number of continuous weeks that the deficit was below 2.

Site code	**Management zone**	**Total obs (weeks)**	**No. obs with light deficit (% of total)**	**No. obs with light deficit >2 mol m^{-2} d^{-1} (% of total)**	**No. obs where light deficit was > 2 mol m^{-2} d^{-1} over a duration of 1-7 weeks**							**Max no. continuous measurements (weeks)**
					1	2	3	4	5	6	7	
AHC	Reference	34	25 (74%)	7 (21%)	3	2	0	0	0	0	0	13
BAT	Reference	46	31 (67%)	14 (30%)	3	3	0	0	1	0	0	19
DUG	Reference	42	32 (76%)	17 (40%)	6	2	1	1	0	0	0	19
ANT	Zone of influence	37	19 (51%)	9 (24%)	3	3	0	0		0	0	11
LNG2	Zone of influence	18	18 (100%)	16 (89%)	1	2	1	2	0	0	0	9
LNG1	Zone of Moderate impact	24	24 (100%)	17 (71%)	2	0	0	1	0	1	1	10
LNG0	Zone of High impact	34	33 (97%)	28 (82%)	3	2	4	1	1	0	0	19

Key Points

- There is a high frequency of light reductions relative to background conditions that would be significant to seagrass habitat (>2 mol m^{-2} d^{-1}). Greater than 70% of observations within 1.1 km of the dredge and 24 to 40% up to 10 km from the dredge.
- The duration of reductions of this magnitude range from 5–7 weeks close to the dredge (up to 1.1 km), and 2–5 weeks away from the dredge (up to 10 km). This may be an underestimate due to missing data.

Predictors of light prior to and during dredging

In section 2.2.2 (predictors of variation in natural light), we developed a model to determine the best predictors of total daily benthic light under natural conditions. Here we re-run this model but include both pre- and during-dredging data to assess if the presence of dredging and distance from dredge are also important at predicting benthic light. All of the previous predictors were included in the model with the addition of two further potential predictors: Presence of dredging (present = during dredging or absent = prior to dredging); and Distance from dredge, which was linked to a site and the distance it was located from the main dredge site. As described previously, as benthic light varies with depth this was included in the null model. The methodology was similar to that described previously.

There was one best-supported model with an AIC value of 19,686 and an AIC weight of 9.99 x 10^{-1}:

Benthic Light ~ 1 + dredging presence + day length + wind speed + wind direction

+ distance from dredge + (dredging presence x distance from dredge).

The inclusion of dredging and distance from dredge within the best-supported model indicates that, despite the highly variable benthic light climate, there is a strong effect from dredging in reducing benthic light. The interaction term (dredging presence x distance from dredge) reflects a reduced effect of dredging with increased distance from the dredge (Figure 9). The models did not include cloud cover, which could potentially affect benthic light. However, it is unlikely that cloud cover could have accounted for the differences between the pre- and during-dredge periods. The pre-dredge period covered one year, from June 2009 to May 2010, while the during-dredge period covered 1.5 years from May 2010 to October 2011. Therefore, the dredge period data contain two sets of June-October data. The nearest location with Bureau of Meteorology cloud cover data is Onslow (http://www.bom.gov.au/climate/averages/tables/cw_005016.shtml), located 90 km from Barrow Island. At Onslow, the mean number of cloudy days per month in June-October is 6, 3.5, 2.2, 1.3 and 0.8 respectively (mean = 2.7), while for the remaining months have a mean of 3.9 (1.2, 2, 4, 4.8, 4.4, 5.5 and 5.7 for November through to May respectively. Therefore, the dredging period data contain a larger number of low cloud-cover months. It is highly unlikely, therefore, that cloud cover would have been responsible for the lower light conditions during the dredge period.

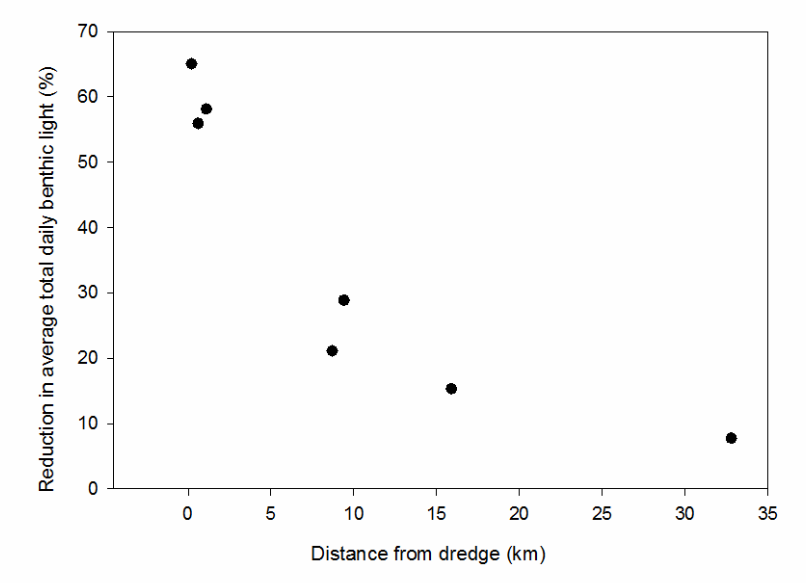

Figure 9: The magnitude of the dredging effect is reduced with distance from the dredge.

Key Points

- Despite high variability in the total daily benthic light, the presence of dredging and the distance from the dredge are significant predictors of total daily light, along with the environmental conditions, which are of importance under background conditions.

2.3 Variation in sedimentation and burial due to dredging

We used three data sets to provide insights into the burial stress from dredging, data from the Rio Tinto Cape Lambert Project (EPA 2010), the Woodside Pluto Project (EPA 2007) and the Chevron Gorgon Project (EPA 2009). Burial stress was not directly measured in these monitoring programs, therefore we estimated it from the sedimentation data derived from sediment traps. These sediment traps were in place for periods of 5–118 days. The temporal resolution of this sediment trap monitoring data was lower than the monitoring data on benthic light presented previously, which was measured at 10–15 min intervals and integrated to a daily reading. Daily burial depth (B in mm) was estimated as:

$$B = \frac{S_{TRAP}}{\rho_b}$$

where S_{TRAP} is the sediment deposition rate determined from the sediment trap data (mg DW cm^{-2} d^{-1}) and ρ_b the sediment dry bulk density (g DW cm^{-3}) (Bowman & Huka 2002).

As the sediment bulk density was not measured in the monitoring program, we used a standard estimate for marine sediments, ranging from 0.96–2.6 g DW cm^{-3} (Tenzer & Gladkikh 2014). The burial depths are presented as a potential range based on the range in bulk density. Other studies, in the Great Barrier Reef (SKM APASA, 2013), have used an estimated sediment bulk density of 1.05 g cm^{-3} based on data for freshly consolidated (1 day) muds (van Rijn 1993). We have used the full range of potential densities to reflect the uncertainty regarding the specific density of dredge sediment that may be formed and released at dredging sites. However, our lower estimates (based on a density of 0.96 g cm^{-3}) would correspond closely to those of studies using van Rijns' (1993) density of 1.05 g cm^{-3}. We calculated the daily burial depth by dividing the sedimentation rate by the bulk density, as detailed above. This gives an approximate height of sediment added per cm^2 of sea floor. The bulk density affects the burial depth, a lower bulk density will result in a greater burial depth. Although our estimates are presented as a range, the lower bulk density more closely reflects our understanding of the bulk density of dredged sediments (McCook et al. 2015), so the higher end of the burial estimate range is more likely to be relevant to dredging scenarios. To improve certainty with these estimates the bulk density of the sediment *in situ* should be measured.

The limitations of estimating burial depth from sediment trap data are:

- sediment traps can overestimate the amount of sediment depositing onto the seafloor because they do not allow resuspension of sediments and may enhance sediment deposition because the traps can reduce waterflow and hence cause particles to drop out of the water column (Storlazzi et al. 2011, Browne et al. 2012). However, this is also what seagrass do by trapping sediments and reducing resuspension of sediments (Gacia & Duarte 2001). So although it may be an overestimate, the significance of this needs to be assessed in relation to the ability of seagrasses to trap and reduce resuspension of sediments; and
- although the rates are expressed as per day, the measurement is made over a longer period of time, in this case 5–118 days. So the timing of sediment delivery is unknown, and this has implications for a burial stress, 0.5 mm per day vs. 1–20 mm per day depending on the temporal nature of sediment deposition.

The form of the data from the three case-studies was slightly different. The most comprehensive data-set was from the Rio Tinto Cape Lambert Project (EPA 2010) where 7 sets of pre-dredging and up to 43 measures during dredging were collected across 13 sites, from High impact (Impact), Moderate impact (Indicator), Zone of influence (Influence) and Reference sites. However, as none of these sites are known to have seagrass the data are not necessarily a representation of the dredging related pressure that seagrasses are exposed to, but are a measure of the changes in burial that may occur with dredging. Site coordinates are detailed in Appendix 9.2. The Woodside Pluto Project (EPA 2007) data-set also contained pre- and during dredging data, but only data from the High impact zone is reported here (Details on sites in Appendix 9.3). Finally the Chevron Gorgon Project (EPA 2009) only contained data during dredging at seven sites, at the spoil ground designated as a Zone of Moderate Impact, and at sites with increasing distance from the dredge, up to 33 km away. Two sites were in the Zone of Influence and the remaining four were Reference sites. See Appendix 9.4 for site details. Each data set is presented below.

All three sites were influenced by cyclone activity at various times during the data collection periods (Table 8). These were likely to represent extreme periods of sediment resuspension and subsequent deposition into sediment traps. To remove potential cyclone effects on the estimated burial rates all measurements taken from the time the cyclone formed through to two days after passing the coast were removed from the data sets.

Table 8: Cyclones affecting the Cape Lambert, Gorgon and Pluto dredging programmes during periods when sediment taps were deployed. Data from these time periods were removed from the sediment trap data sets used to estimate burial rates.

Cyclone	Date	Data sets affected
Tropical Cyclone Bianca	25–30 January 2011	Gorgon Cape Lambert
Tropical Cyclone Carlos	15–17 February 2011	Gorgon Cape Lambert
Tropical Cyclone Heidi	12 January 2012	Cape Lambert
Tropical Cyclone Lua	17 March 2012	Cape Lambert

2.3.1 Rio Tinto Cape Lambert case-study – dredging impacts on burial

There was a large variation in the estimated burial depths among sites (Figure 10; Table 9). Prior to dredging the average burial depth across all sites ranged from 0.08 to 3.6 mm d^{-1} assuming a bulk density of 0.96 g DW cm^{-3} and 0.03 to 1.3 mm d^{-1} assuming a bulk density of 2.6 g DW cm^{-3} (Figure 10). Prior to dredging, sites in the Moderate Impact (MDR), Zone of Influence (MAN, SMSB) and the High Impact zone (PWR) had the highest estimated burial depths.

During dredging the average burial depth across all sites ranged from 0.16 to 2.8 mm d^{-1} assuming a bulk density of 0.96 g DW cm^{-3} and 0.06 to 1.0 mm d^{-1} assuming a bulk density of 2.6 g DW cm^{-3} (Figure 10). During dredging, the average burial depths were lower at the high impact site (PWR) than pre-dredging (0.66x), while at four of the five moderate impact (indicator) sites they were higher (BTR, 6.2x; BZI, 2.6x; BZR, 9.1x; CLW, 3.2x) and likewise at three of the five Zone of Influence sites (BLR, 2.5x; PLR 2.7x; SMSB, 1.4x) and one of the two reference sites (HAT 2.8x).

At the sites which had increased burial rates during dredging, the average across sites ranged from 0.28 to 2.4 mm d^{-1} assuming a bulk density of 0.96 g DW cm^{-3} or 0.10 to 0.89 mm d^{-1} assuming a bulk density of 2.6 g DW cm^{-3}. At these sites, there was also an increase in the 80th and 95th percentile readings and the maximum burial depths (Table 9). For example, based on the more realistic bulk density for dredging sediments (0.96 g DW cm^{-3}) the maximum burial depths recorded ranged from 1.4 to 18.5 mm d^{-1}. The Zone of Influence and Reference sites that had high burial depths prior to dredging, continued to have relatively high rates during dredging.

Focusing only on those sites that were predicted to be within the Zone of High Impact or the Zone of moderate impact (PWR, BTR, BZI, BZR, CLW & MDR), 4 of the 6 showed an increase in estimated average burial rates during dredging compared to pre-dredging (Fig 10). Across these sites, the average burial rates during dredging ranged from 0.10 to 1.03 mm d^{-1} based on a bulk density of 2.6 g DW cm^{-3} or 0.28 to 2.8 mm d^{-1} based on a bulk density of 0.96 g DW cm^{-3}. At these same sites, the estimated maximum sediment burial rates ranged from 0.52 to 6.85 mm d^{-1} based on a bulk density of 2.6 g DW cm^{-3} or 1.39 to 18.5 mm d^{-1} based on a bulk density of 0.96 g DW cm^{-3}.

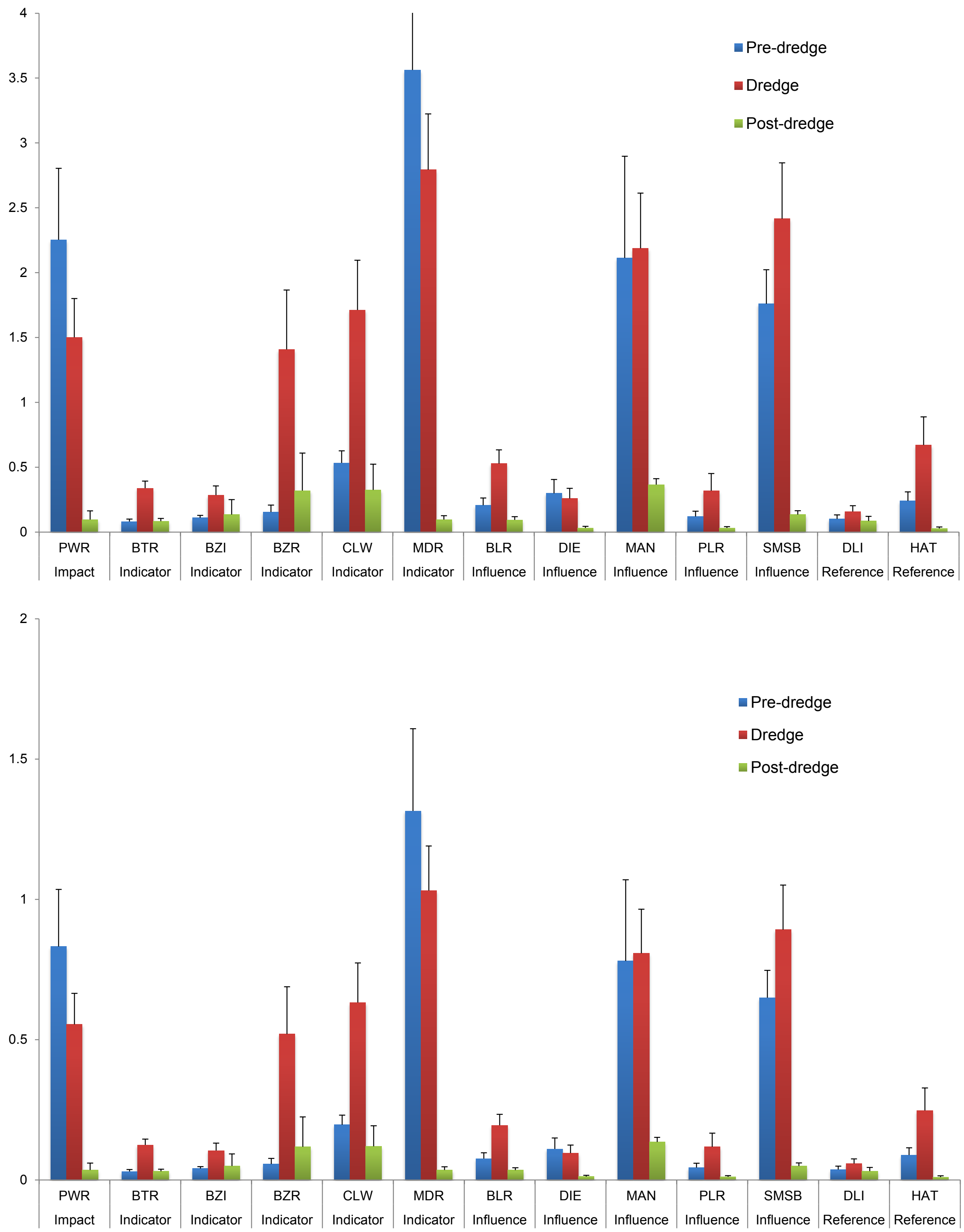

Figure 10: Burial rates (mm d^{-1}) estimated from sediment traps where sediment was assumed to be predominantly dredging sediments with a bulk density of 0.96 g DW cm^{-3} (Top), or marine sediment with an average bulk density 2.6 g DW cm^{-3} (Bottom), across a range of sites monitored in the Rio Tinto Cape Lambert dredging program. Sites were identified as Impact, in the High impact zone, Indicator in the Moderate impact zone, Influence in the Zone of influence and Reference, outside of the Zone of influence.

Table 9: Burial depth (mm d^{-1}) prior to (Before) and during (During) dredging at the Rio Tinto Cape Lambert Project at a range of sites with increasing distance from the dredge site. Burial depths are quoted as a range based on bulk density of the sediment 0.96 g DW cm^{-3} the commonly measured bulk density of dredged sediments or 2.6 g DW cm^{-3}, an average bulk density of marine sediments.

			Burial (mm d^{-1})					
Site code	**Management zone**	**Dredging**	**Median**	**80th**	**95th**	**Max**	**N**	**Dates**
PWR	Impact	Before	1.06–2.25	1.29–2.88	1.31–2.49	1.31–2.55	7	22/5/2010–6/12/2010
		During	0.29–0.78	1.06–2.87	1.80–4.87	2.10–5.71	34	19/12/2010–24/9/2012
BTR	Indicator	Before	0.02–0.06	0.04–0.12	0.06–0.15	0.06–0.16	7	24/5/2010–9/12/2010
		During	0.07–0.18	0.18–0.49	0.42–1.14	0.52–1.39	39	22/12/2010–26/9/2012
BZI	Indicator	Before	0.03–0.08	0.05–0.13	0.07–0.19	0.08–0.21	7	20/5/2010–9/12/2010
		During	0.03–0.09	0.15–0.40	0.42–1.14	0.73–1.98	42	22/12/2010–25/9/2012
BZR	Indicator	Before	0.03–0.07	0.12 –0.31	0.13–0.35	0.13–0.35	7	20/5/2010–9/12/2010
		During	0.12–0.33	0.70–1.90	1.73–4.69	6.85–18.55	43	22/12/2010–25/9/2010
CLW	Indicator	Before	0.17–0.47	0.24–0.65	0.33–0.88	0.36–0.98	7	23/5/2010–7/12/2010
		During	0.22–0.60	0.96–2.59	2.82–7.64	3.74–10.12	42	21/12/2010–25/9/2012
MDR	Indicator	Before	1.15–3.13	2.11–5.72	2.34–6.33	2.35–6.36	7	22/5/2010–8/12/2010
		During	0.83–2.25	1.90–5.14	2.90–7.87	3.92–10.61	41	19/12/2010–24/9/2012
BLR	Influence	Before	0.07–0.18	0.10–0.29	0.15–0.42	0.17–0.47	7	23/5/2010–7/12/2010
		During	0.08–0.22	0.32–0.86	0.64–1.75	1.12–3.03	41	21/12/2010–25/9/2012
DIE	Influence	Before	0.09–0.25	0.12–0.32	0.27–0.72	0.33–0.89	7	25/5/2010–10/12/2010
		During	0.03–0.08	0.16–0.44	0.27–0.73	1.10–2.99	41	21/12/2010–25/9/2012
MAN	Influence	Before	0.51–1.39	1.00–2.70	1.96–5.30	2.35–6.36	7	23/5/2010–7/12/2010
		During	0.40–1.08	1.47–3.96	1.91–5.19	5.69–15.40	41	21/12/2010–25/9/2012
PLR	Influence	Before	0.03–0.10	0.06–0.16	0.10–0.29	0.12–0.33	7	21/5/2010–6/12/2010
		During	0.03–0.07	0.69–0.18	0.56–1.52	1.88–5.10	41	19/12/2010-26/9/2012
SMSB	Influence	Before	0.70–1.89	0.83–2.24	0.89–2.41	0.91–2.48	7	22/5/2010–6/12/2010
		During	0.54–1.47	1.37–3.72	3.12–8.46	4.30–11.64	42	19/12/2010–24/9/2012
DLI	Reference	Before	0.02–0.07	0.07–0.19	0.08–0.22	0.08–0.22	7	24/5/2010–10/12/2010
		During	0.04–0.10	0.06–0.16	0.16–0.43	0.66–1.79	40	23/12/2010–27/9/2012
HAT	Reference	Before	0.07–0.19	0.13–0.36	0.19–0.52	0.21–0.58	7	21/5/2010–8/12/2010
		During	0.05–0.14	0.23–0.61	1.43–3.87	2.31–6.24	41	22/12/2010–26/9/2012

2.3.2 *Pluto case-study – dredging impacts on burial*

For the Pluto dredging project, sediment deposition was measured for three months prior, and three months during dredging at the same time of year, November to February 2006–07 and 2007–08 (Table 10). Once again this was at sites where seagrass was not present, so does not reflect pressures that seagrass were exposed to, but sediment deposition and burial within a High impact zone. Two sites were consistently monitored in the High impact zone, but both had gaps in the data, so are pooled here (See Appendix 3 for site information). There were significant increases in sediment deposition as measured by sediment traps during the dredging period compared to baseline in the High Impact Zone (Table 10). However, these data are not directly comparable due to differences in instrumentation used in the pre- and during-dredging periods (MScience 2008). Based on the more realistic bulk density of 0.96 g DW cm^{-3} the estimated burial depth prior to dredging averaged around 0.05 mm d^{-1}, with a maximum of 0.30 mm d^{-1}. During dredging the average burial rate increased 12 fold, to 0.58 mm d^{-1} and the maximum increased 4 fold, to 1.14 mm d^{-1}. Compared to the Cape Lambert Dredging program, burial depths during dredging were lower for the Pluto project.

Table 10: Burial depth (mm d^{-1}) prior to (Pre) and during (During) dredging at the Woodside Pluto Project in the High impact zone. Burial rates were estimated from the sediment trap data. Burial depths are quoted as a range based on bulk density of the sediment (0.96 g DW cm^{-3} the commonly measured bulk density of dredged sediments or 2.6 g DW cm^{-3}, an average bulk density of marine sediments. (x) indicates the increase relative to background levels.

	Burial depth (mm d^{-1})			
Time	**Avg.**	**Median**	**Max**	**Dates**
Pre-dredge	0.02–0.05	0.01–0.02	0.11–0.30	11/2006–02/2007
During dredge	0.22–0.58	0.15–0.41	0.42–1.14	11/2007–02/2008
Change	12x	16x	4x	

2.3.3 *Gorgon case-study – dredging impacts on burial*

The Gorgon case-study does not have pre-dredging data, so we only compare sites across a gradient, away from the dredge and at the spoil ground (Table 11). The estimated burial rates were lower than in the two previous case-studies. Once again there was variation among sites, although without background data it is impossible to separate site variation and any influence of dredging. Across all sites and during the dredging period, the average estimated sediment burial rates were 0.03 - 0.09 mm d^{-1} based on a bulk density of 0.96 g DW cm^{-3}, and were 0.09–0.25 mm d^{-1} based on a bulk density of 2.6 g DW cm^{-3}. Generally the Reference site LNG3 had the highest burial rate, followed by the Spoil ground and MOF3, the Zone of Influence.

In the spoil ground site (LONE), which is the only site predicted to be within an impact zone (Zone of Moderate Impact), the estimated mean burial rate was 0.19 mm d^{-1} and the maximum 1.24 mm d^{-1} based on a bulk density of 0.96 g DW cm^{-3} (Table 11). Based on the spoil ground average burial rates, the maximum possible sediment accumulation over a two week period is estimated at 2.6 mm, or based on the maximum burial rates, 17.4 mm.

Table 11: Range of estimated burial rates (mm d^{-1}) at sites monitored during the Gorgon Dredging project during non-cyclone periods. Note no pre-dredging data is available. The sites were located at the spoil ground and then with increasing distance from the dredge. All sites were considered to be in the Zone of Influence or beyond the influence of the dredging activity. Burial rates were estimated from the sediment trap data. Burial depths are quoted as a range based on bulk density of the sediment (0.96 g DW cm^{-3} the commonly measured bulk density of dredged sediments or 2.6 g DW cm^{-3}, an average bulk density of marine sediments.

			Burial (mm d^{-1})						
Site code	**Management zone**	**Dist. from dredge (km)**	**Avg.**	**Median**	**80th**	**95th**	**Max**	**N**	**Dates**
LONE	Zone of Moderate impact	Spoil ground	0.07–0.19	0.03–0.09	0.13–0.34	0.22–0.59	0.46–1.24	30	19/5/2010–25/11/2011
MOF3	Zone of influence	1.5	0.08–0.23	0.04–0.11	0.13–0.35	0.21–0.57	0.45–1.22	33	26/5/2010–17/11/2011
LOW1	Zone of influence	1.6	0.03–0.09	0.02–0.07	0.04–0.10	0.08–0.23	0.13–0.34	22	8/8/2010–26/11/2011
LNG3	Reference	5.0	0.09–0.25	0.04–0.11	0.12–0.33	0.28–0.76	0.62–1.67	31	12/5/2010–4/11/2011
DUG	Regionally significant area	9.4	0.04–0.12	0.02–0.05	0.06–0.16	0.19–0.50	0.27–0.73	30	17/6/2010–18/11/2011
ELS	Regionally significant area	24	0.04–0.12	0.01–0.03	0.05–0.13	0.17–0.47	0.34–0.92	20	9/2/2010–16/11/2011
SBS	Regionally significant area	30	0.04–0.11	0.01–0.05	0.02–0.16	0.06–0.28	0.26–0.71	26	5/5/2010–16/11/2011

2.3.4 Dredging impacts on burial summary

We have provided the estimated sediment burial depths in order to provide some insights into the sorts of burial stresses that seagrasses might experience in NW Australia. However, it is crucially important that the potential errors associated with these estimates are understood. In the absence of direct measurements of sediment accretion at sites within the zone of influence of a dredge plume, we have had to estimate likely burial rates from sediment trap data. A number of recent studies have questioned the usefulness of sediment traps for measuring net sediment accumulation rates. Storlazzi et al., (2011) consider sediment traps as only providing approximations of the amount of sediment that deposits, while others have suggested that they may be more useful for describing sediment dynamics than provide any useful data on sedimentation (Buesseler et al., 2007; Gardner, 1980; Gardner et al., 1983). Ridd et al. (2001) suggests that traps collect sediments that never actually settle because the natural erosional forces cannot act once material has dropped into the traps. Two very recent studies compared sediment trap data to data collected using other methods that were not prone to the resuspension-limitation of traps and showed that sedimentation rates estimated by traps were at least one and possibly as much as two order of magnitude higher than those derived using the alternative methods (Browne et al. 2012; Field et al. 2012). Of course, those other methods may also have inherent limitations and the studies did not always have tightly paired data for both methods. However, they do suggest that sediment trap data can potentially produce significant over-estimates of net sediment accumulation. With the above discussion in mind, the burial rates presented here need to be interpreted with caution. In all likelihood the estimated sediment burial rates represent the gross sediment burial depth rather than the net depth that would be the sum of deposition and removal through resuspension. Similarly, it is not clear whether the sediment deposited in the traps arrived at a constant rate over the deployment period or in discreet events. Given the considerable concerns that sediment traps likely over-estimate sediment deposition, the burial rates and depths presented here equate to the theoretical maxima that a seagrass growing at the sites would experience.

Across the three data sets, the estimated maximum burial rates were 1.14, 1.67 and 18.5 mm d^{-1} at the Pluto, Gorgon and Cape Lambert projects, respectively. Without reliable field data, it is impossible to determine the timescale over which this sediment accumulation would occur before a resuspension event resulted in a loss of sediment and a reduction in the burial depth or slowing of the rate of accumulation. However, if we assume totally calm conditions with no resuspension, then, at the estimated maximum sediment burial rates, it would require between 2 and 35 days to accumulate a sediment depth of 40 mm, which has been shown to induce negative effects on some seagrasses (see Section 3.2.2). Again, in the absence of field measurements it is impossible to validate these estimates and the upper estimates of burial depths and burial rates presented here should be taken as extremes.

Key Points

- There are no direct measurements of burial depths during dredging campaigns, and under natural conditions.
- Burial depths have been estimated from sedimentation rates, although there are limitations in this approach and they should be interpreted with caution and only as theoretical estimates.
- Burial depths estimated from sedimentation rates are higher during dredging compared to before dredging conditions at most sites in the High and Moderate impact zones, and sometimes in the Zone of Influence. The increase based on average burial rate ranges from 1.4 to 13 fold.
- The estimated burial rates varied among sites:
- During dredging periods and across all sites measured in the Cape Lambert, Pluto and Gorgon projects, the estimated <u>average</u> sediment burial rates during dredging periods ranged from 0.09 to 2.8 mm d^{-1} based on a sediment density of 0.96, and from 0.03 to 1.0 mm d^{-1}, based on a sediment density of 2.6 g DW cm^{-3}. Over the same period, the estimated <u>maximum</u> burial rates ranged from 0.34 to 18.5 mm d^{-1} based on a sediment density of 0.96, and from 0.13 to 6.8 mm d^{-1}, based on a sediment density of 2.6 g DW cm^{-3};

- During dredging periods, and at sites that were predicted to be impacted by increased sedimentation (i.e. only sites within High or Moderate Impact Zones), the <u>average</u> burial rates ranged from 0.19–2.8 mm d^{-1} assuming a bulk density of 0.96 g DW cm^{-3} or 0.07–1.0 mm d^{-1} assuming a bulk density of 2.6 g DW cm^{-3}. <u>Maximum</u> burial rates at the same sites ranged from 1.1–18.5 mm d^{-1} assuming a bulk density of 0.96 g DW cm^{-3} or 0.42–6.8 mm d^{-1} assuming a bulk density of 2.6 g DW cm^{-3}.

3 Globally derived thresholds for seagrasses in relation to dredging related stressors

This section of the Review focuses on thresholds of tolerance that have been developed for light reduction and sediment burial. Available data are reviewed for adult (adult survival and growth) and juvenile life-history stages (seed germination and seedling growth).

3.1 Thresholds for adult plants

3.1.1 Light

A number of threshold metrics related to light requirements have been developed for survival of adult plants (Table 12). Light threshold analysis can be applied to different components of the environment including: the entire water column, through light attenuation coefficients (e.g. Duarte et al. 2007) or Secchi disk depths (e.g. O'Brien et al. 2011); or light at the top of the seagrass canopy, expressed as percentage of surface irradiance (e.g. Dennison et al. 1993, Kemp et al. 2004), instantaneous, mean daily or total daily irradiance (Collier et al. 2012, Gacia et al. 2012) or the number of hours of saturating irradiance per day (H(sat), e.g. Collier et al. 2012). These thresholds can also be integrated over time, which is relevant to management when pressures persist over particular durations, e.g. dredging or flood plumes. The percentage of days below a particular mean daily irradiance (Collier et al. 2012) or the sum of the hours below saturating irradiance compared to reference conditions (Lavery et al. 2009) are two examples where thresholds have been proposed to predict the onset of seagrass mortality. In a recent large-scale dredging project in Gladstone, Queensland, a threshold based on a two-week rolling average of the total daily irradiance was set at 6 mol m^{-2} d^{-1}. This was derived from long-term monitoring and experimental shading and based on the most sensitive species (Chartrand et al. 2012).

Table 12: Light thresholds for adult plants of NW seagrass species. (MLR = Minimum Light Requirement; LAC = Light Attenuation Coefficient; PSN = Photosynthesis; PPFD = Photosynthetic Photon Flux Density)

Species	Intensity of light reduction			Duration of light reduction			
	Avg Daily Irrad. (mol photon-m^{-2} d^{-1})	**% Surf. Irrad.**	**LAC**	**Hrs saturated PSN**	**Months Survival Below MLR**	**% Days below 3 mol m^{-2}d^{-1}**	**Avg. PPFD over 2 weeks (mol m^{-2} d^{-1})**
Hydrocharitaceae							
Enhalus acoroides							
Halophila decipiens[1,2,3,4,5]		2.8–8.8	0.08–0.01				
Halphila ovalis (inc ovata, minor)[5,6,7]	<5	6–16			1		
Halophila spinulosa[8,9]		5–6					
Thalassia hemprichii							
Cymodoceaeceae							
Cymodocea angustata							
Cymodocea rotundata							
Cymodocea serrulata							
Halodule uninervis (inc pinifolia)[10, 11]	4.8–10	14–19		3.9–4.2	3–4	15–18	
Syringodium isoetifolium							
Thalassodendron ciliatum							
Mixed meadows[12]							6

1. (Dennison 1987) 2. (Williams & Dennison 1990) 3. (Fourqurean et al. 2003) 4. (Duarte 1991) 5. (Dennison et al. 1993) 6. (Schwarz et al. 2000) 7. (Longstaff et al. 1999) 8. (Udy & Levy 2002) 9. (Knowles 2005) 10. (Longstaff & Dennison 1999) 11. (Collier et al. 2012) 12. (Chartrand et al. 2012).

Only four of the eleven species found in the NW have had light threshold criteria derived for them, and none of these were derived locally (Table 12). There is a range of ways that the light stress has been expressed in the different studies, so the same metric cannot be compared across all species of seagrass. Within studies of individual species, where the same metric was used to describe the light stress and the same method used to generate the threshold, there is a range in the threshold value. This can be explained by the location and environment the species is growing in (Collier et al. 2012, Yaakub et al. 2014). For example, when a similar level of light reduction (% of ambient) was applied to *H. ovalis* in a turbid- and a clear-water environment, the clear water populations were more resilient to light reduction than the turbid-water populations (Yaakub et al. 2014).

All of the published and grey-literature thresholds of tolerance relating to change in light that were collated during this review are based on light quantity, not quality. They have also been based on survival of adult plants, though the light requirements to sexually reproduce may be higher than those required to sustain adult plants (Rollon et al. 2003). Therefore, for populations or species where sexual reproduction is important for the maintenance of the population, thresholds relevant to sexual reproduction and seedling establishment should be considered.

The thresholds which have been developed to date indicate a wide variability in the sensitivity of species of seagrass to light reduction. For example, some populations can survive with 3% of surface irradiance (*H. decipiens*) while other have a threshold of 19% surface irradiance (*H. uninervis*). Due to the variability found in thresholds within and across species, studies to determine the thresholds of species in NW Australia need to impose a range of light reductions, including very severe reductions (>80%). The results also indicate that some of the species commonly found in NW Australia can persist at light levels below what some studies have determined as the minimum light requirement for between 1 and 4 months. In the next section, we overlay the known thresholds for seagrasses presented here with the conditions experienced during dredging from a NWWA perspective based on the Chevron Gorgon Project to identify if dredging in NWWA is likely to impact seagrass habitat based on the currently known thresholds.

Key Points

- Absence of locally-derived thresholds for NW Australian seagrasses.
- Absence of thresholds related to reproductive capacity of seagrasses.
- Absence of a standardised approach to deriving thresholds to light reduction.

3.1.2 Sediment burial

The level of sedimentation or burial that species can cope with has been studied for 7 out of 13 species in NW Australia (Table 13), and a burial of 8 cm has been identified as a critical level for some tropical species (Ooi et al. 2011). Generally, larger species such as Enhalus can cope with greater sediment burial depths, and species with the ability to elongate vertical stems, such as *Cymodocea serrulata, Thalassia hemprichii, Syringodium isoetifolium* and *Halodule uninervis*, can escape the impacts of sedimentation (Vermaat et al. 1997, Mills & Fonseca 2003, Eldridge et al. 2004). However, this ability to elongate is dependent in some species on clonal integration, the sharing of resources within a ramet or connected piece of rhizome, and species such as *C. serrulata* and *S. isoetifolium* are more likely to elongate vertical stems if clonal integration is not present (Ooi et al. 2011). Therefore, in a dredging context, if a large area is impacted and clonal integration is impaired, species would still have the ability to elongate their vertical stems. In addition, responses to sedimentation vary seasonally, so some species may be more resilient to sediment burial at different times of year (Vermaat et al. 1997).

All of the studies reviewed imposed burial as a single allocation of sediment on top of the seagrass. In some cases, the focus of the studies was on bioturbation, which is likely to produce deep (several cm) and sudden burial (Ooi et al. 2011). Leaving aside dredge spoil dumping, dredging produces a suspended sediment plume that is subject to deposition and resuspension, the balance of which will be a function of the settling velocity of the particles, the shear stress acting on them and the distance from the point of origin. Since the shear acting on the particles will vary with time, plume sediments may be continually depositing and resuspending over a variety of timescales, particularly in the far-field area of plume distribution. This will affect both the depth of sediment deposition on top of a seagrass as well as it persistence. Therefore, it is unclear whether a single depositional event, such as those imposed in many experimental studies, is the sort of stress experienced by seagrasses around dredge plumes, and whether the thresholds derived from them are transferable to a dredging context. At this point in time, we are not able to discern this because the current sediment deposition rates are based on sediment traps which integrate over 5–118 days (see above). In addition as sediment traps do not allow resuspension (Storlazzi et al. 2011), this is a gross deposition estimated from a week to month timescale.

Notwithstanding the above limitations, the existing thresholds provide some insights into the range of burial depths appropriate for developing dredging-related thresholds. Clearly, 8 cm appears to be an upper limit of tolerance and 2–4 cm imposes a severe stress on most species studied. Therefore, burial depths less than 8 cm, and probably less than 4 cm, are likely to be required to develop lethal, sub-lethal and lowest observable effects thresholds. The effects measured in the published studies were recorded after 27 days. Any experimental studies should be prepared to run for at least this length of time to detect effects. The significance of periodic burial by, and removal of, sediment may also need to be addressed, though more data on sediment dynamics around in dredging plumes (WAMSI Dredging Science Program Theme 3) is required to confirm the relevant dynamics (depth of burial and persistence).

Table 13: Sediment burial thresholds for adult plants of NW seagrass species.

Species	Sedimentation threshold (cm yr^{-1})	50% Mortality (cm)	100% Mortality (cm)	Impacts after 27 days
Hydrocharitaceae				
Enhalus acoroides[1,2]	10	4	Did not occur at 16 cm	
Halophila decipiens				
Halphila ovalis (inc ovata, minor)[1,2,3]	2	2	2	4
Halophila spinulosa				
Thalassia hemprichii[2]		4	Did not occur at 16 cm	
Cymodoceaeceae				
Cymodocea angustata				
Cymodocea rotundata[1,2]	1.5	2	8	
Cymodocea serrulata[1,2,3]	13	2	Did not occur at 16 cm	4
Halodule uninervis (inc pinifolia)[2,3]		4	Did not occur at 16 cm	4
Syringodium isoetifolium[2,3]		8	Did not occur at 16 cm	4
Thalassodendron ciliatum				

1. (Vermaat et al. 1997) 2. (Cabaco et al. 2008) 3. (Ooi et al. 2011)

Key Points

- Limited data on the magnitude and temporal dynamics of sediment deposition and resuspension in the far-field of dredging sediment plumes.
- To date, thresholds have been developed based on annual sediment addition, or total burial depth from a single depositional event, but not with periodic sediment deposition and removal which is more likely to be the pathway that impacts seagrasses.

3.2 Thresholds for juvenile phases

Of the eleven species of seagrass found in the NW, one produces seeds without a seed coat and without a distinct dormancy period, and seedlings that develop for some time on the parent plant (*Thalassodendron ciliatum*); two produce seeds that have a fleshy or membranous seed coat and no distinct dormancy period (*Enhalus acoroides, Thalassia hemprichii*); and the remaining eight species *(Halophila decipiens, H. ovalis (inc. ovata, minor), H. spinulosa, Cymodocea angustata, C. rotundata, C. serrulata, Halodule uninervis (inc. pinifolia)* and *Syringodium isoetifolium*) produce seeds with a hard seed coat and distinct dormancy period (based on categorization by seed anatomy and germination history (Kuo & Kirkman 1996)). The species with a distinct dormancy have a greater potential to persist as a seed bank during unfavourable environment conditions and then germinate when conditions become more favourable.

3.2.1 Light thresholds

Only two of the eleven species found in the NW have had light threshold data derived for early life-stages (seed/seedlings) and none of these were derived from local populations (Table 14). The two reported studies on *Halophila decipiens* and *H. spinulosa* did not show consistent trends with light availability. More importantly, for these studies light thresholds for germination (ie. dormant seed species) should not be considered reliable because of discrepancies with pre-treatments (exposure to a range of environmental conditions prior to experimental manipulation with light) that may indeed induce/prevent seed germination (Orth et al. 2000). There has been one study that examined the effects of light quality on the germination of *Thalassia hemprichii* seeds, but no thresholds were developed. It found that blue light enhanced germination of seeds (Soong et al. 2013).

Table 14: Light thresholds for juvenile phases of NW seagrass species.

Species	Life-Stage	Intensity		Duration
		Avg Daily Irrad. (Id – mol photon $m^{-2}d^{-1}$)	**% Surf. Irrad.**	**Duration of survival below minimum light (days)**
Hydrocharitaceae				
Enhalus acoroides				
Halophila decipiens [6]	Seed (germination)	Require light to germinate		
Halphila ovalis (inc ovata, minor)				
Halophila spinulosa [2]	Seed (germination)	0.26–10.8 No consistent germination		
Thalassia hemprichii				
Cymodoceaeceae				
Cymodocea angustata				
Cymodocea rotundata				
Cymodocea serrulata				
Halodule uninervis (inc pinifolia)				
Syringodium isoetifolium				
Thalassodendron ciliatum				
Other Species				
Zostera marina [1,8]	Seedling	2.58 (±3.034)	11–34	< 40 days
Zostera marina [7]	Seed	No effect		
Halophila engelmannii [3,4,5]	Seed	Germinated in light & dark (pre-exposure to light may be influential)		

1. (Biber et al. 2009) 2. (Birch 1981) 3. (McMillan 1988) 4. (McMillan 1986) 5. (McMillan 1991) 6. (McMillan 1988) 7. (Moore et al. 1993) 8. (Ochieng et al. 2010)

3.2.2 Sediment burial thresholds

Only one of the eleven species found in the NW has had sediment burial threshold data derived for early life-stages and this was for *Thalassia hemprichii*, a species that produces seeds with a fleshy or membranous seed coat and no distinct dormancy period (Table 15). Rollon et al. (2003) found that *T. hemprichii* seedlings could not withstand sediment burial greater than 5cm. However, this value maybe even lower, since this value was the shallowest burial depth treatment.

Reports on other species not found in NW Australia, but which produce seeds with a hard seed coat and distinct dormancy period (e.g. *Zostera marina*, temperate species) suggests that the critical burial depth could be dependent on the maximum height that the cotyledon extends post-germination (Greve et al. 2005, Valdemarsen et al. 2011).

Table 15: Sediment burial thresholds for juvenile phases of NW seagrass species.

Species	Life-Stage	Deposition Threshold 100% mortality (cm)
Hydrocharitaceae		
Enhalus acoroides[1]		
Halophila decipiens		
Halphila ovalis (inc ovata, minor)		
Halophila spinulosa		
Thalassia hemprichii [2]	Seedling	5
Cymodoceaeceae		
Cymodocea angustata		
Cymodocea rotundata		
Cymodocea serrulata		
Halodule uninervis (inc pinifolia)		
Syringodium isoetifolium		
Thalassodendron ciliatum		
Other Species		
Zostera marina [1, 3]	Seed	5.5

1. (Greve et al. 2005) 2. (Rollon et al. 2003) 3. (Valdemarsen et al. 2011)

Key Points

- There is a poor understanding of thresholds of tolerance for juvenile life-history stages (i.e. seed germination and seedling survival).
- There are no locally derived thresholds.

3.2.3 Interactions with light reduction and sediment burial thresholds

No studies to our knowledge have examined the combined effects of light reduction with sediment burial to give insight into these interactions, and how this effects the development of thresholds. It is possible that there could be a trade-off between responding to reduced light and burial, particularly in terms of investing energy into vertical rhizome extension when resources are limited.

4 Comparison of seagrass thresholds with pressure fields from dredging in NWWA assess if local dredging pressures could impact seagrass

Previously we presented the known seagrass thresholds of tolerance for light reduction and sediment burial as well as the light reductions and sediment burial stresses measured during dredging in NWWA from three different projects. In this section, these two sets of data are brought together to assess whether the sorts of light reduction and burial changes dredging has created in NWWA are likely to significantly affect seagrasses in that region. We use three different case-studies, the Chevron Gorgon dredging project for predicted light impacts, and for sediment burial impacts the Rio Tinto Cape Lambert, Woodside Pluto and Chevron Gorgon dredging project. As stated previously, none of the thresholds of tolerance were derived from studies in NW Australia and so these should be viewed as indicative only until more reliable, locally-derived thresholds become available.

4.1 Predicted impacts with light reduction

We assessed if seagrass habitat would be impacted by the reductions in the total daily benthic light data from the DUG site, where seagrass has been observed. This site was ~ 10 km away from the dredge and was categorised as a reference site. However, reductions in light were observed at DUG that appeared to be related to dredging. We used the thresholds from Table 11 that could be applied to the industry data, and where necessary recalculated the industry data to assess against these thresholds:

- the average daily irradiance, % days below 3 mol m^{-2} d^{-1}; and
- the average light over two weeks (Table 16).

Due to the limited number of species where thresholds have been derived, the assessment was limited to two species, *H. uninervis* and *H. ovalis*. At the DUG site, the total daily irradiance was, on average, less than 4.8 mol m^{-2} d^{-1} (Table 6). This amount of light during dredging triggered the threshold for *H. ovalis* and *H. uninervis*. In fact, the light dropped below 5 mol m^{-2} d^{-1} in 58% of the observations during the dredging period, compared to 25% in the pre-dredging time. The percentage of days below 3 mol m^{-2} d^{-1} during the dredging period was 29%, therefore this threshold is also triggered (15–18%), indicating there would likely have been impacts to *H. uninervis* seagrass if present. During the background period only 8% of days were below this threshold. Finally, the threshold of average daily light over a two-week period was also triggered. Over the dredging period, the 2 weekly running mean of total daily light was below 6 mol m^{-2} d^{-1} in 72% of occasions, compared to 40% in the pre-dredging time. Therefore if Halophila or Halodule seagrass was present, it is likely to have been impacted.

Table 16: The percentage of sampling occasions that light thresholds for adult plants of NW seagrass species are potentially breached based on dredging conditions in the Chevron Gorgon Project. Highlighted cells indicate this threshold is likely to be exceeded or exceeded more often under dredging conditions.

Species	**Literature derived thresholds**					
	Average Daily Irradiance (mol photon-m^{-2} d^{-1}) <5 (*H. ovalis*) <4.8 (*H. uninervis*)		**15–18% of days below 3 mol m^2d^{-1}**		**Avg. PPFD over 2 weeks <6 mol m^{-2} d^{-1}**	
	Reference conditions	**Dredging conditions**	**Reference conditions**	**Dredging conditions**	**Reference conditions**	**Dredging conditions**
Hydrocharitaceae						
Enhalus acoroides						
Halophila decipiens						
Halphila ovalis	25% of days	58% of days				
Halophila spinulosa						
Thalassia hemprichii						
Cymodoceaeceae						
Cymodocea angustata						
Cymodocea rotundata						
Cymodocea serrulata						
Halodule uninervis	25% of days	58% of days	8% of days	29% of days		
Syringodium isoetifolium						
Thalassodendron ciliatum						
Mixed meadows					40% of days	72% of days

4.2 Predicted impacts with sedimentation

Assessing whether the burial conditions that were characterised from the analysis of the industry data above, would likely impact seagrasses based on the thresholds extracted from the literature is challenging due to the differences in measurements and the uncertainty associated with the delivery and removal of sediments. Here we used the average and maximum daily burial rates estimated during each dredging campaign (see Section 2.3) to assess how long it would take to reach a threshold of 50% mortality in the seagrass species. We assume that sediment is not resuspended and exported over this time, and acknowledge that this is a significant assumption which potentially leads to over-estimating effects, a potential that was extensively discussed in Section 2.3. On the other hand, seagrasses do reduce resuspension of sediments (Gacia & Duarte 2001), so do have the potential to facilitate sediment accumulation over time. Clearly, more field data on the delivery, accretion and erosion of sediment in the far-field is required to understand the burial pressure field that seagrasses encounter. We present here an assessment based on the maximum estimated burial rates (from Section 3.2) and caution the reader to be aware that these are first-order theoretical estimates of the potential burial pressures rather than empirical measurements.

At the estimated average burial rates from Cape Lambert (range of site averages), it would take 7–71 days to exceed a burial threshold of 2 cm or 1–14 days with the maximum estimated burial rate (Table 17). The range in number of days is based on two different calculations across all sites that were predicted to be in the dredging footprint: one using the range of estimated average sediment deposition rates at the sites; and one using the range of estimated maximum deposition rates at the sites. For species with higher burial thresholds i.e. 8 cm, the number of days to reach the threshold are 29–286 at the average burial rate or 4–57 at the maximum rate. These are well within the range of the duration of dredging programs. At the two other dredging programs where the burial rates were much lower, the timescales to cause 50% mortality are much longer, based on the average rates, 34–421 days, or 18–64 days based on the maximum rates. As discussed previously, in the absence of *in-situ* sediment accumulation data it is unclear what the actual net rates of sediment accumulation are near dredging projects. The rates we have applied here are based on sediment trap data and there is a general view in the published literature that trap data are likely to over-estimate net sediment accumulation rates, possibly by orders of magnitude. If we assume, therefore, that the sediment accumulation rates are at the extreme upper end of what might occur *in situ*, then in most cases it is likely to require even longer periods of time than those indicated in Table 17 to reach the burial thresholds.

At this point, then, it is relevant to consider how likely it is that the sediment burial thresholds will be experienced at a seagrass site, given the lengths of time required to reach those thresholds. Because there are no readily available data on sediment resuspension at the sites, we cannot determine how likely it is that periods of 2–421 days without resuspension occur. However, it is unlikely that periods where there is no sediment resuspension for more than 10 days occur with regularity. On that basis, it might be concluded that the conditions required to allow the 50% mortality threshold to be breached are unlikely to be common. Importantly, however, there is photographic and anecdotal evidence of deep accumulations of very fine muddy sediments, (in the order of 10–15 cm deep, occurring in seagrass meadows north of a dredging operation at Geraldton, WA (R. Masini , Office of the EPA pers. comm.). This suggests that seagrass canopies may play a role in reducing resuspension and facilitating the accumulation of fine dredge-sediments. Clearly, this is an area requiring significantly more research supported by field data in order to provide more definitive advice on the pressures seagrasses experience near dredging projects.

Table 17: Sediment burial thresholds and time required to breach these for adult plants of NW seagrass species. Estimates relate to burial rates observed only at sites within the Zones of Moderate or High Impact.

		Days required to exceed 50 % mortality burial threshold based on:					
		Cape Lambert		Pluto		Gorgon	
Species	**50% Mortality Threshold (cm)**	**Avg. burial rate 0.28–2.8 mm d^{-1}**	**Max. 1.4–18.5 mm d^{-1}**	**Avg. 0.58 mm d^{-1}**	**Max. 1.14 mm d^{-1}**	**Avg. 0.19 mm d^{-1}**	**Max. 1.24 mm d^{-1}**
Hydrocharitaceae							
Enhalus acoroides	4	14–143	2–29	69	35	210	32
Halophila decipiens							
Halphila ovalis	2	7–71	1–14	34	18	105	16
Halophila spinulosa							
Thalassia hemprichii	4	14–143	2–29	69	35	210	32
Cymodoceaeceae							
Cymodocea angustata							
Cymodocea rotundata	2	7–71	1–14	34	18	105	16
Cymodocea serrulata	2	7–71	1–14	34	18	105	16
Halodule uninervis	4	14–143	2–29	69	35	210	32
Syringodium isoetifolium	8	29–286	4–57	138	70	421	64
Thalassodendron ciliatum							

Key Points

- Notwithstanding the significant assumptions made in the above comparisons, based on the light reduction measured during dredging campaigns in NWWA, seagrass species are likely to be exposed to reduced light conditions outside their tolerance thresholds in areas adjacent to dredging projects.
- With respect to sediment burial stress, there is more uncertainty regarding the levels of stress that plants would experience near dredging projects. Theoretically, it is possible that seagrasses could experience sediment burial pressures likely to induce 50% mortality, though this is based on the theoretical maximum sediment deposition rates (for non-cyclone periods) and assumes those rates occur for periods of several hundreds of days with no resuspension. In the absence of field data it is not possible to reliably confirm the actual pressures burial pressure seagrasses experience.
- The analysis highlights the significant lack of region-specific seagrass threshold data, and data that meaningfully quantify the pressure fields that are generated by dredging projects. Both these data deficiencies need to be addressed in order to improve the capacity to predict the impacts of dredging on seagrasses.

5 Bioindicators of dredging related stressors

Understanding how seagrasses respond to dredging related pressures allows the development of early warning bioindicators for use in the monitoring and management of dredging events. Here we summarise our understanding of how seagrass species respond to the dredging related-stressors, reduced light and sediment burial.

5.1 Response pathway to light reduction

There is a general understanding of the cause-effect pathway for light reduction in adult seagrasses (McMahon et al. 2013) (Figure 11). Generally there are physiological changes such as photosynthetic adaptations and reduction in storage carbohydrates, then changes in growth, and finally morphological adaptations such as loss of leaves or shoots, though the level of stress and extent of response varies between species.

The most consistent variables that are recommended to use as bioindicators of low light stress are those that respond early and could be used as sublethal indicators. These potential sublethal indicators include rhizome sugars, shoot C:N, leaf growth and the number of leaves per shoot, as well as those that respond at the meadow scale, including shoot density and above-ground biomass (McMahon et al. 2013) (Figure 12).

Only a few studies have assessed the effects of light quality on seagrasses. Ruppia was shown to change growth patterns when the R:FR ratio changed (Rose & Durako 1994) and Thalassia had higher rates of germination under blue rather than red light (Soong et al. 2013). Based on this very limited work, the implications for dredging related stresses are not clear.

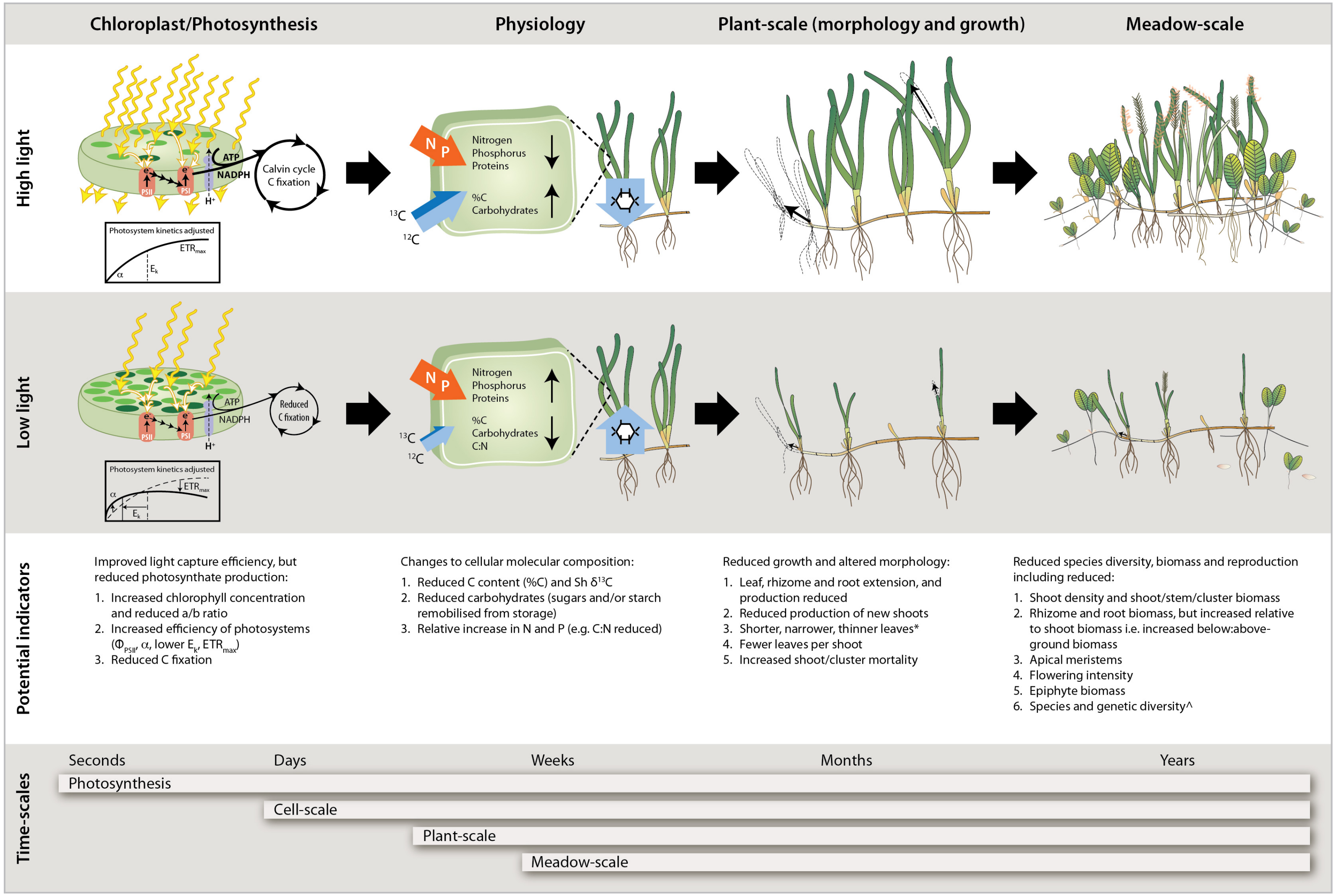

Figure 11. Responses of seagrass to low light stress (from McMahon et al. 2013). The author retains the right to use this published figure. The original is available at doi:10.1016/j.ecolind.2013.01.030.

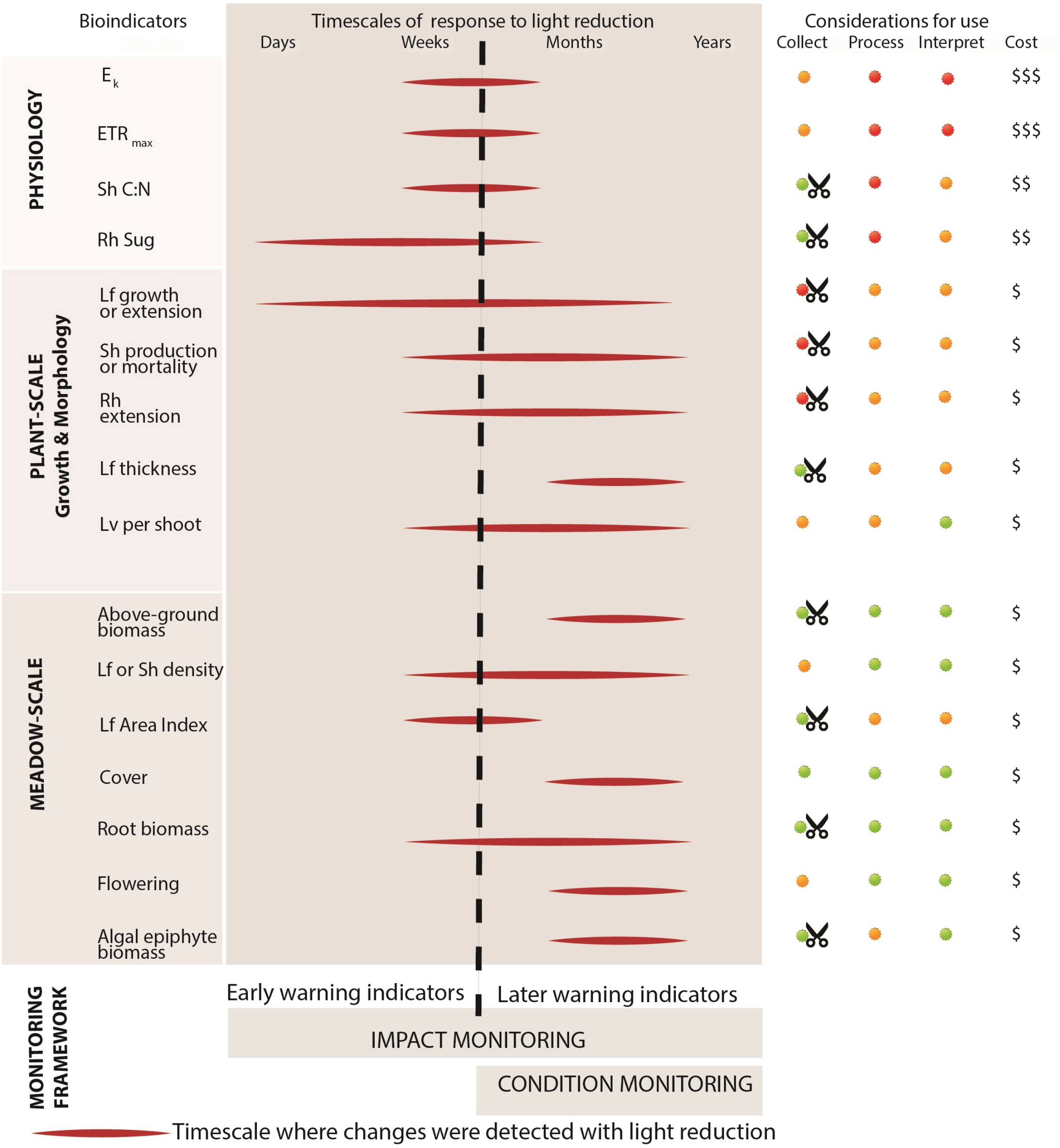

Figure 12. Most consistent bioindicators of light stress and the timescales which they respond over. The considerations when selecting these bioindicators including ease of collection, processing and Interpretation are colour coded with green the easiest and red the most difficult. Scissors indicate that destructive harvesting is required. The relative cost of taking this measure is also included where more $ indicate a greater cost (from McMahon et al. 2013). The author retains the right to use this published figure. The original is available at doi:10.1016/j.ecolind.2013.01.030.

5.2 Response pathway to sediment stress

The cause-effect pathway of seagrass responses to burial has been described in a number of studies, and tabulated in Cabaco et al. (2008). Here we have analysed this data set and subsequent studies to identify the consistent responses in adult plants to sediment burial. Here we present the findings from response variables that had five or more independent observations (Table 18).

In 100% of cases shoot mortality increased and in 80% of cases leaf growth declined with burial. Vertical internode length (60%) increased with burial, whereas specific leaf weight, shoot size and sheath length most consistently showed no change with burial, although in 38% of cases shoot size declined. Shoot density declined in 75% of cases with burial. There were only three studies which examined changes in above and below-ground biomass with burial, and all three showed a decline. This is another potential bioindicator, although further research is required to gain confidence in this measure.

Table 18. Response variables and potential bio-indicators of burial stress. Bolded numbers indicate a response of >50% of observations to this category for a particular variable.

Plant response	Increase	Decline	No change	Total studies
Growth				
Leaf growth	0	**4**	1	5
Shoot mortality	**5**	0	0	5
Morphology				
Vertical internode length	**6**	1	3	10
Leaf specific weight	0	3	**7**	10
Shoot size	0	5	**8**	13
Sheath length	2	1	**9**	12
Meadow-scale				
Shoot density	1	**9**	2	12

5.3 Interactions with light reduction and sediment burial

From the information presented above on bioindicators, we can identify three key variables that respond consistently to both light reduction and burial. These are leaf growth, shoot mortality and shoot density. In contrast vertical internode length did not show a consistent response to light reduction but does with burial, and there are a number of photosynthetic (Ek, ETRmax), physiological (storage carbohydrate, shoot C:N), growth (rhizome extension), morphology (leaf thickness and leaves per shoot) and meadow-scale response variables (cover, biomass, leaf-area-index, flowering, algal epiphyte biomass) that do respond to light reduction, but based on current knowledge, do not show a consistent response to burial. Further studies on burial responses may reveal some more similarities, particularly for variables such as rhizome carbohydrates, biomass. Ideally it would be informative to have reliable bioindicators for seagrass decline, such as shoot density or biomass, and bioindicators to indicate particular stressors such as reduced light (Ek, ETRmax) or burial (vertical internode length).

Key Points

- Bioindicators of responses to reduced light is relatively well-understood for seagrasses in general.
- Bioindicators of responses to burial stress is not well understood.
- Bioindicators of responses to multiple stressors is not well understood.

6 Insights for impact prediction, monitoring and management of dredging in seagrass habitat of NWWA

In this section we summarise the approaches that have been used for impact prediction, monitoring and management of dredging projects in NWWA and identify areas where there are opportunities for improvement. The analysis is based on review of some of the dredging projects in NWWA (Table 18, Lists projects and cites the relevant references).

6.1 Significance of seagrass habitat

6.1.1 Where was seagrass detected?

Of the 13 projects assessed, nine detected seagrass habitat in the surveys conducted prior to dredging (Table 19).

6.1.2 How was seagrass detected?

Method

The general approach to characterising habitats was to use drop-down, towed video in a defined area, stratified to target particular habitat types and cover the predicted footprint of the development. Usually, transects were used and the presence and, in some cases, cover of seagrass recorded in images captured along the transects. Habitat maps were generated from the resultant data. For small seagrasses, such as those growing in NWWA, there are challenges in detecting seagrass with dropdown, towed video. Video is typically of lower resolution thus still images are often blurred, which impacts the ability to see seagrass and increases the probability of not detecting it when it is present. Further investigation is required to develop the best approach for detecting seagrass habitat in this region.

Timing

The timing of surveys varied depending on the project. Most habitat maps were developed for one time period, with the exception of James Price Point, where mapping was carried out twice, at similar times of the year but in consecutive years. Most commonly habitat mapping was carried out from May–August.

From a management perspective it is critical to know the best time to undertake surveys for the detection and mapping of seagrass habitat. Many areas may contain significant habitat (e.g. dugong forage) at some times of the year but not at others, especially in NWWA. As was shown in WAMSI DSN Project 5.1.2 (McMahon et al. 2017) the dynamics of meadows may vary depending on the location and the type of meadow. At present we are not in a position to advise the best time of year to survey for all conditions. However, for deeper-water locations where seagrass meadows follow an annual cycle (e.g. James Price Pt, see WAMSI DSN Project 5.1.2 (McMahon et al. 2017)) the end of the dry season, around October, appears to be the best time to survey. For perennial meadows surveying at the time of year of maximum growth and biomass would be ideal. For intertidal meadows, such as those around Broome, this is October to January (see WAMSI DSN Project 5.1.2 (McMahon et al. 2017)). This understanding of the natural dynamics should be incorporated into standard operating procedures to guide habitat mapping, in order to maximise the chance of detecting these ecologically (e.g. dugong and turtle forage) significant habitats.

6.1.3 What was the rationale for deeming seagrass significant to assess for potential impacts?

Very few of the nine projects that detected seagrass considered that it was necessary to determine impacts to seagrass habitat from dredging (Table 19), for three reasons:

- in 4 of 9 cases the seagrass detected was outside of the dredge footprint (e.g. Thalassia, Thalassodendron and Halophila at Cape Lambert A and Dampier Marine Services Facility);
- in 3 of 9 cases it was patchily distributed and/or of low abundance and cover and difficult to map (e.g. Port Hedland Outer Harbour, Pilbara LNG, Anketell); and

- in 4 of 9 cases, there was seagrass present, that could be mapped but as it was predominantly Halophila species, which was considered very good at recovering from disturbance and was, therefore, predicted to suffer only short-term impacts, no further impact assessment or monitoring was considered necessary (e.g. Cape Lambert A, Gorgon). In these cases, it was also considered that as seagrass was growing close to coral habitat the thresholds developed for corals would protect seagrasses.

Table 19: Summary of seagrass habitat detection methods, significance and response variables from dredging projects in NWWA.

Project	Reference	Seagrass present	Method	Predicted impact	Measure of biota
Dampier Port Upgrade	(SKM 2006)	No		-	-
Port Hedland Finucane Island (RGP5)	(BHP 2008)	No		-	-
Port Hedland South West Creek	(PHPA 2010)	No		-	-
Pluto Mermaid Sound	(Approval 2007)	No		-	-
Anketell	(MScience 2008) (AECOM 2010b, AECOM 2010a, API 2010)	Yes	Drop down video transects (July–Sept 2009)	Minimal, not considered significant Sparse *H. ovalis*, 0% loss predicted as outside area of interest	Turbidity measure will be undertaken during dredging program will occur to manage TSS and sedimentation impacts
Cape Lambert A	(SKM 2007)	Yes	Drop down video (Nov 2008)	None Sparse Halophila previously recorded in impact area but not in surveys for this project. Thought that meadows recover quickly, so no impact. Thalassia*,* Thalassodendron and Halophila in reference area (5% cover)	None- not considered significant
Cape Lambert B	(SKM 2008, 2010b)	Yes	Drop down video	None Short term, localised. Very sparse ephemeral patches of Halophila, none is dredge footprint. Not considered to be a major contributor to BPPH. Halophila is a colonising species and so can tolerate frequent disturbances	
Gorgon	(RPS 2005, Chevron 2009)	Yes	Drop down video Photo quadrats for % cover; biomass (Nov 2008–Jul 2009)	Yes (in dredge spoil area), but short-term impact, as Halophila and will recover easily	None
James Price Point	(SKM 2010a, 2011a)	Yes	Drop down video, grab samples (June 2008; May 2009)	Yes, low cover over extensive area	Not yet determined
Wheatstone	(Chevron 2010)	Yes	Drop down video, grab samples (Aug 2009)	Yes (trunkline)	Seagrass cover and biomass monitoring during dredging activity
Dampier Marine Services Facility	(WorleyParsons 2009)	Yes	Drop down video (October, 2009)	None, outside dredge footprint	-
Port Hedland Outer Harbour	(SKM 2011b)	Yes	Drop down video (May 2009)	None, low abundance, could not model, nor assess significance	-
Pilbara LNG	(BHP 2004)	Yes	Drop down video	None, not mapped nor assessed Site selection study – Onslow Industrial preferred, minor marine habitat disadvantage – namely a small coral reef off the coast.	

7 Conclusion

From the above, the process of assessing the significance of seagrass habitat for dredging impact prediction and management would benefit from a number of standardised approaches. These include:

Timing of habitat characterisation

If the natural dynamics of the local seagrasses are known, ensure habitat characterisation is carried out at the time of year when the maximum abundance occurs, to maximise chance of detecting habitat.

If the natural dynamics are not known, carry out surveys over multiple time-periods to help understand the natural dynamics and determine the optimum time to survey.

Definition of a significant habitat

It would be beneficial for proponents of dredging projects to have guidance on what constitutes significant seagrass habitat in NWWA. Tropical seagrasses, particularly in turbid waters, tend to have much lower cover and biomass than their temperate counterparts. For example, a biomass of <10 g DW m^{-2} is common in the Great Barrier Reef Marine Park (Coles et al. 2000, Coles et al. 2002) and a cover of 5% or less is considered significant habitat, particularly for dugong forage (e.g. GHD 2012). In fact, biomass in dugong protection areas (DPA) in the Great Barrier Reef Marine Park which are in shallow (<6 m water depth), ranges on average from 2–22 g DW m^{-2} with an average of 10 g DW m^{-2}. Deeper water habitats (i.e. 10–20 m) have much lower biomass again. For example in Point Abbot, there are deep water seagrass habitats that vary in abundance over the year, from <1 to 12.7 g DW m^{-2} with an average of 2 g DW m^{-2} and these are considered a significant habitat warranting protection during dredging, with ecological significance as fisheries habitat and dugong forage (Unsworth et al. 2010). Factors such as species composition, spatial extent (i.e. ha), cover and biomass could help guide the decision on whether the seagrass detected constitutes a significant habitat.

Use of potential seagrass habitat as a predictor of seagrass distribution

Due to the variable nature of low biomass tropical seagrass meadows, a useful approach has been to characterise historical seagrass distribution as potential seagrass habitat. This can be generated by overlaying all seagrass observations or maps generated over time to produce a layer which defines the potential habitat in which low biomass seagrass can grow (e.g. Waycott et al. 2007) and subsequently be applied in a dredging program (GHD 2012). Seagrass maps and observations generated over time by different proponents in NWWA could be used to develop these products.

7.1 Recommendation

Impact prediction and management of seagrasses would be improved by:

- developing guidance on what constitutes significant seagrass habitat;
- developing guidance on the most appropriate methodology and season for detecting seagrass habitat, particularly in turbid waters where seagrass species are very small and temporally variable; and
- where the same areas are mapped multiple times, collating the different data sets to create a time-series, which could provide an indication of potential seagrass habitat, particularly for annual or transitory communities.

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9 Appendix

9.1 Modelling drivers of total benthic daily light

To explain the variation in total benthic daily light (mol m^{-2} d^{-1}) at a number of sites around Barrow Island, Western Australia, we used an information theoretic approach to evaluate the fit of a set of generalised linear models representing credible multiple working hypotheses (Burnham & Anderson 2002). The total benthic daily light was collected as part of the Gorgon dredging project and included data prior to dredging (20 June 2009 – 18 May 2010) and during dredging (19 May 2010–31 October 2011). Seven of the sixteen monitoring sites were used in this analysis, as they had the most complete data set (i.e. less missing data) and covered a range of distances from the dredge site, as well as the range of management zones (See Table 3 for detailed list of sites). The factor site was included in the null model, as the range of sites for which we had data varied in depth, and this would affect total daily benthic light due to the attenuation of light with depth. The explanatory variables for these models were depth (m), day length (hours), tidal range (m), average wind speed (km hr^{-1}) and direction of dominant wind (°). The sources of the data are detailed in Table 4. All variables, apart from depth had matching daily data, whereas depth was fixed over the entire data set.

We used the R statistical computing environment version 3.0.1 (R Development Core Team 2014) to generate all possible model formulas, including both additive and interactive effects. These were then fitted to a generalised linear model and the best models selected using the Akaike Information Criteria (Aike 1974). The glmulti package with automated model selection and multi-model inference was used (Calcagno & de Mazancourt 2010). The benthic light data was continuous but not normally distributed so it was log transformed. In the R statistical environment a link function is required to assess the relationship between the predictor and explanatory variables, in this case the gamma family log function was selected. The best model was selected using the Akaike’s Information Criterion (AIC). It estimates the best model fit based on the set of models. The lowest AIC, which indicates the least information lost when building the model is designated as the best model fit. However, as there may be a number of possible options, we selected the models within the lowest 2 AIC units as representing the best fit. The weight of each explanatory variable was assessed to show the explanatory variables that were most important in explaining total daily benthic light. Once the models that best explained the variation in benthic light. The relative evidence weight was calculated as the sum of the relative evidence weights of all models in which the term appears, and then divided by the total number of models. Any explanatory variable with a relative evidence weight > 0.8 was deemed an important predictor of total daily benthic light.

9.2 Site locations of sediment trap data from the Rio Tinto Cape Lambert Project

Site code	Management zone	Depth	Latitude	Longitude
PWR_1	Impact	6	20°35.440'S	117°10.685'E
BTR_1	Indicator	9	20°33.750'S	117°10.621'E
BZI_1	Indicator	3	20°33.213'S	117°10.311'E
BZR_1	Indicator	4	20°33.823'S	117°09.682'E
CLW_1	Indicator	4	20°36.090'S	117°09.756'E
MDR	Indicator	3	20°35.817'S	117°11.862'E
BLR_1	Influence	3	20°35.052'S	117°08.456'E
DIE_1	Influence	7	20°37.084'S	117°04.143'E
MAN	Influence	3	20°37.555'S	117°07.988'E
PLR	Influence	3	20°39.249'S	117°14.415'E
$SMSB_1$	Influence	4	20°37.337'S	117°11.890'E
DLI	Reference	9	20°27.736'S	117°03.916'E
HAT	Reference	4	20°40.105'S	117°17.136'E

9.3 Site locations of sediment trap data from the Woodside Pluto Project

Site code	Management zone	Easting	Northing
HOLD	High impact	474662	7721057
CHC4	High impact	474819	7721959

9.4 Site locations of sediment trap data from the Chevron Gorgon Project

Site code	Management zone	Dist. from dredge (km)	Easting	Northing
LONE	Zone of Moderate impact	Spoil ground	348068	7687353
MOF3	Zone of influence	1.5	341412	7696411
LOW1	Zone of influence	1.6	343904	7700915
LNG3	Reference	5.0	343157	7692657
DUG	Regionally significant area	9.4	340099	7687998
ELS	Regionally significant area	24	352950	7718100
SBS	Regionally significant area	30	345599	7666195