PORT OF ABBOT POINT:

INITIAL LIGHT THRESHOLDS FOR MODELLING IMPACTS TO SEAGRASS FROM THE ABBOT POINT GROWTH GATEWAY PROJECT

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A Report for WorleyParsons

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EXECUTIVE SUMMARY

- This technical report provides the support and basis for initial light threshold values for seagrasses to model zones of impact from dredging activities including return water discharge associated with the proposed Abbot Point Growth Gateway project.

- Seagrass light thresholds for the model input were derived by:
    1. A review of the range of species specific light requirements from existing literature as well as data from ongoing studies to establish likely ranges of light required for the species of concern.
    2. Analysis of *in situ* data on light and seagrass change collected at Abbot Point between August 2013 and May 2015.
    3. Examination of how the literature and ongoing study derived values fit with the recorded light history and occurrence of seagrass at the Abbot Point monitoring sites.

- Based on these assessments we recommend the following initial modelling thresholds:
    1. For the offshore areas of deep water *Halophila* species the modelling threshold is **1.5** mol m^{-2} day^{-1} over a rolling **7 day average**.
    2. For the shallow inshore areas potentially effected by outfall discharges (dominated by *Halodule uninervis*) the modelling threshold we recommend is **3.5** mol m^{-2} day^{-1} over a rolling **14 day average**.

- The upper limit of threshold values for the model was heavily informed by the *in situ* light monitoring at Abbot Point. The paired light and seagrass monitoring program provided critical information on the light environment associated with the maintenance or increase in seagrass at the sites. This emphasizes the value of keeping these loggers and seagrass monitoring in place leading up to dredging to further refine the relationships into an operational tool for management during dredging.

- Future plans for incorporating light based triggers for seagrass management at Abbot Point should remain flexible to allow additional information from the ongoing data collection on site, or any additional new studies to be incorporated in refining the initial threshold. As a priority to improve certainty around the threshold levels we recommend:
    1. Continuing the quarterly seagrass monitoring and ongoing light assessment to provide additional data around the relationship. The primary concern is for coastal meadows where seagrass has only recently returned and only limited local information was available to inform the initial threshold; and
    2. Increasing to monthly seagrass sampling between July and December (growing season) to develop better relationships between fluctuating light levels and seagrass change.

  There are a range of other additional research activities that would also be valuable to better understand the light requirements of local seagrasses including: field shading studies to manipulate light levels; laboratory trials to test observed relationships; and investigations of dredging related spectral shifts (colour) of light and its impacts on seagrass light requirements.

- In the absence of additional information being available, we recommend adopting more conservative initial values for management especially for the coastal *Halodule uninervis* where the least local information was available at the time of this report. This could include using a value of **5** mol m^{-2} day^{-1} over a rolling **7 day** average until further data is available.

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INTRODUCTION

Background

James Cook University's Seagrass Ecology Group in the Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) has been engaged in a seagrass research and monitoring program at Abbot Point since 2008 funded by North Queensland Bulk Ports Corporation (NQBP). The program was initially developed to aid in the management of planned port expansions and the potential dredging-related impacts associated with these expansions, and to assess the long-term condition and trend of marine habitats, particularly seagrass. The areas that were selected for long-term monitoring (Figure 1) represent the range of seagrass communities within the port and include meadows considered most likely to be impacted by port activity and development, as well as areas unlikely to be impacted by port development to assist in separating out port-related and regional causes of seagrass change.

WorleyParsons has been engaged by the Department of State Development to prepare an Environmental Impact Statement (EIS) for the proposed Abbot Point Growth Gateway Project (the Project). The Project includes undertaking dredging and onshore material placement to support the development of the Abbot Point T0 project. As part of preparations for the EIS, WorleyParsons engaged TropWATER to characterise initial seagrass light requirement values for Abbot Point seagrasses suitable for pre-dredging planning and modelling zones of likely impact to seagrass. A light requirement threshold as used here, is defined as the point at which a change in external conditions will likely cause a significant negative change in seagrass condition (measured as above-ground biomass).

Seagrass and light

Seagrass growth and distribution is primarily driven by the availability and quality of light, which if changed, can lead to large scale loss of seagrasses over relatively short time scales (Dennison 1987; Duarte 1991; Ralph et al. 2007; Chartrand et al. 2012; Collier et al. 2012a & 2012b). Seagrasses commonly exist in a variable and low light environment that can easily be disrupted by anthropogenic activities such as dredging, resulting in elevated stress and mortality (Erftemeijer and Lewis, 2006). The process of marine dredging can place pressure on adjacent seagrass meadows as associated turbidity plumes reduce water quality and increase light attenuation (Grech et al. 2013).

Physiological and morphological strategies to tolerate temporary light reductions are broadly the same for all species: adjusting light harvesting capacity and the efficiency of light use (Abal et al. 1994, Enriquez 2005); adjustments to rates of growth and plant turnover (Collier et al. 2009; Collier et al. 2012b) and drawing upon carbohydrate reserves to maintain a net positive carbon balance (Burke et al. 1996; Touchette & Burkholder 2000). Physiological responses to changes in light availability may occur first, providing short term relief from low light conditions, followed by morphological responses, and finally, as low light conditions are prolonged biomass loss occurs and meadow-scale loss becomes apparent (Longstaff and Dennison 1999; Ralph et al. 2007; Collier et al. 2012b). The nature of the response of seagrass to low light and the level of impact of light reductions is often species- and site-specific and depends on the intensity and duration of low light stress.

The prediction, management and mitigation of the risk of turbidity plumes associated with dredging to sensitive habitats such as seagrass meadows involves having an understanding of the light requirements of local seagrasses and the effect of a reduction in this light on seagrass survival.

Abbot Point seagrasses and their light requirements

Extensive areas of inshore and offshore seagrass habitat (27,830 ha) comprising eight species: *Zostera muelleri* spp. *capricorni*, *Halophila ovalis*, *Halophila decipiens*, *Halophila spinulosa*, *Halophila tricostata, Halodule uninervis, Cymodocea serrulata and Cymodocea rotundata* have been mapped in the Abbot Point area since 2005 (McKenna & Rasheed 2014). *Halophila spinulosa* dominates the deeper subtidal areas while traditionally *H. uninervis* dominates the inshore meadows.

Significant losses of seagrass biomass and area at Abbot Point were observed following Tropical Cyclone Hamish (March 2009), the 2010/11 La Niña events, Tropical Cyclone Yasi (February 2011), and Tropical Cyclone Oswald (January 2013) (Rasheed et al. 2014). Since the 2010/11 La Niña and TC Yasi related losses, there has been a species shift in the majority of inshore meadows from the foundation species *H. uninervis* to the pioneering species *H. ovalis*, and recovery has been limited at inshore meadows (McKenna et al. 2015). In contrast, the offshore *Halophila* meadow showed signs of recovery by the end of 2014, with significant increases in biomass since TC Oswald (McKenna et al. 2015).

Good growing conditions for Abbot Point seagrasses exist from approximately July to December followed by a period of senescence from January to June, when above-ground biomass and distribution is reduced or lost completely. Seagrasses in turn rely on reproductive capacity and/or below ground storage in rhizomes to proliferate when suitable growing conditions return. Results of regular monitoring of seagrass in the Abbot Point area have highlighted significant inter-annual variation in seagrass biomass in meadows with patchy distribution. The key species in the Abbot Point area that may be affected by the Project include the deep water species *H. spinulosa, H. ovalis, H. decipiens* and the inshore species *H. uninervis*.

Halophila species are generally small bodied opportunistic seagrasses that exhibit fast growth habits, are considered well adapted for recovery after disturbance events and are able to exploit resources under high light conditions, but are quick to disappear when light levels deteriorate (Longstaff et al. 1999; McMillan 1991; Hammerstrom et al. 2006; Ralph et al. 2007). Disturbance experiments at Abbot Point demonstrated that *Halophila* spp. can recover quickly (ca. 3 months) through a combination of sexual and asexual reproduction and were capable of complete meadow turnover of biomass within 10 days based on productivity measurements (Unsworth et al. 2010; Rasheed et al. 2014). *Halophila* species typically produce large seed banks; 134 - 13,500 m^{-2} (McMillan 1988; Hammerstrom et al. 2006) from which recovery can occur. A *Halophila* species seed bank at Abbot Point has been previously quantified through disturbance experiments (Rasheed et al. 2014), however multiple years of seagrass decline due to climate events may have depleted offshore *Halophila* spp. seed banks, (Erftmeijer and Stapel 1999; Hammerstrom et al. 2006). *Halophila* spp. tend to be structurally deplete below-ground compared to other large and long-lived species which rely on below-ground reserves to compensate for poor light and water quality over short durations (Collier et al. 2009; Longstaff et al. 2009; Collier et al. 2012b).

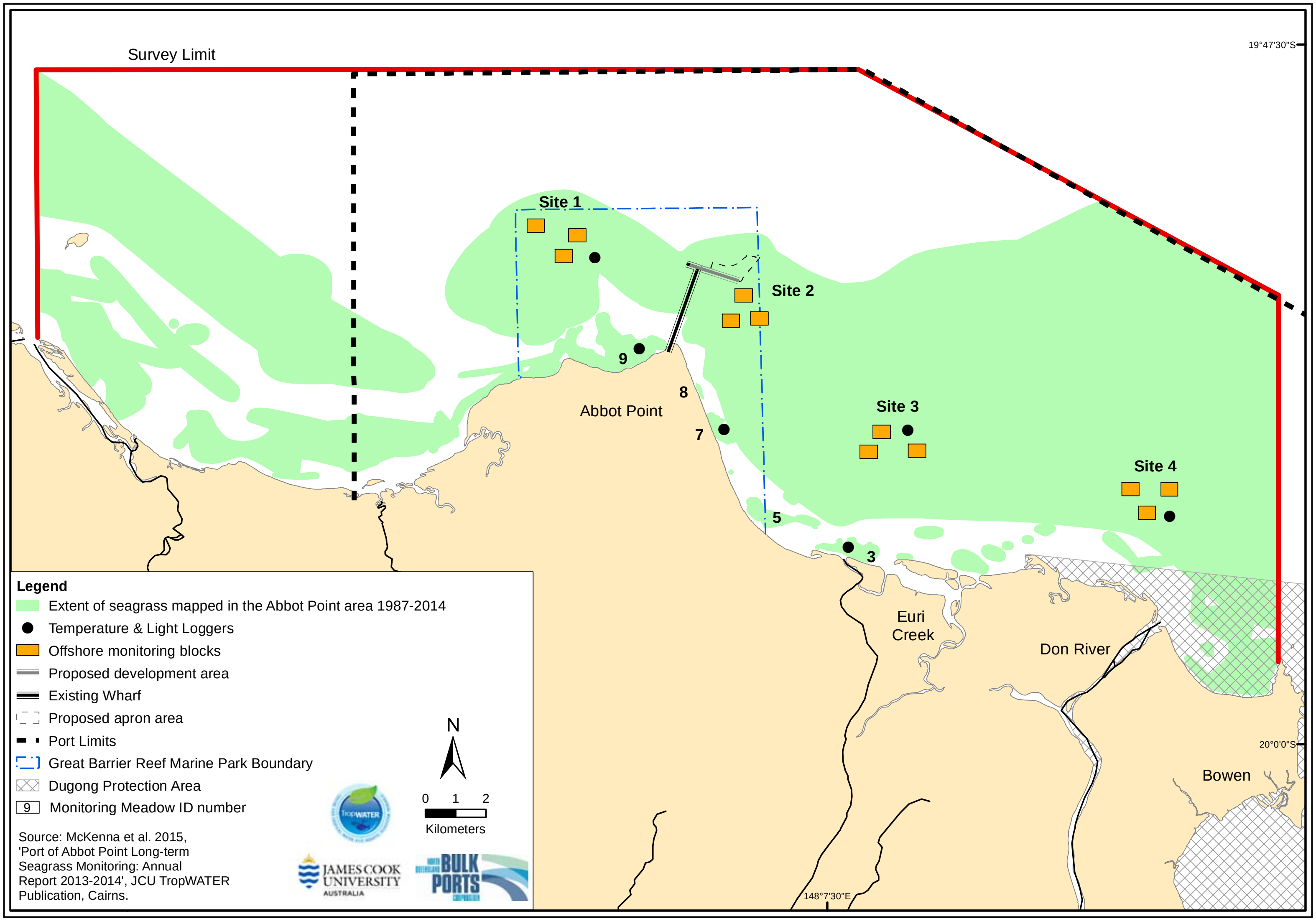
Halodule uninervis is the dominant species in many shallow subtidal and intertidal coastal regions of northern Australia and has been known to rapidly re-colonise after disturbances (Green and Short 2003; Waycott et al. 2004; Aragones et al. 2006; Rasheed et al. 2014). In contrast to this general perception, disturbance experiments at Abbot Point, found that *H. uninervis* had a high reliance on asexual reproduction with no successful recovery from seeds for the life of the study (7 months) (Rasheed et al. 2014). The production of seed banks for this species appears to be highly site-specific, with some meadows capable of forming large seed banks: Townsville (7000 seeds m^{-2}) (McKenzie et al. 2010), while at Abbot Point and Cairns the *H. uninervis* seed bank at study sites was 4 - 25 seeds m^{-2} and 9 seeds m^{-2} respectively (Rasheed et al. 2014; Jarvis et al. 2015). *Halodule uninervis* is generally known to have significantly greater light requirements than *Halophila* species (Bach et al. 1998; Longstaff and Dennison 1999).

Seagrass species vary widely in their tolerance to the (a) magnitude and (b) duration of light deprivation (Ralph et al. 2007). Seagrass light requirements are often discussed and compared in the literature in terms of minimum light requirements of a species (MLR). Minimum light requirements can be measured in several ways with the most common being percentage of surface irradiance (% SI). Use of %SI is unreliable due to the inconsistency of light conditions across latitudes, seasons and cloud cover (Longstaff 2003). Using MLR or %SI can further be problematic as it implies light is the sole driver of seagrass condition when in reality seagrass condition is an integrated response to multiple environmental factors including temperature, tides, nutrient availability and sediment dynamics which interact and affect the light requirement needs of a species. Advancements in technology have led to more accurate estimates of the light environment *in situ* for seagrasses as light loggers and the ability to maintain those loggers long term has advanced. Estimates of light requirements for seagrasses are therefore more accurate compared to earlier work where %SI values were derived from limited boat-based sampling events and from approximations of relative light at the deepest growing edge of the meadow (Duarte 1991; Dennison et al. 1993). Continuous light monitoring provides accurate information about the temporal variability of light that is not easily gained from boat-based instantaneous sampling methods. Only with continuous long-term light monitoring can the effects of pulsed seasonal light reduction events be accurately assessed (Longstaff 2003). For comparative purposes and for completeness, we have included %SI values for both *Halophila* spp. and *H. uninervis* in this review; however we report our suggested light thresholds in the more biologically relevant mol photons m^{-2} day^{-1}.

The objectives of this work were to:

- Establish a range of biologically relevant light requirement values for the dominant seagrass species in the Abbot Point area using *in situ* data from the Abbot Point seagrass monitoring program, ongoing field and laboratory studies and literature values;
- Refine this range of values and provide to WorleyParsons initial biological light thresholds that can be used to interrogate the hydrodynamic modelling for the Project to model zones of likely impact to seagrass.

The seagrass light thresholds developed for this modelling exercise were based on the data available at the time and suitable for pre-dredging planning and modelling zones of likely impact to seagrass. Future plans for incorporating light based triggers for seagrass management at Abbot Point should remain flexible to allow additional information from the ongoing data collection on site, or any additional new studies to be incorporated in modifying the initial threshold. In the absence of additional information being available, we recommend adopting more conservative initial values for dredging management purposes.



Source: McKenna et al. 2015, 'Port of Abbot Point Long-term Seagrass Monitoring: Annual Report 2013-2014', JCU TropWATER Publication, Cairns.

Figure 1. Location of coastal monitoring meadows, offshore monitoring sites and light (PAR) and temperature loggers

2 METHODS

2.1 Literature review and other studies

To help refine a range of light values relevant to the dominant seagrass species at Abbot Point a thorough review of peer reviewed and grey literature for relevant information on seagrasses in the Queensland area was conducted. Where specific information was lacking due to an absence of local studies, a broader search of Australian and international literature on locally occurring species was used. The summary data of the most relevant literature is presented in Section 3.1 and as described below.

In conjunction with literature values, we also drew on information from studies that the Seagrass Ecology Group are currently undertaking, and analysing data that had been collected as part of the groups' other projects examining light and seagrass change. The Seagrass Ecology Group at TropWATER are currently undertaking field and laboratory studies on deep water seagrass meadows along the coast of Queensland to determine what drives the seasonal recruitment and senescence of deep water seagrasses.

2.2 Abbot Point seagrass and light data

Seagrass biomass and irradiance (light) data was collected from the established Abbot Point seagrass program. Five inshore seagrass meadows and four offshore areas (Figure 1) have been monitored approximately quarterly for seagrass presence, biomass, area (inshore meadows only) and species composition since 2008.

Seagrass biomass and change

Methods for assessing inshore and offshore seagrasses followed those established for the Abbot Point seagrass program (see McKenna et al. 2008; Unsworth et al. 2010 and McKenna & Rasheed 2011). The application of standardised methods at Abbot Point and throughout Queensland allows for direct comparison of local seagrass dynamics with the broader region. Free-diving and deep water sled tows using an underwater CCTV camera system were used to survey inshore and offshore areas for seagrass (Figure 2) (see McKenna et al. 2008 for full description). At each survey site, seagrass habitat observations included seagrass species composition, above-ground biomass, percent algal cover, depth below mean sea level (MSL), sediment type, time and position (GPS). The percent cover of other major benthos at each site was also recorded. At sites where seagrass presence was noted seagrass above-ground biomass was determined. Above-ground seagrass biomass was estimated using a "visual estimates of biomass" technique (Kirkman 1978; Mellors 1991). At free diving sites this technique involved an observer ranking seagrass biomass within three randomly placed 0.25m^2 quadrats at each site (Figure 2). At CCTV camera sled tow sites this technique involved an observer ranking seagrass at 10 random time frames allocated within the 100m of footage for each site. The video was paused at each of the ten time frames then advanced to the nearest point on the tape where the bottom was visible and sled was stable on the bottom. From this frame an observer recorded an estimated rank of seagrass biomass and species composition. A 0.25m^2 quadrat, scaled to the video camera lens used in the field, was superimposed on the screen to standardise biomass estimates.

Ranks at all sites were made in reference to a series of quadrat photographs of similar seagrass habitats for which above-ground biomass has previously been measured. The relative proportion of the above-ground biomass (percentage) of each seagrass species within each survey quadrat was also recorded. Field biomass ranks were then converted into above-ground biomass estimates in grams dry weight per square metre (g DW m^{-2}). At the completion of sampling, each observer ranked a series of calibration quadrats that represented the range of seagrass biomass in the survey. After ranking, seagrass in these quadrats was harvested and the actual biomass determined in the laboratory. A separate regression of ranks and biomass from these calibration quadrats was generated for each observer and applied to the field survey data to standardise the above-ground biomass estimates.

Figure 2. Sampling sites were assessed by deep water sled tows with CCTV mounted camera system and free-divers to measure seagrass biomass and species composition.

Light and its' effect on seagrass biomass

Irradiance (Photosynthetically Active Radiation (PAR) mol photons m^{-2} day^{-1}) conditions within the seagrass meadows at Abbot Point have been assessed at three inshore meadows and at three offshore sites since September 2011 using custom built benthic data logging stations (Figure 3). A dual logger system was introduced to the program in April 2013. Each logging station consisted of 2π cosine-corrected irradiance loggers (Submersible Odyssey Photosynthetic Irradiance Recording System, Dataflow Systems Pty. Ltd., New Zealand) with supporting electronic wiper units. Irradiance loggers were calibrated using a cosine corrected Li-Cor underwater quantum sensor (LI-190SA; Li-Cor Inc., Lincoln, Nebraska USA) and corrected for immersion effect using a factor of 1.33 (Kirk 1994). Readings were made at 15 minute intervals and used to estimate total daily irradiance (PAR) reaching seagrasses. The electronic wiper unit fitted to each irradiance logger automatically cleaned the optical surface of the sensor every 15 minutes to prevent marine organism fouling.

Figure 3. Diver deploying PAR loggers and associated wiper units

Generalized additive mixed models (GAMM) were used to examine the effects of irradiance (PAR) on seagrass biomass using the "mgcv" package for R (Wood 2014). GAMMs were used because the functional form of the response variable biomass to the continuous covariate light was unknown; GAMMs fit a non-parametric model to the data where the functional form is not specified a priori, but instead additive non-parametric functions are estimated using smoothing splines to model covariates (Zuur et al. 2014).

For offshore sites seagrass biomass was modelled separately as a function of 7, 14 and 30 days mean irradiance leading up to the sampling period. Two offshore sites were sampled (sites 3 and 4) therefore 'meadow' was modelled as a random effect term in each model. For inshore seagrass the effect of 14, 30 and 90 days mean irradiance on seagrass biomass, and only *H. uninervis* biomass, were run as separate models. Analysis was only conducted on the *H. uninervis* dominated meadow 7 so no random effect term was included.

For both offshore and inshore meadows only the growing season data were modelled. Normalised residuals were inspected for each model using residual plots and qq-plots for violations of the assumptions of homogeneity of variance and normality (Zuur et al. 2014).

2.3 Developing Abbot Point seagrass light thresholds

Once a range of biologically relevant light values were established from the literature review and ongoing studies, we used those values as a starting point to interrogate the Abbot Point light and seagrass biomass dataset to further refine the light threshold values for *Halophila* spp. and *H. uninervis*; the key species in the Abbot Point area that may be affected by the Project.

Biomass and irradiance data were assessed at offshore sites 3 and 4 and at inshore meadow 7. Inshore meadow 3 was excluded as it was deemed outside the area likely to be affected by dredging. Inshore meadow 9 was also excluded as it has not had any significant amounts of *H. uninervis* recorded at the site since light loggers were deployed and therefore would not provide evidence of light that supports this species' growth. Offshore site 1 was excluded because it is located on a shallow shoal (Clark shoal) which is traditionally dominated by *H. uninervis* and not considered to be a true deep water site. *Halodule uninervis* has not been present at the site consistently since TC Yasi and therefore would not provide evidence of light that supports this species' growth.

Light and biomass were only evaluated from August 2013 onwards as there was only one logger deployed at each site before this time. Using the period when dual loggers were available at each site allowed for a higher level of confidence in the light data as any potential and non-obvious erroneous data could be removed, and relationships between light and seagrass biomass could not be interrogated with confidence.

To evaluate light over a practicable timeframe for measuring impacts to the plant at the inshore sites dominated by the larger growing *Halodule uninervis*, light data was integrated as a rolling fourteen day mean of the total daily irradiance. Current understanding of seagrass response pathways indicates under low light stress conditions, physiological adjustments first occur over a matter of days whereas plant-scale changes take place after a number of weeks (McMahon et al. 2013). An assessment of integrated light over a two-week period is therefore in line with both tidally-driven fluxes in light (e.g. re-suspension of bottom sediments due to shear stress) as well as a period of time preceding apparent morphological change. Abbot Point light trends were compared against changes in seagrass between consecutive sampling events.

At offshore sites, light was integrated over a seven day period instead of fourteen days. A shorter interval was used due to the fast response time of *Halophila* spp. to light and the comparative lack of below ground energy stores for these species compared with the shallow species *H. uninervis*. There are little to no carbohydrate reserves to rely on when light is limiting and physiological acclimation is limited prior to seeing apparent morphological changes or shoot loss in *Halophila*. While it is unclear how quickly changes may occur in some populations, a seven day average should mainly remove the extreme variability from the dataset and provide an opportunity to discern if clear trends between light and seagrass abundance exists at the offshore sites.

3 RESULTS AND DISCUSSION

3.1 Literature values and other studies

For the purposes of this report and to help frame a range of biologically relevant light thresholds for Abbot Point seagrasses, we have only interrogated and discussed below the results from studies that occur in the same region as Abbot Point, describe actual benthic light in mol photons, and examine the same species or the same genus to the key species that will potentially be affected by dredging at Abbot Point; *Halophila* spp. and *H. uninervis*.

Below are some of the key findings of the most relevant studies that contributed to framing biologically relevant range of light thresholds for seagrasses at Abbot Point.

***Halophila* species**
Chartrand et al. (2014) collected *H. decipiens* from Green Island (offshore from Cairns) and *H. spinulosa* from Abbot Point and subjected the samples to different light and temperature regimes in mesocosm experiments. The key findings of the studies so far show that deep water *H. decipiens* and *H. spinulosa* shoot density was negatively affected by light treatments of 1 mol photons m^{-2} d^{-1} compared to typical ambient growing season conditions and control light treatments of 3.2 mol photons m^{-2} d^{-1}. A critical light threshold in the range of 1-2 mol photons m^{-2} d^{-1} was identified from the study and the long-term field monitoring program, and is currently being examined further as part of ongoing field monitoring and research for its validity. *Halophila decipiens* shoot density significantly declined after 2 weeks under low light treatments whereas *H. spinulosa* was not affected until 4 weeks.

Based on this study and other relevant literature (Table 1) we used a likely threshold range of between 1 and 2 mol photons m^{-2} d^{-1} to interrogate the Abbot Point light and seagrass change data set for deep water *Halophila* species (see 3.2).

Halodule uninervis
Halodule uninervis is known to have generally higher light requirements than *Halophila* species (Bach et al. 1998; Longstaff and Dennison 1999). Collier et al. (2015 subm) also found this to be true in a recent lab experiment on *H. uninervis* from Magnetic Island, Townsville. They tested the response of *H. uninervis* shoot density and growth rates to six light levels ranging from 0 to 23 mol photons m^{-2} d^{-1} in cool (~23°C) and warm (~28°C) temperatures over 14 weeks. The impact of light deprivation on shoot densities and growth rates was faster in *H. ovalis* than in *H. uninervis*. This study found that low light levels (≤3.3 mol photons m^{-2} d^{-1} treatments) had a significant negative affect on shoot density in cool temperatures between 10 – 14 weeks and in warm temperatures between 4 – 7 weeks.

Previous work at Magnetic Island off Townsville (Collier et al. 2012a) determined light thresholds required for the long-term survival of tropical seagrass meadows dominated by *H. uninervis* identified during 'real-time' loss of seagrass. The thresholds in this study were determined during natural *in situ* reductions in light and concurrent with seagrass loss. Natural variability of the light environment was captured and incorporated changes in light colour, diurnal fluctuations in intensity, tides and seasonality (Collier et al. 2012a). The study found that a significant loss (>50%) in seagrass occurred at <4 mol photons m^{-2} d^{-1}, while minimum light levels associated with seagrass gain occurred when light was >5 mol photons m^{-2} d^{-1}. In a separate study, Collier et al. (2012b) also found *H. uninervis* shoot density declined in the lab after 8.7 weeks when held under 4.4 mol photons m^{-2} d^{-1}.

Based on these studies and other relevant literature (Table 1) we used a likely threshold range of between 3 and 5 mol photons m^{-2} d^{-1} to interrogate the Abbot Point light and seagrass change data set for *Halodule uninervis* (see 3.2).

Table 1. Light thresholds (expressed as % of surface irradiance (%SI) and total daily mol photons m^{-2} d^{-1}), impact and time (days) to impact of the seagrass species at Abbot Point. Studies shaded in grey are those that contributed to refining the initial light thresholds of key seagrass species at Abbot Point to interrogate the Abbot Point light and seagrass change data set.

Species	**Location**	**Impact**	**Light intensity**	**Time to Impact (days)**	**Zone**	**Study Location**	**Notes**	**Reference**
Zostera muelleri* ssp. *capricorni	Moreton Bay	Shoot density	30 %SI	≤62	Sub-tropical	Lab	Not measured prior to 62 days	Abal et al. 1994
	Moreton Bay	Max depth limit of meadow	4.6 mol photons m^{-2} d^{-1}		Sub-tropical	Intertidal		Longstaff 2003
	Port Hacking	Biomass (dry weight)	1.7 mol photons m^{-2} d^{-1}	≤86	Sub-tropical	Lab	Shading exp- not measured prior to 86 days	Fyfe 2004
	Port Hacking	**No impact found** - Biomass	7.2 mol photons m^{-2} d^{-1}	86	Sub-tropical	Lab	Shading exp- not measured prior to 86 days	Fyfe 2004
	Magnetic Island	Leaves per shoot Shoot density	4.4 mol photons m^{-2} d^{-1} 4.4 mol photons m^{-2} d^{-1}	46 61	Tropical	Lab		Collier et al. 2012
	Magnetic Island	Leaf photosynthesis	1.7 mol photons m^{-2} d^{-1}	≤6	Tropical	Lab	under 27, 30 and 33˚C treatments	Collier et al. 2011
	Magnetic Island	Above-ground biomass	1.7 mol photons m^{-2} d^{-1}	≤34	Tropical	Lab	Biomass only measured at time 3 (days 28-34).	Collier et al. 2011
	Lake Macquarie	Above-ground biomass	2 mol photons m^{-2} d^{-1}	≤84	Sub-tropical	Lab	Shading exp- not measured prior to 86 days	York et al. 2013
	Lake Macquarie	**No impact found** – Above-ground biomass	4.8 mol photons m^{-2} d^{-1} 6.9 mol photons m^{-2} d^{-1}	≤84	Sub-tropical	Lab	Shading exp- not measured prior to 86 days	York et al. 2013
	Gladstone	Above-ground biomass Percent cover	≤5 mol photons m^{-2} d^{-1} (14 day mean)	30-40	Sub-tropical	Intertidal	In situ shading exp; season has a strong effect with light; Interaction between light and temp likely a major driver.	Chartrand et al. 2015 in prep
Halophila ovalis	Magnetic Island	Shoot density	0, 1.6 & 3.3 mol photons m^{-2} d^{-1}	7-28	Tropical	Lab	Shading exp – measured at time 0 then at 4, 7, 10 and 14 weeks. Declines under warm temperature (27.7˚C) treatment.	Collier et al. 2015 subm.

Halophila decipiens	Green Island	Shoot density	1 mol photons m^{-2} d^{-1}	14	Tropical	Lab	Shading exp- measured weekly. Declines under 26 ˚C and 30 ˚C treatments	Chartrand et al. 2014
	US Virgin Islands	Growth rate and depth limit	4.4% SI		Tropical	Subtidal		Williams and Dennison 1990
Halophila spinulosa	Moreton Bay	Biomass	≤50 %SI	≤30	Sub-tropical	Lab	Shading exp- not measured prior to 30 days.	Grice et al. 1996
	Bowen	Shoot density	1 mol photons m^{-2} d^{-1}	28	Tropical	Lab	Shading exp- measured weekly. Declines under 26 and 30 ˚C treatments	Chartrand et al. 2014
	Bowen	**No impact found –** Shoot density	3.2 mol photons m^{-2} d^{-1}	28	Tropical	Lab	Shading exp- measured weekly.	Chartrand et al. 2014
Halodule uninervis	Moreton Bay	Biomass	≤50% SI	≤30	Sub-tropical	Lab	Shading exp- not measured prior to 30 days.	Grice et al. 1996
	Magnetic Island	**No impact found –** Photosynthesis	1.7 mol photons m^{-2} d^{-1}	≤34	Tropical	Lab	No impact at 27 or 33 ˚C.	Collier et al. 2011
	Magnetic Island	Above-ground biomass	1.7 mol photons m^{-2} d^{-1}	≤34	Tropical	Lab	Biomass only measured at time 3 (days 28-34).	Collier et al. 2011
	Magnetic Island	Percent cover loss	<4 mol photons m^{-2} d^{-1}	≤84	Tropical	Subtidal	Seagrass cover loss relates to the entire meadow which includes other spp.	Collier et al. 2012a
	Magnetic Island	Percent cover gain	>5 mol photons m^{-2} d^{-1}	≤84	Tropical	Subtidal	Seagrass cover loss relates to the entire meadow which includes other spp.	Collier et al. 2012a
	Gulf of Carpentaria	Biomass Shoot density Canopy height	≤1% SI	>38	Tropical	Intertidal		Longstaff and Dennison 1999
	Magnetic Island	Shoot density	4.4 mol photons m^{-2} d^{-1}	60	Tropical	Lab		Collier et al. 2012b
	Magnetic Island	Shoot density	0, 1.6 & 3.3 mol photons m^{-2} d^{-1}	28-49	Tropical	Lab	Shading exp – measured at time 0 then at 4, 7, 10 and 14 weeks. Declines under warm temperature (27.7˚C) treatment.	Collier et al. 2015 subm.

3.2 Review of Abbot Point light history and seagrass change

Offshore Meadows – *Halophila* species

An interrogation of the literature derived light threshold range for deep water *Halophila* species between 1-2 mol photons m^{-2} d^{-1} with the recorded light history and seagrass change measurements at Abbot Point found a threshold of 1.5 mol photons m^{-2} d^{-1} best described the light conditions at which seagrass biomass was maintained (Figure 4).

Offshore *Halophila* spp. above-ground biomass was significantly correlated with average light intensities at 7 days ($p<0.001$), 14 days ($p<0.01$) and 1 month ($p< 0.05$) prior to sampling events during the growing season when analysed. The most recent sampling of *Halophila* spp. at offshore site 3 found light stayed relatively constant between 1-1.5 mol photons m^{-2} d^{-1} for longer than one month prior to sampling and resulted in the highest total biomass recorded at the site since dual light loggers were deployed in 2013 (Figure 4A).

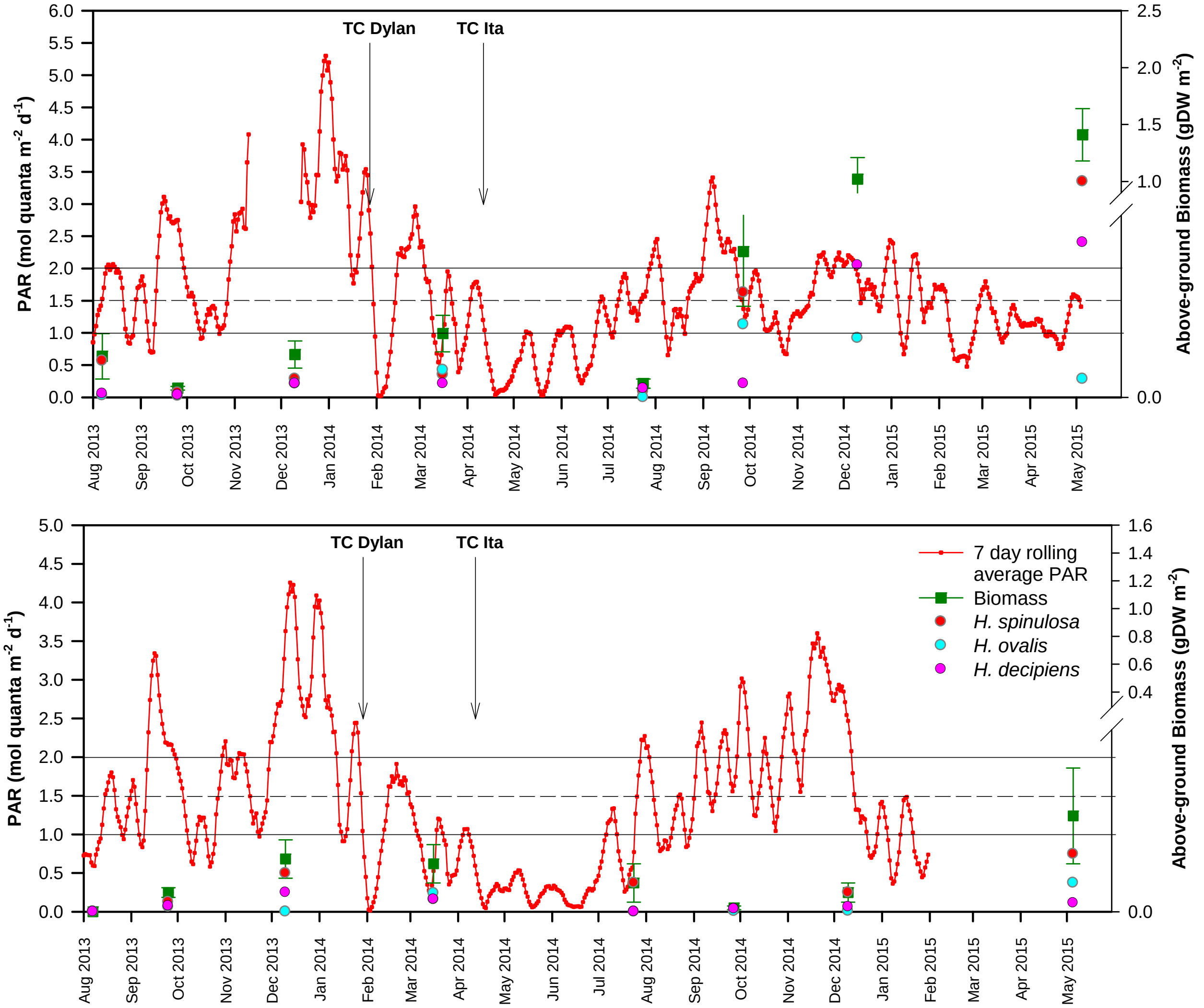


Figure 4. Rolling seven day average light (mol photons m^{-2} d^{-1}) at offshore monitoring sites 3 (A) and 4 (B) from August 2013 to May 2015 and mean (±SE) above-ground biomass at quarterly sampling events.

Inshore Meadows – *Halodule uninervis*

An interrogation of the literature derived light threshold range for *Halodule uninervis* of between 3-5 mol photons m^{-2} d^{-1} with the recorded light history and seagrass change measurements at Abbot Point found a threshold of 3.5 mol photons m^{-2} d^{-1} best described the light conditions at which seagrass biomass was maintained (Figure 5). In particular three sampling intervals provided an indication that when light leading up to sampling was ≥3.5 mol photons m^{-2} d^{-1} for approximately one month prior to sampling, seagrass was present or had increased from the previous sampling event (Figure 5). These trends are also in line with experimental results from Collier et al. (2015 subm) analysing *H. uninervis* collected at nearby Magnetic Island.

Due to the 3 month period between seagrass sampling it was difficult to interpret some sections of the data when light was low the month before seagrass sampling with confidence. This was due to the possibility of seagrass having declined from a higher level within the 3 monthly seagrass sampling window. For example, seagrass appeared to be relatively stable between September and December 2013 (Figure 5). However during that 3 month period light was high early on before declining to below 3.5 mol photons m^{-2} d^{-1} in the month leading up to the December 2013 seagrass assessment. It is possible that seagrass had increased during the early high light period but there was no seagrass sampling to record this, and yet subsequent sampling in December 2013 represented a decline in seagrass biomass from three months prior. An increased frequency of seagrass sampling (monthly) would improve the resolution of this relationship.

It was difficult to refine the threshold with further confidence due to the impact of tropical cyclones and major storm events on the coastal seagrass meadows during the monitoring period. This resulted in very low abundances of *H. uninervis* at the meadows and limited the ability of statistical analyses to model any trends in seagrass biomass with light (Figure 5). It was only since December 2014 that coastal seagrass had returned in reasonable densities, and indeed the increase in biomass at this time was preceded by more than one month of light above 3.5 mol photons m^{-2} d^{-1}. In addition the light loggers at the key coastal *H. uninervis* meadow were (as well as Meadow 9) stolen at some point after the December 2014 logger exchange so no light data was available for comparison at these meadows between December 2014 and May 2015. Large changes in light history were also recorded between the 3 monthly sampling events earlier in the monitoring program. So it was difficult to resolve the seagrass condition between these events and whether biomass had in fact increased as a response to high light between quarterly seagrass sampling but had once again declined with the lower light in the month preceding sampling. As a consequence of these issues the statistical analysis failed to find significant relationships.

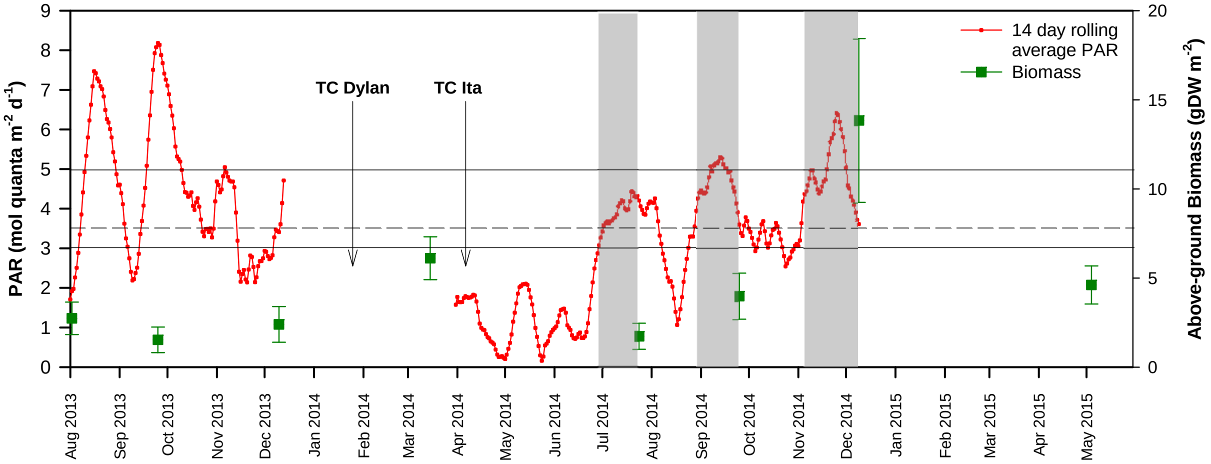


Figure 5. Rolling fourteen day average of light (mol photons m^{-2} d^{-1}) at inshore meadow 7 from August 2013 to May 2015 and mean (±SE) above-ground biomass at quarterly sampling events. Shaded areas represent periods of time leading up to sampling where ≥3.5 mol photons m^{-2} d^{-1} for at least one month and seagrass increases were observed. Note, light logger data loss during 2014 is related to major storm events (TC Dylan), while missing data in 2015 is due to logger units being stolen from the site.

3.3 Conclusion and Recommendations

Based on assessments of relevant literature values, ongoing studies and analysis of *in situ* light and seagrass change data collected at Abbot Point, preliminary light thresholds for *H. uninervis* and *Halophila* spp. were determined for input into modelling. The thresholds developed were based on the need to ensure the protection of seagrasses from potentially deteriorating light conditions associated with planned dredging and disposal options, while also having a credible fit with measured background light variability inherent within the local meadows, and local light requirements for the species. Using this approach provides a site and species relevant value of light that accommodates uncertainty or risk around light thresholds for input into models examining potential impact zones from dredging operations.

For the shallow inshore areas potentially affected by discharge of return water (inshore *H. uninervis* dominated meadows), a requirement of a fourteen day rolling average of 3.5 mol photons m^{-2} d^{-1} should be applied when analysing model outputs on dredging plume effects, and modelling zones of likely impact to seagrass. This value is a biological threshold derived from the literature, recent laboratory experiments and light trends in the inshore Abbot Point seagrass meadow 7 (Figure 1).

Due to the limited light history and seagrass trend data available, as well as the lack of a statistical relationship between *H. uninervis* and light, we suggest adopting more conservative values if an operational threshold for dredging management was to be used. This could include using a value of 5 mol m^{-2} day^{-1} over a rolling 7 day average until further data is available to tighten the relationship between Abbot Point *H. uninervis* trends and light.

To maintain seagrass above-ground biomass at offshore areas of deepwater *Halophila* spp., a light requirement threshold of a seven day rolling average of 1.5 mol photons m^{-2} d^{-1} should be used based on literature-derived values, recent laboratory experiments and light and seagrass trends in the offshore Abbot Point seagrass meadows.

While the results of this project have produced a set of light threshold values for inshore *H. uninervis* dominated meadows and offshore deep water *Halophila* spp. meadows, these values should be viewed as an initial planning instrument. Although achieving and maintaining these light levels is important, in reality seagrass condition is an integrated response to multiple environmental factors including temperature, tides, nutrient availability, sediment dynamics and the quality of light reaching the seagrass which interact and affect the light requirement needs of a species (Udy et al. 1999; Collier et al. 2011; Rasheed and Unsworth 2011; Collier and Waycott 2014). An applied light management strategy during dredging would benefit through further investigations to further refine and test field results and various light triggers, and management actions.

Future plans for incorporating light based triggers for seagrass management at Abbot Point should remain flexible to allow additional information from the ongoing data collection on site, or any additional new studies to be incorporated in refining the initial threshold. As a priority to improve certainty around the threshold levels we recommend:

- Continuing the quarterly seagrass monitoring and ongoing light assessment to provide additional data around the relationship. The primary concern is for coastal meadows where seagrass has only recently returned and only limited local information was available to inform the initial threshold; and
- Increasing to monthly seagrass sampling between July and December (growing season) to develop better relationships between fluctuating light levels and seagrass change.

These steps would significantly improve resolution and confidence in the light threshold values by addressing the two major issues in developing the initial light requirements: (i) the relatively limited set of local correlative data for seagrass and light (particularly inshore *Halodule*) due to the recent recovery of seagrasses post cyclones and; (ii) increasing the frequency of seagrass sampling so that tighter relationships with the changes in light history can be developed.

In the absence of additional information being available, we recommend adopting more conservative initial values for management especially for coastal *H. uninervis* meadows where the least local information was available at the time of this report. This could include using a literature-derived value from nearby Magnetic Island studies of 5 mol m^{-2} day^{-1} (Collier et al 2012a) over a rolling 7 day average until further data is available.

A range of additional research would also be highly valuable to better understand the light requirements of local seagrasses. Each of the following studies would significantly strengthen the link between seagrass health and light thresholds:

- Field shading experiments to manipulate light levels under in situ growing conditions;
- Laboratory trials to test the relationship between light and seagrass health in isolation; and
- Investigations into the effects of dredging plumes on the spectral quality (colour) of light associated and how this impacts light requirement values.

The upper limit of threshold values for the species derived in this report was heavily informed by the *in situ* light and seagrass monitoring at Abbot Point. This monitoring has provided critical information on the light environment associated with the maintenance or increase in seagrass at the sites and emphasizes the value of keeping these loggers and seagrass monitoring in place leading up to dredging. In addition, given the large changes that have occurred in Abbot Point seagrass biomass and distribution as a result of climatic events, it will be important to maintain monitoring as multiple years of climate induced seagrass decline are likely to have left a legacy of reduced resilience to further impacts. Continued monitoring throughout the dredging program will also help assist in separating out port related versus regional causes of seagrass change detected in the monitoring program.

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