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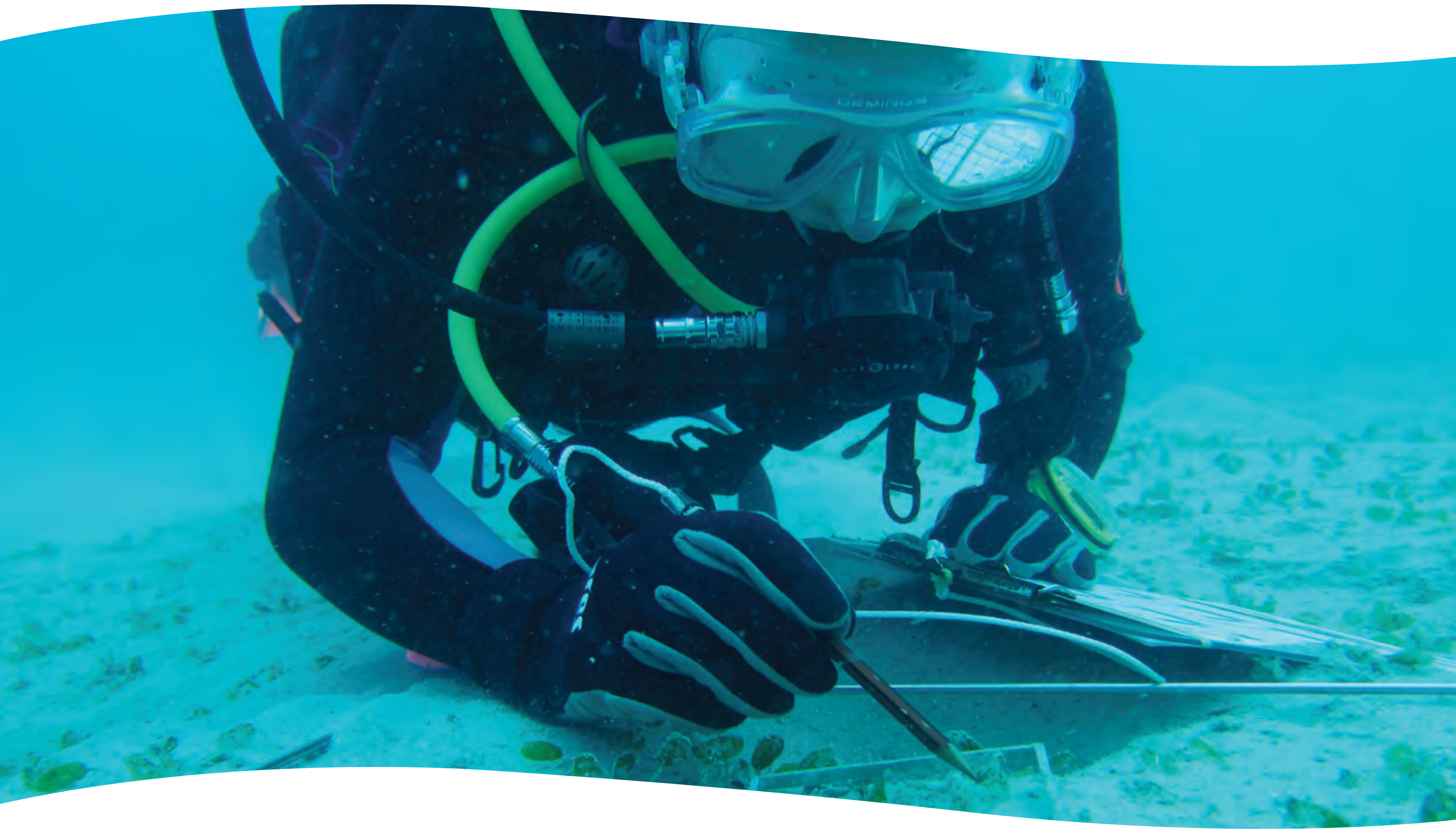
Final Report

Light thresholds for seagrasses of the GBRWHA: a synthesis and guiding document

Including knowledge gaps and future priorities

Catherine Collier, Katie Chartrand, Carol Honchin, Adam Fletcher and Michael Rasheed



JAMES COOK UNIVERSITY AUSTRALIA

Light thresholds for seagrasses of the GBRWHA: a synthesis and guiding document

Including knowledge gaps and future priorities

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ACRONYMS

GBR............... Great Barrier Reef
GBRWHA ...... Great Barrier Reef World Heritage Area
MMP .... Marine Monitoring Program
MTSRF .... Marine and Tropical Sciences Research Facility
NERP............. National Environmental Research Programme
NESP............. National Environmental Science Programme
TWQ .... Tropical Water Quality

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KEY FINDINGS

This synthesis contains light thresholds for seagrass species in the Great Barrier Reef World Heritage Area (GBRWHA). The thresholds can be applied to ensure protection of seagrasses from activities that impact water quality and the light environment over the short-term, such as coastal and port developments. Thresholds for long-term maintenance of seagrasses are also proposed.

- The synthesis provides clear and consistent guidance on light thresholds to apply in managing potential water quality impacts to seagrass.

- All available information on *biological light thresholds* was tabulated and conservative *management thresholds* were identified to ensure seagrass protection.

- Acute management thresholds are suited to compliance guidelines for managing short-term impacts and these and are the focus of this synthesis. Long-term thresholds are suited to the setting of water quality guidelines for catchment management.

- The synthesis identified key areas where further information is required, including:
    - species for which almost no information on light thresholds exists;
    - location and population-specific thresholds particularly for the most at-risk species;
    - definitions of desired state to underpin the development of long-term light guidelines to meet them;
    - the effect of spectral quality on light thresholds; and, consideration of cumulative impacts (temperature, nutrients, sedimentary conditions) on acute and long-term light thresholds.

- Light management thresholds for acute impacts are presented for twelve species. Colonising species are the most sensitive to light reduction (i.e. lowest thresholds) and have the shortest time to impact while larger, persistent species have higher light thresholds and a longer time to impact.
- The recommended acute management thresholds are ready for application, as the conservative approach (higher light threshold, shortest time to impact) for species with low confidence should ensure protection to seagrass meadows at risk from acute light stress.

EXECUTIVE SUMMARY

Seagrass meadows occur in habitats with high risk of exposure to water quality deterioration from coastal development and terrestrial discharge. Improvement in water quality is one of four challenges identified in the *Reef 2050 Long-term sustainability plan* that will improve meadow condition and support ongoing development of resilience. To meet water quality improvement targets, the GBRMPA sets compliance standards for activities such as coastal development, which have the potential to threaten water quality and ecosystems of the GBR. Seagrass meadows are the habitat most likely to be directly affected by coastal and port developments due to their proximity inshore and along sheltered parts of the coast. Development approvals therefore require that water quality, and specifically light, are maintained within acceptable levels. Until recently, there has been little biologically relevant information available to set appropriate thresholds. Furthermore, the GBRMPA has water quality guidelines that can be used to set targets for catchment management.

Water quality affects light reaching seagrass meadows, and light in turn controls the productivity, abundance and distribution of seagrasses. Therefore, guidelines for light are recommended as a management trigger for seagrass meadows at risk from declining water quality. Use of light as a management trigger for dredge management in Gladstone Harbour has set a precedent for incorporating light into guidelines for similar future activities. Furthermore, recent research into seagrass light thresholds and mature light monitoring programs (>8 years) are providing the information required to develop these guidelines. Up to now, most of this information has been spread amongst multiple reports and scientific publications.

Therefore, the aims of this project were to:

- provide clear and consistent guidance to environmental managers and regulatory authorities on light thresholds to apply for GBR seagrasses;
- synthesise current state of knowledge of light effects on seagrasses;
- develop a conceptual framework to guide threshold application;
- deliver a table of light thresholds and associated indicators of stress; and
- highlight critical information gaps.

All available information on seagrass light requirements was tabulated. This highlighted that there are two critical time-scales for consideration of light thresholds – acute and long-term thresholds – and these also correspond to guidelines for acute compliance standards, and water quality guidelines for catchment management, respectively. These findings were used to recommend acute management thresholds for 12 species occurring in the GBR. The management thresholds range from 2 to 6 mol m^{-2} d^{-1} depending on species (Table 1). The thresholds are presented together with an integration time (1 – 14 days), time to impact (7 – 50 days) and confidence score (1 – 5). Colonising species that dominate in deepwater habitat are the most sensitive to light reduction and therefore they have the lowest light thresholds (2 – 6 mol m^{-2} d^{-1}) and shortest time to impact (14 – 28 days) depending on species. Opportunistic species have higher light thresholds (5 – 6 mol m^{-2} d^{-1}) and longer time to impact (28 – 50 days). Recommended light management thresholds were similar for persistent species 5 – 6 mol m^{-2} d^{-1}), but with longer time to impact (50 days); however, there is very little information available on light thresholds for persistent species and they have the lowest confidence scores. The highest confidence in management thresholds was given to *Z. muelleri* (rating of 2 where 1 is the highest) as a range of approaches including *in situ* monitoring and experimental manipulation, as well as lab experiments have verified the thresholds, but for limited populations. The conservative approach applied (higher light threshold, shortest time to impact) for species with low confidence should ensure that the recommended light management thresholds provide protection to seagrass meadows at risk from acute light stress.

Table 1: Suggested management light thresholds of acute water quality impacts for GBRWHA seagrasses

Species	*Classification*	*Suggested management threshold (mol m^{-2} d^{-1})*	*Integration time (days)**	*Time to impact (days)***	*Confidence Score*[+]
Halophila decipiens	Colonising	2	1	14	3
Halophila ovalis^	Colonising	2	7	14	3
Halophila ovalis^	Colonising	6	7	28	3
Halophila tricostata	Colonising	2.5	1	14	5
Halophila spinulosa	Colonising	2.5	7	28	4
Zostera muelleri	Colonising/ opportunistic	6	14	28	2
Halodule uninervis	Colonising/ opportunistic	5	14	40	3
Cymodocea rotundata	Opportunistic	6	14	28	5
Cymodocea serrulata	Opportunistic	5	14	50	4
Syringodium isoetifolium	Opportunistic	6	14	28	5
Thalassodendron ciliatum	Persistent	5	14	50	5
Thalassia hemprichii	Persistent	5	14	50	4
Enhalus acoroides	Persistent	5	14	50	5

*Averaging time used to describe light history and as first signal to trigger management plan

**Time to impact expected and a management plan should be implemented before this time

^Two-step threshold applies due to species plasticity, see full synthesis document for details

[+]Confidence score is detailed in the following table

Water quality guidelines for longer time frames will be based on long-term light thresholds, but these are not as clearly defined owing to a paucity of data. As an estimate, 10 – 13 mol m^{-2} d^{-1} is likely to prevent light limitation for the long-bladed species (but this range is not suitable for deepwater species, which require less light). Defining site-specific desired state and then setting light targets to achieve it will advance the establishment of long-term light thresholds.

The following recommendations can be made on the basis of this synthesis:

1. adopt recommended acute light management thresholds;

2. develop a method to determine desired state so that long-term light thresholds can be advanced for contribution to regional water quality guidelines;
3. develop locally-specific acute thresholds for application in local management; and,
4. explore the effects of cumulative impacts (temperature, nutrients, sedimentary conditions) and light quality, on acute and long-term light thresholds.

1. INTRODUCTION

1.1 Guidelines and compliance standards in the GBRWHA

There are a number of threats to water quality within the Great Barrier Reef World Heritage Area (GBRWHA), including terrestrial discharge laden with sediments, nutrients and pesticides (Brodie, et al., 2013; Coles, et al., 2015; Fabricius, et al., 2014), and coastal development can locally threaten water quality through dredge material handling and the suspension of fine sediments (Erftemeijer and Robin Lewis III, 2006; Grech, et al., 2011; Hughes, et al., 2015; York, et al., 2015). The overarching aim of the *Reef 2050* plan is "to ensure the GBR continues to improve on its outstanding universal value every decade between now and 2050 to be a natural wonder for each successive generation to come" and water quality is one of four key challenges in achieving this goal (Great Barrier Reef Marine Park Authority and Queensland Government, 2015). Water quality improvements are tracked through the flagship monitoring program, the inshore Marine Monitoring Program (e.g. Martin, et al., 2014) and reported through the Reef Water Quality Protection Plan's annual report card (http://www.reefplan.qld.gov.au/measuring-success/report-cards/). This is coupled with local monitoring from over 90 monitoring programs and detailed seagrass monitoring in high risk locations such as Queensland Ports (Coles, et al., 2015; Rasheed, et al., 2014).

According to *Reef 2050*, seagrass meadows are one of the habitats that best represent the key ecological and biological processes of the Great Barrier Reef (hereafter referred to as the Reef); provide habitat for biodiversity including threatened species; increase resilience to climate change; and provide economic and community benefits (Great Barrier Reef Marine Park Authority and Queensland Government, 2015). With this ecosystem health role in mind, seagrass condition is an important indicator for acute water quality impacts and for long-term water quality guidelines in the Reef (Great Barrier Reef Marine Park Authority, 2014).

1.1.1 Compliance standards for short-term impacts

In support of the water quality objectives set out in guiding policies and legislation such as *Reef 2050* and the *Environmental Protection Act 1994*, state and federal regulators set protocols for monitoring condition relative to aquatic ecosystem guidelines. These are to be implemented by proponents wanting to undertake discrete activities that have the potential to threaten the water quality and ecosystems within the GBRWHA. These protocols outline recommendations for water quality guidelines, sample number, sampling frequency, and reporting protocols (e.g. statistics). The protocols themselves are Reef-specific (where possible), and are based on scientifically derived information.

In some locations, such as Gladstone Harbour, investment into research and monitoring has enabled the development of locally-specific compliance standards for management of a major dredging operation. This included management thresholds for light with the explicit aim of maintaining seagrass biomass (Gladstone Ports Corporation Pty Ltd 2014). Light was included in the management framework because it was recognised that seagrass condition and resilience is largely driven by incoming light, and research had been undertaken that could enable light to be used as a threshold during dredging scenarios. This light-based management plan has set a precedent for inclusion of light in future compliance monitoring (see case study below).

In a recent review of dredge management priorities, the development of ecological tolerance thresholds for regulation, was highlighted as one of three key priority areas for future investment (Schaffelke, et al., 2016). There has been considerable research into light requirements and thresholds for seagrasses of the Reef (e.g. Chartrand, et al., 2012; Chartrand, et al., Subm; Collier, et al., 2012a; Collier, et al., In Press; Mckenna, et al., 2015b) and monitoring to characterise light levels within seagrass meadows (Bryant, et al., 2014; McKenzie, et al., 2016). Most of this research has focussed on short-term light thresholds that are applicable to compliance monitoring (detailed below) and integration into management frameworks. However, the research findings, apart from the Gladstone case study, have not been readily available to managers to incorporate into compliance standards.

1.1.2 Water quality guidelines for long-term targets

For establishing longer-term and regional water quality guidelines (i.e. not linked to a development activity), the Great Barrier Reef Marine Park Authority (GBRMPA) prepared water quality guidelines for the Great Barrier Reef (2010) with trigger levels that are protective of a desired ecosystem state. These are developed for the Reef based on locally-derived thresholds and local priorities, as recommended through the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC). If levels are outside the guidelines, it is a prompt for managers to take action. The guidelines focus on sediments, nutrients and pesticides, which are the main catchment run-off pollutants that affect water quality reaching the Reef. *Reef 2050* outlines the procedures for adaptive management of the the Reef whereby guidelines are modified due to emerging threats and/or enhanced understanding (through research). Therefore, the GBRMPA, in collaboration with the Queensland Government, is taking the opportunity to implement additional guidelines through catchment-level schedules.

Furthermore, the Queensland government prepares water quality guidelines for Queensland waters (generally superseded by local guidelines within the GBRWHA) to protect environmental values (EVs). These are derived from 1. direct measurement of biological impacts (e.g. experiments), or 2. acceptable departure from a reference condition (Department of Environment and Heritage Protection, 2009). As all of Queensland's seagrass species occur within the Reef, the research undertaken on light requirements for seagrasses within the Reef are also relevant to the Queensland water quality guidelines.

1.2 GBRWHA seagrasses

The GBRWHA includes one of the world's greatest areas of seagrass (35,000km^2) (Coles, et al., 2015). Across this range, seagrass inhabits estuarine (or semi-enclosed), coastal, reef and deepwater habitats. These are distributed in a cross-shelf gradient, except for deepwater habitats which occur throughout the Reef in water >10–15m. The inshore habitats (estuarine and coastal) are exposed with the greatest frequency to turbid and nutrient-enriched water from terrestrial discharge and resuspension (Devlin, et al., 2015; Fabricius, et al., 2014; McKenzie, et al., 2016). Reef habitats and mid-shelf deepwater habitats have infrequent exposure to terrestrial discharge. Cumulative risk is generally highest in the southern two thirds of the GBRWHA within highly developed ports and urbanised catchments where the threats from terrestrial discharge are combined with local development pressures (Grech, et al., 2011).

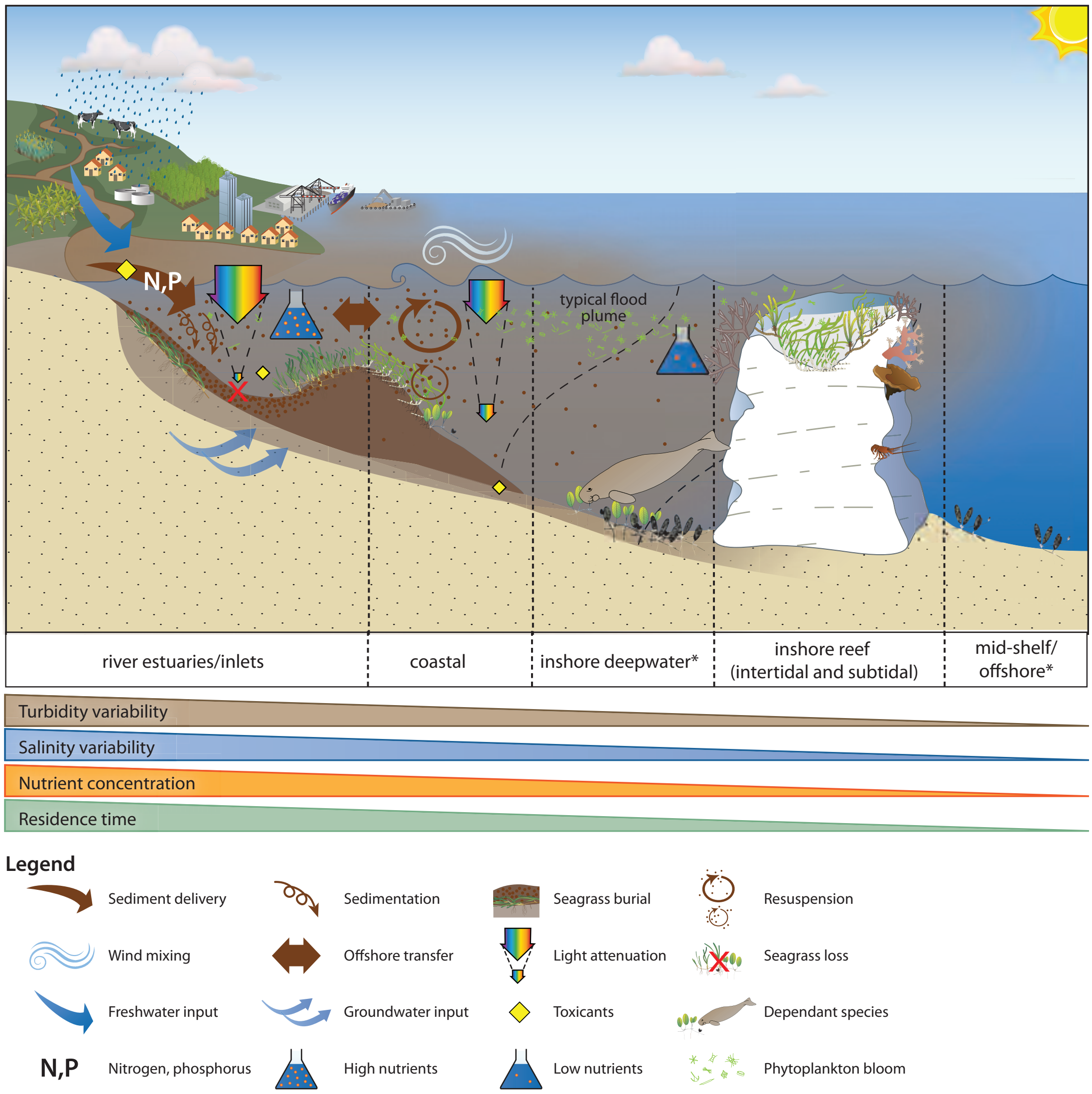

Figure 1: Seagrass habitats of the GBRWH. Adapted from McKenzie, et al. (2016)

There are 15 seagrass species in the GBRWHA from three different families (Waycott, et al., 2004). The dominant species varies among the habitats. For example, *Zostera muelleri* predominantly occupies habitat with high mud content. In contrast, *Thalassia hemprichii* and *Cymodocea rotundata* occupy coarse carbonate sand with low mud content and therefore occur more commonly in reef habitats. *Halodule uninervis* and *Halophila ovalis* are generalists, occurring in a range of habitat types. These, together with *Zostera muelleri* are the most common species in shallow habitats (<5m), while *Halophila* species dominate in deeper water habitat.

Seagrass species can be classed as colonising, opportunistic, or persistent (Figure 2); (Kilminster, et al., 2015). Persistent species occupy relatively stable habitats and form enduring meadows (e.g. Thalassia and Enhalus), while colonising species tend to be transitory. Colonising and opportunistic species succumb to disturbances (such as light limitation) the most quickly and this is due, in part, to lower overall storage capacity (Collier, et al., 2012b; Longstaff and Dennison, 1999). Yet these are the most dominant species in the the Reef, particularly in the inshore regions where water quality presents the greatest risk. These colonising and opportunistic species have been the focus of research into light requirements owing to their sensitivity to low light and their occurrence in at-risk inshore habitat.

The long-term presence of colonising species in at-risk habitats can be attributed to their recovery traits, specifically, they can recolonise following small-scale disturbances (such as single short flood events), through rapid expansion (rhizome extension), and from seed banks (McKenzie, et al., 2016; Rasheed, 2004; Unsworth, et al., 2015). Despite this, they remain highly vulnerable to large-scale or repeated disturbances, with many examples throughout the Reef where they have not recovered, or are recovering very slowly following loss in 2009 – 2011 (McKenzie, et al., 2016; Rasheed, et al., 2014). The ecological effects of this loss (record dugong and turtle mortality in 2011 (Meager and Limpus, 2012), have been a reminder of the need to avoid seagrass loss by the implementation of appropriate management measures.

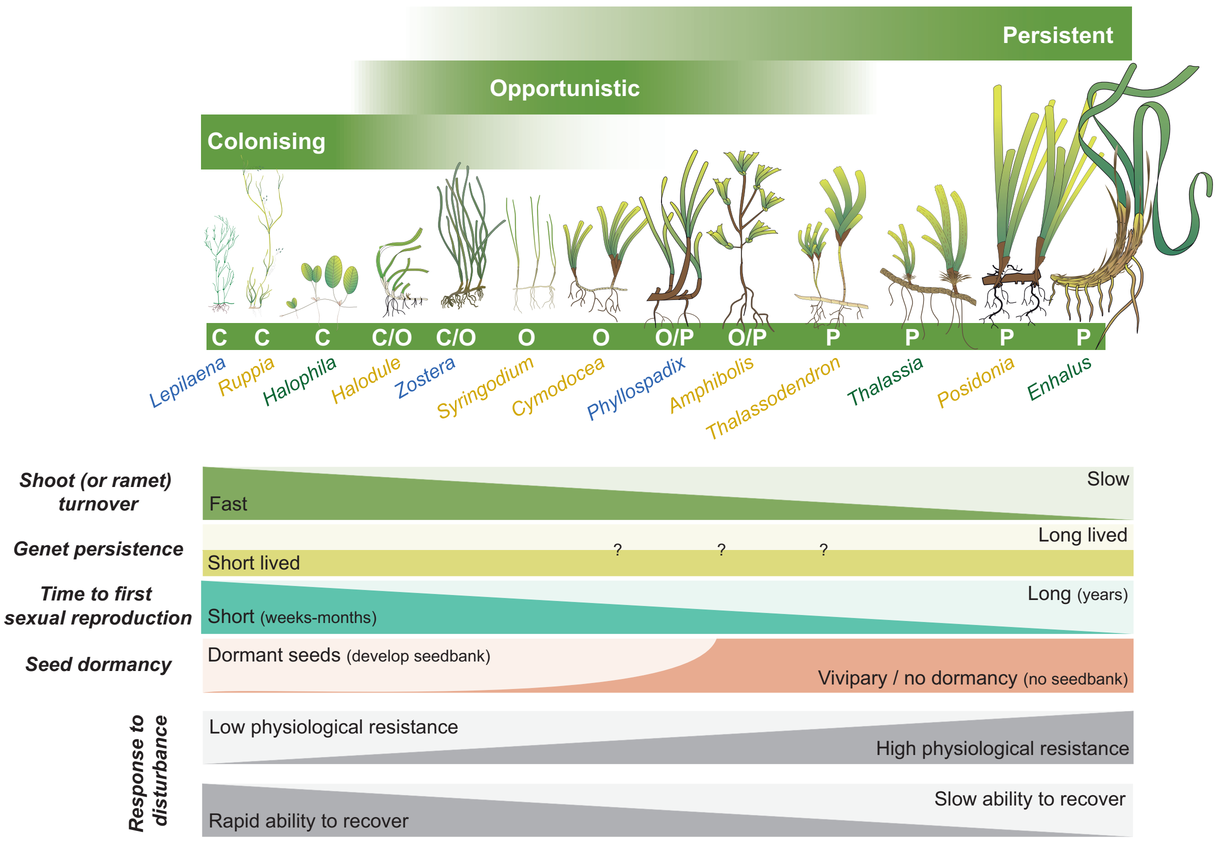

Figure 2: Dominant traits of colonising, opportunistic and persistent seagrass species. There are representatives from all 3 categories: colonising, opportunistic and persistent, within the GBRWHA and therefore these vary in their sensitivity to disturbances. Adapted from (Kilminster, et al., 2015).

1.3 Impacts of light reduction on seagrass

Seagrasses are dependent on light for photosynthetic carbon fixation, growth and biomass production. Among marine plants, seagrasses have relatively high light requirements because they invest in building and maintaining non-photosynthetic structure including rhizomes and roots (Dennison, et al., 1993). They are predominantly found in coastal regions, colonising sediment-rich banks in relatively shallow water in order access light and where nutrients are abundant to support growth (Collier and Waycott, 2009). These habitats are also at risk from terrestrial discharge and from coastal development. The availability of light limits their spatial distribution (depth range), and light limitation can drive seagrass loss (Chartrand, et al., Subm; Collier, et al., 2012a; Collier, et al., 2012b; Rasheed, et al., 2014).

Variable water quality in coastal environments creates perpetually fluctuating light conditions (de los Santos, et al., 2010; Petrou, et al., 2013), which can quickly manifest into changes in plant physiology and ultimately affect morphology and abundance if light drops below a certain point (Ralph et al. 2007). Within the plant, strategies to cope with light reduction include: adjusting light harvesting capacity and the efficiency of light use (Abal, et al., 1994; Enríquez, 2005); adjustments to rates of growth and plant turnover (Collier, et al., 2012b; Collier, et al., 2009); and drawing upon carbohydrate reserves to maintain productivity (Burke, et al., 1996; Touchette and Burkholder, 2000). Molecular signalling drives seagrass responses to light limitation through the expression of stress-inducible genes (Schliep, et al., 2015). However, despite these inbuilt capacities, seagrasses can be acutely sensitive to reductions in light beyond "typical" conditions, which leads to shoot and even meadow-scale seagrass loss with consequences for ecosystem function (Collier, et al., 2012a; Hughes, et al., 2008; McKenzie, et al., 2016; Petus, et al., 2014; Rasheed, et al., 2014).

1.4 Approaches to monitoring and researching light thresholds

Research into seagrass light thresholds has been undertaken using a number of approaches, including:

1. *in situ* light measurements, which can show when reductions in benthic light coincide with seagrass loss (e.g. Chartrand, et al., 2012; Collier, et al., 2012a);
2. in situ experiments, which test light thresholds within local site conditions (Chartrand, et al., Subm);
3. minimum light requirements, which is the annually averaged daily light at the depth limit of the seagrass meadow (Longstaff, 2002); and,
4. laboratory experiments, which enable detailed testing of light thresholds and cumulative effects (Collier, et al., 2012b; Collier, et al., In Press).

In 2016, light is being monitored at 35 locations spanning more than 2000 km and covering all described habitat types (Figure 1), and in all 6 NRM regions within the GBRWHA and also into the Gulf of Carpentaria. Light is recorded using autonomous 2π loggers (Odyssey™) that measure photosynthetically active radiation (PAR) with wiper units to keep sensors clean throughout deployment. Light is recorded as instantaneous light (μmol m^{-2} s^{-1}) every 15 – 30 minutes, and is summed to daily light (mol m^{-2} d^{-1}), which integrates daily light exposure (Bryant, et al., 2014; McKenzie, et al., 2016). Defining the light environment in terms of daily light removes diurnal variability, but daily light is also highly variable among days. Daily light is therefore reported as a (rolling) average of the previous 14 days (Chartrand, et al., 2012) or 28 days (McKenzie, et al., 2016). This enables quantification of the recent light history and detection of trends. The trends in light recorded in these monitoring programs are reported in multiple publications depending on the location and monitoring program (e.g. Bryant, et al., 2014; Chartrand, et al., Subm; McKenna, et al., 2015a; McKenzie, et al., 2016). Seagrass monitoring, in high-risk areas such as urbanised centres, ports and near sources of terrestrial discharge, provides valuable information on ecosystem condition to inform management, planning and compliance of activities with the potential to impact on local seagrasses. Specifically, monitoring data is also used to test and validate light thresholds.

1.5 About this report

The aims of this project were to:

- provide clear and consistent guidance to environmental managers and regulatory authorities on light thresholds to apply for seagrasses with the GBRWHA;
- synthesise current state of knowledge of light effects on seagrasses;
- develop a conceptual framework to guide threshold application;

- deliver a table of light thresholds guidelines and associated indicators of stress for key seagrass species in the Great Barrier Reef for immediate application by multiple end-users (i.e. managers, regulators, modelers etc); and,
- highlight critical information gaps for species and thresholds to focus future research efforts.

The following tables and associated text is a guiding document for managers and regulators to better understand what is known on the light required to sustain seagrasses within the GBRWHA. The report is separated into acute light thresholds typically impacts lasting less than 3 months), for which the majority of information is available and provides guidance for discrete coastal development activities, and long-term light guidelines for catchment-scale water quality concerns. Detailed justification for each species is discussed as well as definitive knowledge gaps that limit our understanding and therefore capacity to set light thresholds for managing impacts to seagrass from both acute and chronic sources.

2. METHODOLOGY

2.1 Tabulating light thresholds

All information on seagrass light thresholds and light requirements were sourced from peer-reviewed publications, the grey literature and unpublished work (unpub. results were restricted to that within the TropWATER group at JCU by the authors of this report). The search was undertaken for all species that occur in the Reef; however, all studies from the tropics and subtropics were sourced and therefore included results from south of the Reef (Moreton Bay and NSW) (Figure 3). The tables provide information on 12 seagrass species found within the GBRWHA. The number of studies varied among species ranging from 0 (*Cymodocea rotundata*, *Thalassodendron ciliatum* and *Syringodium isoetifolium*) to 7 for *Zostera muelleri* (Table 2).

Table 2: Number of studies or entries contributing to the light thresholds for each species. An entry refers to a piece of information, with more than one entry possible for each study. Values in brackets are studies from con-genera from the northern hemisphere used as supporting information only.

Species	*Classification*	*No. entries*	*No. studies*
Halophila decipiens	Colonising	4	3
Halophila spinulosa	Colonising	4	2
Halophila tricostata	Colonising	1	1
Halophila ovalis	Colonising	8	3
Zostera muelleri	Colonising/opportunistic	17	7
Halodule uninervis	Colonising/opportunistic	10	4
Cymodocea rotundata	Opportunistic	0	0
Cymodocea serrulata	Opportunistic	8	3
Syringodium isoetifolium	Persistent	0	0 (+2)
Thalssodendron ciliatum	Persistent	0	0
Thalassia hemprichii	Persistent	2	1 (+6)
Enahlus acroides	Persistent	1	1

The *biological light thresholds* are defined as an intensity below which a significant negative change in seagrass physical condition was observed using monitoring data or experimental approaches. There are many indicators of seagrass light stress, and some of these may be early warning indicators of imminent loss (McMahon, et al., 2013; Ralph, et al., 2007; Roca, et al., 2016; Schliep, et al., 2015). However, in this study, the focus has remained on abundance metrics because they are ecologically significant changes (representing loss of habitat function), sensitive to light reduction, and commonly measured (McMahon, et al., 2013). This approach is consistent with recommended endpoints for water quality guideline derivation, which should be ecologically relevant (e.g. survival, growth and reproduction) (Batley, et al., 2014).

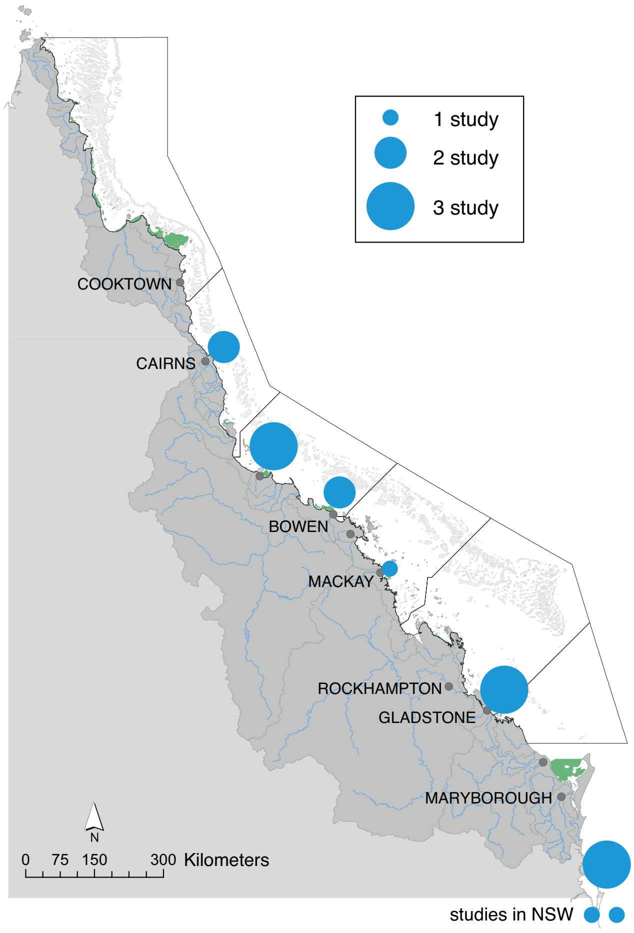

Figure 3: Spatial distribution of studies used in this report.

2.2 Translating biological thresholds into management thresholds

The recommended *light management thresholds* are more conservative than the biological thresholds derived from studies and long-term datasets. If light is maintained above these management recommendations, seagrass abundance (biomass, density, percent cover) and in turn, the structure and habitat function of the meadow should be preserved. Unlike the ecosystem threshold, management thresholds or water quality guidelines typically aim to achieve a pre-determined target such as no loss, undetectable loss, or a set level of acceptable loss (Collier, et al., In Press; Qian and Cuffney, 2011; Schneider, 2013). This approach (no, or undetectable loss) has been adopted in this report for light management thresholds.

Duration of exposure has an effect on biological light thresholds, and it was identified that there were two important time-scales: 1. acute; and, 2. long-term/annual. These time-scales are carried through to the recommended light management thresholds, however the exact time separating acute vs long-term varies among species but typically fell in the range <40 days for acute and 3 months – 1 year for long-term. Also shown is the biological response indicator and degree it was impacted (e.g. loss of biomass), as this can indicate how far beyond the "threshold" light reduction has pushed the biological response. Light thresholds are expressed as a range in mol m^{-2} d^{-1} together with time (days) to impact of the seagrass species. The findings are presented from the most recent to the oldest studies. Species are grouped into life history strategies (colonising, opportunistic and persistent) (sensu. Kilminster, et al., 2015). Data were also grouped into meaningful entries. For example, if the same experiment was run for multiple days, then changing thresholds over time are shown within the same cell, as all other factors for the two entries are the same. Where conditions changed (e.g. new method, or new interactive factor was tested), then a new cell was created.

2.3 Quantifying light

The recommended unit for seagrass light thresholds is daily light (mol photons m^{-2} d^{-1}, hereafter abbreviated to mol m^{-2} d^{-1}), rather than percentage of surface irradiance (%SI), which is another commonly used light indicator. This is because daily light is the diurnally integrated light exposure and is affected by clouds, turbidity or other light reducing properties of the water. That is, it defines the light required for seagrass maintenance irrespective of the cause of light reduction. This is an important distinction (from using %SI) because it means that operations that could affect seagrasses need to consider the light history and condition of the meadow rather than just turbidity. For example, surface irradiance at Low Isles, Green Island and Dunk Island (Wet Tropics region) was 30.1 mol m^{-2} d^{-1}, 33.4 mol m^{-2} d^{-1}, and 31.9 mol m^{-2} d^{-1} (2009 – 2015), respectively. At Magnetic Island (Burdekin) surface irradiance was 23.6 mol m^{-2} d^{-1} while Gladstone Harbour (Fitzroy) was 29.8 mol m^{-2} d^{-1} (2014 – 2015; unpublished data). On average among these sites, surface light was 29.3 mol m^{-2} d^{-1}. For comparison to studies presenting thresholds in %SI, 5 mol m^{-2} d^{-1} is around 16.8 %SI and 10 mol m^{-2} d^{-1} is 33.6 %SI but this will vary depending on incoming solar irradiance. In studies where thresholds were not presented as daily light (in mol m^{-2} d^{-1}), but rather as % surface light, or % reduction then daily light was calculated from information contained within the article, or within the region on surface light (in mol m^{-2} d^{-1}).

3. Biological light thresholds for GBRWHA seagrasses

The following tables and associated text is a guiding document for managers and regulators to better understand what is known about the light required to sustain seagrasses within the GBRWHA. This section details the *biological light thresholds* (i.e. measured thresholds), and the following section provides recommended *management thresholds* and guidelines that will provide protection to seagrasses at risk from water quality impacts.

Experimental studies are generally limited in their treatment resolution (i.e. there is a set number of treatment levels), which usually means that the true “threshold” falls between treatment levels. Hence, interpretations of values in Tables, 3, 4 and 5 need to consider light levels in which there was both loss, and no loss. Some studies avoid this by taking different approaches. For example, the minimum light requirement (MLR) may be used as an annual average light level that a seagrass requires for survival. Other studies adopt a greater number of treatment levels, which can help resolve thresholds (e.g. Abal, et al., 1994) and enable alternate statistical approaches such as curve fitting to calculate thresholds (Collier, et al., In Press).

There has been greatest investment into light requirements for the dominant coastal species of the Reef because they are the species most at risk from water quality impacts caused by coastal development and terrestrial discharge. These include *H. ovalis, H. uninervis* and *Z. muelleri*. These species are classified as fast growing colonising species, or the latter two are often considered opportunistic species (Kilminster, et al., 2015). This means that they are sensitive to environmental perturbations, with limited capacity for resistance. Generally, they are impacted after 28 days under light limitation (

Table 4).

Recent studies on deepwater seagrass species (*H. decipiens*, *H. tricostata*, *H. spinulosa*) have greatly expanded the available information on light requirements for these communities (Chartrand et al., unpubl.). These deepwater species generally grow under low light at depth, forming sparse meadows during the growing season (~Sep – Dec). These can completely die off (*H. decipiens*), or persist but at very low biomass (*H. tricostata*, *H. spinulosa*). *H. decipiens*, is particularly sensitive to light limitation with rapid loss of biomass after just 14 days at 1.1 mol m^{-2} d^{-1} (Chartrand pers. comm, Table 3), or when the average growing conditions are 2 to 2.6 mol m^{-2} d^{-1} (Table 8). *H. ovalis* can be just as sensitive to low light (Chartrand, et al., 2012; Longstaff and Dennison, 1999) rapidly declining after just 12 – 16 days, under very low light. However, *H. ovalis* can also occur in shallow high light habitats and so higher light thresholds have also been identified through a range of studies (Chartrand, et al., 2012; Collier, et al., In Press). *H. spinulosa* and *H. tricostata* can also occur in deepwater habitats, and are more tolerant of low light, likely due to greater investment into below-ground biomass and storage of reserves, which increases their tolerance to short-term light reduction. Hence impacts were observed after a longer time frame (30 days).

The true opportunistic species and the persistent species tend to be more tolerant of periods below light thresholds. Despite this, the light levels leading to an impact can be similar for *H. uninervis* and *Z. muelleri*, but they take longer to take effect (e.g. Collier, et al., 2012b; Collier, et al., In Press). There is, however, considerably less known about the light requirements of the opportunistic and persistent species, with no information available for three species.

Light thresholds are affected by exposure period and acute light stress is tolerated at lower light levels than long-term light stress. The light thresholds measured for *Z. muelleri* (

Table 4) are plotted in Figure 4. Over the short-term (<40 days), measured light thresholds do not exceed 5.4 mol m^{-2} d^{-1}. They can tolerate low light conditions by undergoing some photo-acclimation and by drawing on storage reserves (Ralph, et al., 2007), but as the time of exposure increases towards 28 – 40 days, the energetic imbalances caused by a reduction in photosynthetic rate leads to biomass loss. As the duration of light limitation is extended even further (>80 d), light thresholds increased to a maximum of 10.4 mol m^{-2} d^{-1} (Figure 4). Hence the definition of an acute impact for this species is relevant for <40 days and long-term thresholds refers to impacts lasting ~80 days to annual time-scales. The effect of exposure time on light thresholds has been demonstrated for other species in some studies (Collier, et al., 2012b; Collier, et al., In Press), but there is insufficient information to enable the generation of such time plots for other species. The time over which an impact can be considered "acute" has been generated for these species using a similar approach i.e. the shortest duration in which light reduction takes effect.

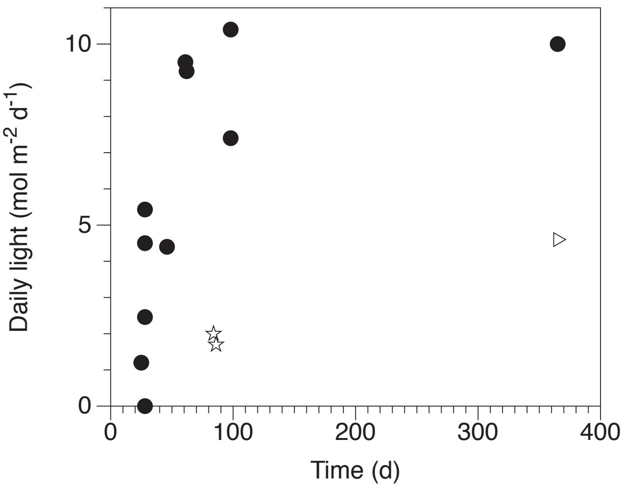

Figure 4: Daily light threshold (i.e. the light level causing an impact) and exposure time to that light level for *Z. muelleri*. Black dots show studies from within Queensland. The white stars are studies from NSW (Fyfe, 2003; York, et al., 2013), and the white triangle is an anomalous depth limit from Moreton Bay (Longstaff, 2002).

As shown in

Table 4 light thresholds can be affected by water temperature (Chartrand, et al., Subm; Collier, et al., In Press). Higher temperatures may increase the rate of respiration (carbon loss), and therefore require higher light to drive photosynthetic rates in excess of respiratory loss (Collier, et al., 2011). Light thresholds could be influenced by a range of other factors including nutrient availability, herbicide exposure and sediment conditions. For example, herbicide exposure, at concentrations that are recorded in Reef coastal waters (0.4 $\mu g\ L^{-1}$), has a potential shading equivalent of 10% based on declines in photosynthetic efficiency (Negri, et al., 2015). Furthermore, genetic composition/diversity can affect tolerance to disturbances (Reusch, et al., 2005), but this has not been tested for light thresholds. Where light thresholds are developed in situ (Chartrand, et al., Subm; Collier, et al., 2012a), the inherent site characteristics (e.g. sediment type and nutrient availability), are included in the derivation of the light threshold. However, how local environmental conditions affect these light thresholds is largely unknown.

Table 3: Summary of light thresholds for the colonising Halophila species

Location	Season/ temperature	Impact	Light intensity	Time to Impact (d)	Zone	Study Location	Notes	Reference
			Halophila decipiens					
Green Island	Oct	Shoot loss No impact found	1.1 mol m^{-2} d^{-1} 3.2 mol m^{-2} d^{-1}	14 30	Tropical	Lab		Chartrand et al *in prep*
Green island	Intra- & inter-annual trends	Above-ground biomass, shoot counts	2.1 mol m^{-2} d^{-1}	Growing seasonal av	Tropical	Deepwater		Chartrand unpubl. data
US Virgin Islands	~20°C	Growth rate and depth limit	4.4% SI		Tropical	Subtidal		Williams and Dennison (1990)
			Halophila ovalis					
Magnetic Island	Sep-Dec 23°C	Shoot density	5.29±2.2 mol m^{-2} d^{-1} 8.99±3.11 mol m^{-2} d^{-1}	49 98	Tropical	Outdoor Experiment	20% loss (80% protection)	Collier, et al. (In Press)
Magnetic Island	Sep-Dec 28°C	Shoot density	5.83±2.58 mol m^{-2} d^{-1} 9.97±2.67 mol m^{-2} d^{-1}	28 98	Tropical	Outdoor Experiment	20% loss (80% protection)	Collier, et al. (In Press)
Gladstone	Sep - Dec	Biomass & Shoot density	1.8 mol m^{-2} d^{-1} 6.5 mol m^{-2} d^{-1}	16 30	Sub-tropical	Intertidal experiment		Chartrand, et al. (2012)
Moreton Bay	Aug, 22°C Oct, 27°C Dec-Jan, 26-30°C	Total biomass (Expt A) Total biomass (Expt B) Total biomass (Expt C)	0.1% SI 0.1% SI 0.1% SI	12 15 14	Sub-tropical	Outdoor Experiment	23% loss 63% loss 59% loss	Longstaff, et al. (1999)
Gulf of Carpentaria	July-Nov	Total biomass	0.1 mol m^{-2} d^{-1}	24	Tropical	Intertidal experiment	63% loss	Longstaff and Dennison (1999)
			Halophila spinulosa					
Abbot Point	Oct	Shoot loss No impact found	1.1 mol m^{-2} d^{-1} 3.2 mol m^{-2} d^{-1}	30 30	Tropical	Lab		Chartrand et al *in prep*
Abbot Point	Intra- & inter-annual trends	Above-ground biomass	1.9 mol m^{-2} d^{-1}	Growing seasonal av	Tropical	Deepwater		TropWATER unpubl. data
Keswick Is (Mackay)	Intra- & inter-annual trends	Above-ground biomass, shoot counts	2.2 mol m^{-2} d^{-1}	Growing seasonal av	Tropical	Deepwater		TropWATER unpubl. data
Moreton Bay	May-June ~20°C	Root biomass	50 %SI (~14.8 mol m^{-2} d^{-1})	≤30	Sub-tropical	Outdoor Experiment	34% loss	Grice, et al. (1996)
			Halophila tricostata					
Keswick Is (Mackay)	Intra- & inter-annual trends	Above-ground biomass, shoot counts	2.2	Growing seasonal av	Tropical	Deepwater	TropWATER unpubl. data	Tropwater unpubl.

Table 4: Summary of light thresholds for the colonising/opportunistic *Zostera muelleri* and *Halodule uninervis*

Location	Season/ temperature	Impact	Light intensity	Time to Impact (d)	Zone	Study Location	Degree of impact	Reference
			Zostera muelleri* ssp. *Capricorni					
Gladstone	Sep – Dec May-June?	Above-ground biomass, percent cover No loss	≤5 mol m^{-2} d^{-1} ≤2 mol m^{-2} d^{-1}	28 – 42 28 – 42	Sub-tropical	Shading Intertidal	~40% loss 0% loss	Chartrand, et al. (Subm.)
Gladstone	Sep – Dec	Above-ground biomass, percent cover	≤6 mol m^{-2} d^{-1}	14	Sub-tropical	In situ light	No loss	Chartrand, et al. (Subm.)
Gladstone	Sep – Dec 23°C	Shoot density	2.46±1.9 mol m^{-2} d^{-1} 7.4±1.9 mol m^{-2} d^{-1}	28 98	Sub-tropical	Outdoor Experiment	20% loss (80% protection)	Collier, et al. (In Press)
Gladstone	Sep – Dec 28°C	Shoot density	5.43±1.77 mol m^{-2} d^{-1} 10.4±2.4 mol m^{-2} d^{-1}	28 98	Sub-tropical	Outdoor Experiment	20% loss (80% protection)	Collier, et al. (In Press)
Lake Macquarie, NSW	24, 27, 30°C	Above-ground biomass No impact found	2.0 mol m^{-2} d^{-1} 4.8 mol m^{-2} d^{-1}	≤84	Sub-tropical	Indoor Lab	~50% loss 0% loss	York, et al. (2013)
Magnetic Island	Mar – May	Shoot density	1.2 mol m^{-2} d^{-1} 4.4 mol m^{-2} d^{-1} 9.5 mol m^{-2} d^{-1}	25 46 61	Tropical	Outdoor Experiment	27% loss 36% loss 47% loss	Collier, et al. (2012b)
Port Hacking, NSW	Feb – April ~19°C	Biomass No impact found	1.7 mol m^{-2} d^{-1} 7.2 mol m^{-2} d^{-1}	≤86	Sub-tropical	Lab	99% loss 0% loss	Fyfe (2003)
Moreton Bay	Annual	Depth limit of meadow (i.e. MLR)	10 mol m^{-2} d^{-1} 4.6 mol m^{-2} d^{-1}	365	Sub-tropical	Subtidal	3-site mean 1 site (considered anomalous)	Longstaff (2002) Dennison and Abal (1999)
Moreton Bay	Mar – May 23°C	Shoot density & Total biomass	30% SI (~9.25* mol m^{-2} d^{-1})	≤62	Sub-tropical	Outdoor Experiment	60% loss shoots 35% loss biomass	Abal, et al. (1994)
			Halodule uninervis					
Magnetic Island	23°C	Shoot density, modelled threshold	3.8±2.3 mol m^{-2} d^{-1}	28 98	Tropical	Outdoor Experiment	No loss 20% loss (80% protection)	Collier, et al. (In Press)
Magnetic Island	28°C	Shoot density, modelled threshold	4.15±6.11 mol m^{-2} d^{-1} 9.2±3.2 mol m^{-2} d^{-1}	49 98	Tropical	Outdoor Experiment	20% loss (80% protection)	Collier, et al. (In Press)
Magnetic Island	Mar – May	Shoot density	0.2 mol m^{-2} d^{-1} 4.4 mol m^{-2} d^{-1} 9.5 mol m^{-2} d^{-1}	46 61 74	Tropical	Outdoor Experiment	40% loss 39% loss 34% loss	Collier, et al. (2012b)
Magnetic Island	Summer, >28°C	Percent cover	4.0 mol m^{-2} d^{-1}	≤90	Tropical	Subtidal	50% loss in *H. uninervis* dominated meadow	Collier, et al. (2012a)
Gulf of Carpentaria		Biomass Shoot density	0.1 mol m^{-2} d^{-1}	38-52	Tropical	Intertidal	~40% loss ~34% loss	Longstaff and Dennison (1999)
Moreton Bay	May-June ~20°C	Productivity (g DW m^{-2} d^{-1})	50% SI (~14.8 mol m^{-2} d^{-1})	≤30	Sub-tropical	Outdoor Experiment	20% reduction	Grice, et al. (1996)

*based on conversion using surface light and daily light from the same region, Moreton Bay in Longstaff (2002); ≤ indicates that measures were not made prior to this day

Table 5: Light thresholds for the opportunistic *C. serrulata, Syringodium isoetifolium* and the persistent *T.hemprichii.*

Location	Season/ temperature	Impact	Light intensity	Time to Impact (d)	Zone	Study Location	Notes	Reference
			Cymodocea serrulata **Opportunistic occurring in coastal, and reef habitat**					
Magnetic Island	Sep – Dec 23°C	Shoot density	NA NA	28 98	Tropical	Outdoor Experiment	No loss, no threshold could be calculated	Collier, et al. (In Press)
	Sep – Dec 28°C	Shoot density	3.61±2.37 mol m^{-2} d^{-1} 8.63±3.84 mol m^{-2} d^{-1}	49 98	Tropical	Outdoor Experiment	20% loss (80% protection)	Collier, et al. (In Press)
Magnetic Island	Mar – May	Shoot density	0.2 mol m^{-2} d^{-1} 4.4 mol m^{-2} d^{-1} 9.5 mol m^{-2} d^{-1}	46 61 74	Tropical	Outdoor Experiment	56% loss 48% loss 26% loss	(Collier, et al., 2012b)
Moreton Bay	May – June ~20°C	Productivity	50% SI (~14.8 mol m^{-2} d^{-1})	≤30	Sub-tropical	Outdoor Experiment	38% reduction	(Grice, et al., 1996)
			Syringodium isoetifolium					
Mauritus	24°C 28°C 24 and 28°C	**Shoot length** **Shoot length** **Shoot density**	75% reduction	21 21 70	Sub tropical	Subtidal	Signif. increase Signif. increase No effect	(Fokeera-Wahedally and Bhikajee, 2005)
Florida *Syringodium filiforme*	Annual	**Minimum light requirement**	24 – 37% SI (8.5 – 13.2 mol m^{-2} d^{-1})	365	Tropical	Subtidal	Depth limit	(Kenworthy and Fonesca, 1996)
			Thalassia hemprichii **Persistent occurring in coastal and reef habitat**					
Magnetic Island	Mar – May	No impact -Shoot density	0 0.2 mol m^{-2} d^{-1}	102	Tropical	Outdoor Experiment	No impact detected[#]	(Collier, et al., 2012b)
Florida *Thalassia testudinum*		Seagrass depth limit (MLR)	18 – 32% SI (~6.4 – 11.4 mol m^{-2} d^{-1})*	Annual	Tropical	Subtidal	Depth limit	(Choice, et al., 2014; Czerny and Dunton, 1995; Dixon, 1999; Tomasko and Hall; Tomasko, et al.)
Florida *Thalassia testudinum*		Shoot density	16% SI (5.6 mol m^{-2} d^{-1})* 13% SI (4.5 mol m^{-2} d^{-1})*	365			95% loss 98% loss	(Czerny and Dunton, 1995)

based on statistical re-analysis of data with species separated

*In Czerny and Dunton Florida ambient light 50% SI = 17.8 mol, 100% SI = 35

4. MANAGEMENT GUIDELINES

The following management guidelines are divided into 1) recommended light management thresholds for acute impacts and 2) light guidelines for long-term maintenance of seagrass in recognition that higher light may be required over the long-term (Figure 4). This is based on a synthesis of all known species-specific light data available to the authors at the time of publication relevant to the GBRWHA (see previous section for details).

4.1 Recommended management thresholds for acute impacts

Acute thresholds can be applied to short-term threats such as dredging or small-scale developments where the management goal is no physical loss of seagrass leaves or shoots. Recommended acute thresholds are tabulated (Table 6) and discussed in detail in this section. Long-term management thresholds are discussed in the following section.

Table 6: Recommended management light thresholds for GBRWHA seagrasses.

Species	*Classification*	*Suggested management threshold (mol m^{-2} d^{-1})*	*Integration time (days)**	*Time to impact (days)***	*Confidence Score[+]*
Halophila decipiens	Colonising	2	1	14	3
Halophila ovalis[^]	Colonising	2	7	14	3
Halophila ovalis[^]	Colonising	6	7	28	3
Halophila tricostata	Colonising	2.5	1	14	5
Halophila spinulosa	Colonising	2.5	7	28	4
Zostera muelleri	Colonising/ opportunistic	6	14	28	2
Halodule uninervis	Colonising/ opportunistic	5	14	40	3
Cymodocea rotundata	Opportunistic	6	14	28	5
Cymodocea serrulata	Opportunistic	5	14	50	4
Syringodium isoetifolium	Opportunistic	6	14	28	5
Thalassodendron ciliatum	Persistent	5	14	50	5
Thalassia hemprichii	Persistent	5	14	50	4
Enhalus acoroides	Persistent	5	14	50	5

*Averaging time used to describe light history and as first signal to trigger management plan

**Time to impact expected and a management plan should be implemented before this time. See section case study for details

[+]Confidence score is detailed in the following table

[^]Species has a two-stage threshold due to species plasticity to growing light conditions. See text for further detail

The recommended acute management thresholds are higher than maximum biological thresholds in order to increase confidence that they will provide protection under acute light stress (Chartrand, et al., Subm). For example, for *Z. muelleri*, the maximum short-term, acute light threshold was 5.4 mol m^{-2} d^{-1} over 28 d, therefore the recommended management threshold is 6 mol m^{-2} d^{-1} with an expected time to impact after 28 days.

An integration time of 14 days is recommended for *Z. muelleri* to account for recent light history of the meadow (Chartrand, et al., Subm). In practice, this refers to a rolling average of daily light recorded at the seagrass site, such that each day, the rolling average moves forward by one day to incorporate the most recent light. With recent advances in light measurement and telemeted data (e.g. Vision Environment 2012), daily light can be provided as live updates. The integration time is also a means to track progress towards meeting the target. If the 14-day rolling average falls below the threshold then this initiates a management plan (see case study below). As an impact is expected after 28 days at that light level, a management action is required between 14 days and 28 days. The integration time should also be considered prior to the initiation of the disturbance, therefore, if the integrated light history (14 days) is below the threshold, then the management plan needs to be put in place even prior to commencing the operation.

The time to impact and the integration times are shorter for the sensitive Halophila species. In *H. decipiens*, a small, fast-growing colonising (ephemeral) species, abundance is expected to decline after just 14 days below the threshold. Physiological changes, including a draw-down on carbohydrate storage reserves can occur within days (Longstaff, et al., 1999), reducing their resilience. Therefore, an integration time of just 1 day is recommended for *H. decipiens*, and 7 days for *H. ovalis* and *H. spinulosa*. Although *H. tricostata* is probably not as sensitive to light stress as *H. decipiens*, as there is little information available on this species, the more conservative 1-day integration time and 14-day time to impact has been applied.

Two light thresholds have been recommended for *H. ovalis* in recognition that it occupies diverse habitats (with a broad range in light levels) and is highly sensitive to disturbance. The abundance of *H. ovalis* can decline within 12 days at very low light levels; therefore a short-term light threshold is required (2 mol m^{-2} d^{-1} over 14 days). However, it frequently occurs in habitats with much higher light levels when 2 mol m^{-2} d^{-1} is unlikely to be breached, but it can none-the-less remain vulnerable to low light hence an additional management threshold of 6 mol m^{-2} d^{-1} over 28 days is proposed, and both thresholds should be complied with to avoid loss.

The confidence score is a critical component of the recommended management table as it highlights the degree of certainty that the light threshold will protect seagrass from an acute disturbance (Table 7). Although there is relatively high level of confidence in recommended management thresholds for *Z. muelleri*, a comprehensive assessment of thresholds has been undertaken for just one population (Gladstone Harbour). Therefore, there is insufficient information from other populations to know whether there are population-specific (i.e. genetic), or local environmental effects on light thresholds. Where the confidence is very low (4 – 5), the most conservative (higher light, shorter duration) recommendations have been made from within the group of species (colonising, opportunistic, or persistent). This can be adjusted through investigations that refine light thresholds and it is expected that such investigations will make thresholds less conservative.

Table 7: Confidence criteria table.

Score	*Description of confidence level*
1	For multiple populations/locations: A strong understanding of light deprivation effects on the species with laboratory experiments, in situ shading studies and multiple peer-reviewed publications documenting the effects of light stress on the species including studies assessing the interactive effect of temperature stress and nutrients on plant condition. Long term light and seagrass trends also monitored in high risk meadows and used to validate experimental results. While knowledge gaps may still exist, good confidence in setting species-specific light thresholds.
2	For limited locations, but the same as above
3	Somewhat confident but also lacking information in some of the categories above
4	Low confidence but some studies available or light history within seagrass meadows available for analysis
5	Almost no data available, based on expert consensus only

4.2 Case study: developing and applying acute light thresholds in Gladstone

Shading studies were conducted from 2010 to 2013 to simulate the effects of a dredge-related reduction in light from increased turbidity over an intertidal seagrass meadow and to establish an initial range of light required for local seagrass survival. Studies were carried out twice during the growing season (July to January) and twice in the senescent season (February to June) to assess seasonal differences in seagrass response. Results of these studies established significant differences in light requirements between seasons and that *Z. muelleri* required between 4 – 5 mol m^{-2} d^{-1} during the growing season to survive with significant declines between four to eight weeks if light levels were not maintained above this point (Chartrand et al., Subm). During the senescent season, seagrasses declined naturally without any further impact from experimental reductions in light.

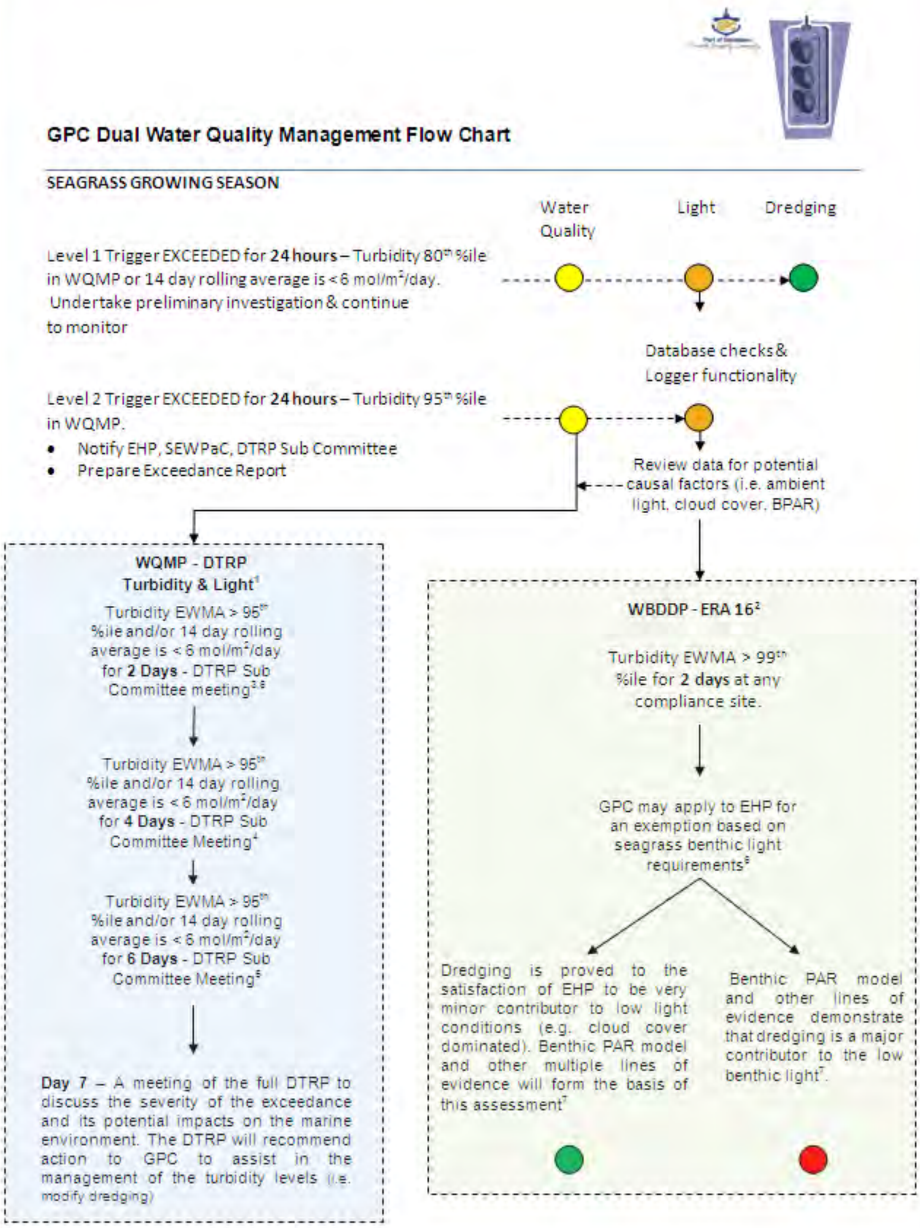

Figure 5: Dual water quality management flow chart from Gladstone Western Basin Dredging Program (Dredge Technical Reference Committee, GPC flyer) demonstrating use of turbidity and light management strategies to ensure seagrass condition was maintained during dredging operations.

Findings were resolved into an applied threshold of 6 mol m^{-2} d^{-1} over a rolling two week average, under which management actions and alerts were proposed to ensure appropriate steps are taken to mitigate seagrass declines. This light management threshold formed the basis of a reactive management strategy successfully implemented to ensure positive ecological outcomes for local seagrasses.

Importantly the management plan incorporated a multi-staged approach where alerts and actions could be implemented within a timeframe that allowed action to occur before actual seagrass declines were likely. The experimental field studies revealed that the earliest declines were recorded from light deprivation at 28 days. The management action plan (Figure 5) had initial management measures at Level 1 (14 days below threshold) to investigate data and possible causes, escalating at Level 2 after 16 days to bring together the technical management group, and again at 18 days and 20 days with final mitigation action (stop or modify dredge activity to be implemented at 21 days below the threshold, 7 days before the first declines were recorded during the experimental studies.

4.3 Management thresholds for long-term maintenance of seagrass

Maintaining seagrass condition over the long-term may require greater light than set out under the acute disturbance thresholds in order to ensure capacity for plant resilience and longstanding preservation (Unsworth, et al., 2015). Long-term light requirements can be used for setting water quality guidelines (GBRMPA, 2009), to identify management priorities (e.g. Waterhouse, et al., 2012) and to identify current and potential changes in seagrass extent (Brodie, et al., Subm. ; Steward, et al., 2005). A recommended long-term light management threshold is ~10 – 13 mol m^{-2} d^{-1} (34 – 44% SI) for species other than deepwater species. This threshold should ensure that meadows are not limited by light (Figure 6); however, these recommended thresholds are based on relatively limited evidence. The upper light threshold (10.4 mol m^{-2} d^{-1}) for four species over 98 days (Collier, et al., In Press) and 102 days (Collier, et al., 2012b) was detected using experimental approaches. However, the annual minimum light requirement for *Z. muelleri* meadows was 10 mol m^{-2} d^{-1} at the depth limit (where it survives, but it is light limited), indicating that this is the minimum amount of light required for long-term maintenance (MLR). Therefore, the error estimates in Collier, et al. (In Press) were used to estimate an upper conservative management threshold from the 10.4 mol m^{-2} d^{-1} (13 mol m^{-2} d^{-1}). This should ensure that the meadow is maintained in a productive, resilient state, and is not light limited.

The long-term light requirement for deepwater Halophila species needs to be based around their growing season. The long-term thresholds are also likely similar to the acute thresholds, however further work is needed to better refine these values. It is also important to recognise that not all deepwater Halophila species use the same strategy to ensure meadow longevity. Some, such as *H. decipiens*, rely heavily on local seed banks to regenerate entirely from seed each year while others have little to no seed bank and rely on below-ground energy stores similar to their shallow water counterparts (Chartrand pers obs).

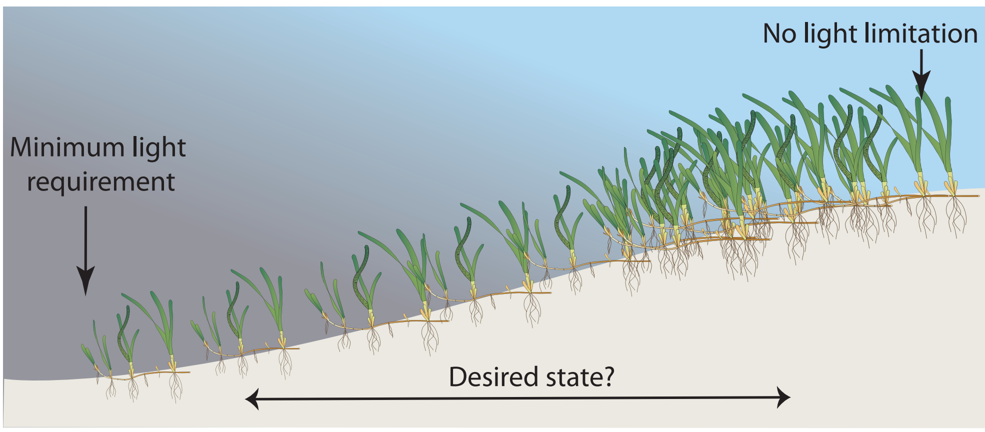

Figure 6: Long-term light thresholds can be described as light levels required to ensure meadows are not limited, by their minimum light required, or by the light level required to maintain a pre-determined desired state.

A light threshold which defines the light above which it does not limit seagrass growth is a useful management tool to enable management prioritisation based on its light limitation status. For example in the MMP, the long-term (2008 – 2015) average daily light for 6 out of 22 sites (Figure 7) fall below 10 mol m^{-2} d^{-1}, and 12 sites fall below 13 mol m^{-2} d^{-1}, indicating that growth is light limited in these inshore meadows. If a meadow is not light limited, but its' abundance is declining, then it may be necessary to look for other potential drivers of seagrass loss.

Many studies use minimum light requirements (MLR) and K_d established from seagrass depth limits (SDL), to set water quality targets (Dennison, et al., 1993; Steward, et al., 2005). This is a useful way to set a target for maximum seagrass extent, and it is assumed that meadows shallower than the SDL are protected, and even more productive and abundant (Figure 6). However, the depth limit of meadows can be difficult to define in the GBRWHA because the meadow boundary can be poorly defined, and even mobile (Collier pers obs). Furthermore, many meadows may have their maximum extent defined, not by light, but by a reef crest or a channel with fast flowing tidal currents that prevents meadow establishement. Thus the SDL will not be realised even light is managed for a theoretical MLR and this approach does not provide a realistic strategy to ensure seagrasses are receiving sufficient light.

At many locations, the "no light limitation" threshold proposed above (10 – 13 mol m^{-2} d^{-1}) is unlikely to be achieved even with water quality improvement, owing to natural site conditions. Thus, there is a need to refine long-term light thresholds on the basis of the "desired state" for the seagrass meadow i.e. desired seagrass abundance, a goal that has been highlighted as a research priority (Great Barrier Reef Marine Park Authority, 2014; Great Barrier Reef Marine Park Authority and Queensland Government, 2015). Desired state should reflect management goals, and be defined using attributes of healthy, resilient, functioning systems (Foley, et al., 2010; Kilminster, et al., 2015; Unsworth, et al., 2015). This could be quantified in highly variable habitat such as the seagrass meadows of the GBRWHA using knowledge of site history (Carter, et al., 2015) or reference meadows (McKenzie, et al., 2016) together with local light conditions. Relevant light thresholds could then be applied to achieve the characterised desired state and ensure a realistic management goal.

Future development of long-term light thresholds based on the desired state for meadow condition may need to distinguish among water bodies. Most of the existing long-term seagrass abundance and light monitoring data are from open coastal waters, one of the cross-shelf boundaries used to delineate water quality targets (Figure 7) (GBRMPA, 2009). Daily light reaching intertidal meadows in these coastal waters can vary from 0 to 45.8 mol m^{-2} d^{-1} (Table 8) and have an annual mean ranging from 5.3 to 22.4 mol m^{-2} d^{-1}. As you increase in depth, the range in light declines (Table 8). In midshelf waters, the peaks in light and mean annual values are higher due to less influence from terrestrial discharge and coastal development. These large-scale water quality patterns likely drive local seagrass acclimation and their capacity to resist or succumb to further reductions in light from ambient conditions.

Table 8: Long-term mean daily light (mol m^{-2} d^{-1}) in seagrass meadows of the GBRWHA separated into water bodies (Figure 7). Site-specific mean annual light is provided as a range with the daily light range in brackets. Superscript numbers indicate the number of sites contributing to the data. From Chartrand unpubl and McKenzie et al 2016.

Habitat	*Intertidal*	*Shallow (<5m)*	*Deepwater (>10 – 15m)*
Enclosed and open coastal water	5.3 – 22.4 (0 – 45.8)^{22}	5.9 – 7.0 (0 – 18.9)^{2}	2.0 (0 – 6.6)^{1}
Mid-shelf water	15.8 – 17.7 (0 – 46.2)^{2}	6.5 – 11.1 (0 – 22.0)^{2}	2.6 (0 – 8.2)^{2}

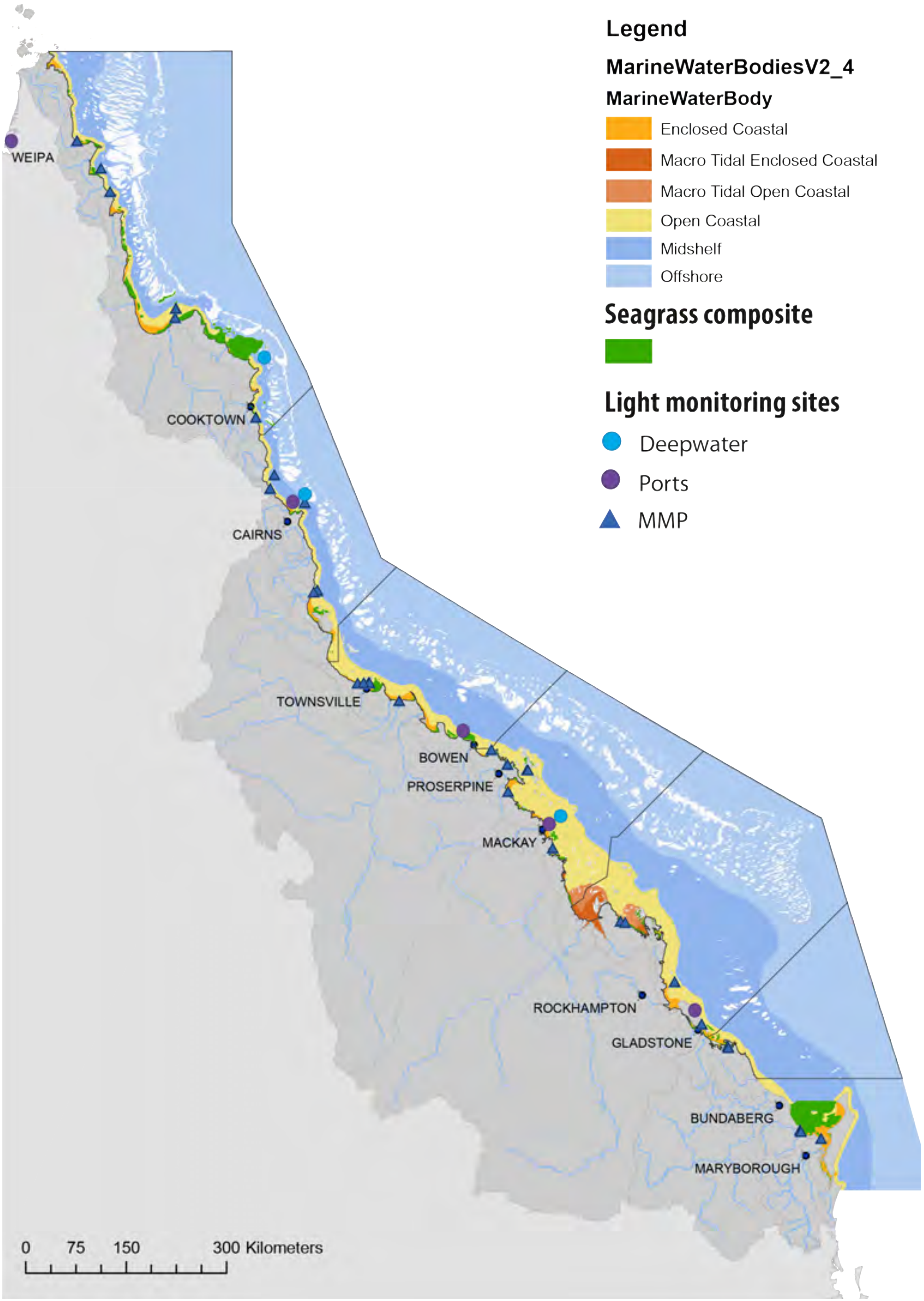

Figure 7: Light monitoring sites within seagrass meadows of the GBRWHA, water bodies, and seagrass distribution (composite).

4.4 Considerations and caveats

The recommended light thresholds were derived from the best available scientific knowledge and expert opinion but are based on relatively limited data with no species achieving the highest confidence score. The following outlines some considerations and caveats when applying the thresholds:

- a potential disturbance should be managed for the most sensitive species present;
- locally-specific guidelines are highly recommended as these capture inherent site conditions (including tidal exposure) that could affect seagrass light thresholds;
- thresholds are based on total photosynthetically active radiation (400 – 700nm), and do not account for spectral quality, which could affect light thresholds;
- there may be a need for seasonally varying light thresholds;
- an assessment of local seagrass condition leading up to an acute disturbance will help identify whether prevailing environmental conditions have altered seagrass health before a light threshold management plan is in place;
- thresholds are average values, while light levels are naturally variable. Peaks in light well above guidelines are likely to be important for some biological processes such as reproduction and meadow expansion;
- based on morphological response (shoot, biomass loss); resilience may be affected earlier/at higher light;
- effects of interactive factors on thresholds are largely unquantified (*in situ* experiments capture naturally changing site conditions);
- thresholds for >3 months are not tested over annual time frames. In particular, these thresholds have not been tested for maintenance of resilience (e.g. capacity to sexually reproduce and expand in biomass and area); and
- measurement of light as an approval condition or for compliance needs to be performed at the seagrass canopy (i.e. benthic light) of the meadow to be protected. Monitoring light at a shallower or deeper depth will not be an accurate application of the management threshold.

4.5 Knowledge gaps

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

- definitions of desired state to underpin the development of long-term light guidelines to meet them;
- species with no information on acute or long-term light thresholds;
- location and population-specific thresholds particularly for the most at risk species;

- cumulative effects of other environmental conditions on light thresholds (e.g. temperature, herbicides, sedimentary conditions); and
- investigations into the effect of spectral quality on light thresholds, and an exploration of other light indicators (e.g. H_{sat}).

5. RECOMMENDATION AND CONCLUSIONS

All available studies on seagrass light requirements were tabulated. This highlighted that there are two critical time-scales for consideration of light thresholds: acute and long-term. These findings were used to recommend acute management thresholds for 12 species occurring in the GBRWHA and which ranged from 2 to 6 mol m^{-2} d^{-1} depending on species. The thresholds are presented together with an integration time (1 – 14 days), time to impact (7 – 50 days) and confidence score (1 – 5). Deepwater species are the most sensitive to light reduction and therefore they have the lowest light thresholds and shortest integration time and time to impact. Persistent species are the most resistant to light deprivation, but there is very limited data on their light thresholds. There is the greatest amount of data available for *Z. muelleri*, and this was given a confidence rating of 2 (where 1 is the highest). Despite the low confidence for many species, these acute management thresholds are ready for application in compliance guidelines, as the conservative approach taken here should provide protection to seagrass meadows at risk from acute light stress.

Water quality guidelines should be based on long-term light thresholds, but these are not as clearly defined owing to a paucity of data. As an estimate, 10 – 13 mol m^{-2} d^{-1} is likely to prevent light limitation for strap-bladed species (not deepwater species, which require less light). Defining site-specific desired state and then setting light targets to achieve it will advance the establishment of long-term light thresholds.

The following recommendations can be made on the basis of this synthesis:

- adopt recommended acute light management thresholds;
- establish a clear definition of seagrass desired state within the GBRWHA in order to set long-term light guidelines for managing catchment-scale water quality threats to seagrass health;
- develop locally-specific acute thresholds for application in local management; and
- explore the effects of cumulative impacts and spectral properties (temperature, nutrients, sedimentary conditions), on acute and long-term light thresholds.

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APPENDIX 1: SYNTHESIS OF LIGHT THRESHOLDS AND MANAGEMENT GUIDELINES FOR END-USERS



Tropical Water Quality Hub

National Environmental Science Programme

Light thresholds for managing seagrass meadows at risk from acute water quality impacts

Catherine Collier, **Katie Chartrand**, **Carol Honchin**, **Adam Fletcher** and **Michael Rasheed**

Seagrass meadows are a critical part of the Great Barrier Reef World Heritage Area's outstanding universal value, but they are at risk from declining water quality due to coastal development and terrestrial discharge. One of the key controlling factors of seagrass growth is the amount of light they receive and in this document we detail appropriate light thresholds for the management of seagrass meadows in the GBR. These recommendations come from a synthesis of recent research funded by the National Environmental Research Programme, Tropical Water Quality Hub (NESP TWQ) project (Project 3.3).

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Background

Water quality affects light reaching seagrass meadows, and light in turn controls the productivity, abundance and distribution of seagrass meadows. If light is reduced, then seagrass abundance will decline with subsequent impacts to the ecological function of the seagrass meadow. Therefore, guidelines that are based on light are recommended as a complimentary management trigger for seagrass meadows at risk from declining water quality. Recen. research into seagrass light thresholds and mature light monitoring programs (>8 years) have provided light thresholds for this synthesis.

Approach

Available information on seagrass light requirements and thresholds were tabulated for the species occurring in the GBRWHA. These are based on thresholds that cause reductions in seagrass abundance (biomass, shoot density, percent cover). Full method details can be found in the synthesis report Collier *et al.* (2016). This synthesis highlighted two critical time-scales – acute and long-term thresholds – which also correspond to guidelines for acute compliance standards, and water quality guidelines for catchment management, respectively. The information presented here is for the recommended management thresholds for acute light stress (i.e. impacts of up to 3 months duration) and their application in compliance monitoring.

Findings

Recommended light management thresholds for acute impacts are based on integrated daily light and range from 2 to 6 mol m^{-2} d^{-1} depending on the species (Table 1). The thresholds are presented in conjunction with:

- Time to impact (7 – 50 days), which is based on the time until seagrass abundance is affected by light below the threshold;
- Integration time (1 – 14 days), which describes both the averaging time for monitoring daily light and a means to track progress towards meeting the light threshold before the time to impact is reached;
- Confidence score, which is defined by the amount of information available for each species (Table 2); and
- Species classification:
  - » **Colonising** — fast-growing and sensitive to disturbances including light reduction
  - » **Opportunistic** — able to adapt to local environmental conditions, with intermediate sensitivity to stress
  - » **Persistent** — form enduring meadows that resist stress but are slow to recover.

Colonising

Opportunistic

Persistent

Table 1: Suggested management light thresholds for GBR seagrasses

Species	Classification	Suggested management threshold (mol m^{-2} d^{-1})	Integration time (days)*	Time to impact (days)**	Confidence score⁺
Halophila decipiens	Colonising	2	1	14	3
*Halophila ovalis^*	Colonising	2	7	14	3
. . . . -	Colonising	6	7	28	3
Halophila tricostata	Colonising	2.5	1	14	5
Halophila spinulosa	Colonising	2.5	7	28	4
Zostera muelleri	Colonising/opportunistic	6	14	28	2
Halodule uninervis	Colonising/opportunistic	5	14	40	3
Cymodocea rotundata	Opportunistic	6	14	28	5
Cymodocea serrulata	Opportunistic	5	14	50	4
Syringodium isoetifolium	Opportunistic	6	14	28	5
Thalassodendron ciliatum	Persistent	5	14	50	5
Thalassia hemprichii	Persistent	5	14	50	4
Enhalus acoroides	Persistent	5	14	50	5

* Averaging time used to describe light history and as first signal to trigger management plan
** Time to impact expected and a management plan should be implemented before this time
^ Two-step threshold applies due to species plasticity, see full synthesis document for details
\+ Confidence score is detailed in the following table

Table 2: Confidence criteria table

Score	Description of confidence level
1	For multiple populations/locations: A strong understanding of light deprivation effects on the species with laboratory experiments, in situ shading studies and multiple peer-reviewed publications documenting the effects of light stress on the species including studies assessing the interactive effect of temperature stress and nutrients on plant condition. Long term light and seagrass trends also monitored in high risk meadows and used to validate experimental results. While knowledge gaps may still exist, good confidence in setting species-specific light thresholds.
2	For limited locations, but the same as above
3	Somewhat confident but also lacking information in some of the categories above
4	Low confidence but some studies available or light history within seagrass meadows available for analysis
5	Almost no data available, based on expert consensus only

Considerations and Caveats

The recommended light thresholds were derived from the best available scientific knowledge, but are based on relatively limited data. Some considerations and caveats to consider when applying the thresholds include:

- Managing for the most sensitive species at a given location;
- Ideally develop locally-specific guidelines as they best encapsulate local growing conditions;
- Incorporate seasonally varying light thresholds where appropriate
- For species with a low confidence score the thresholds are likely to be highly conservative and further study is recommended to improve applicability of the thresholds.

Other important considerations are detailed in Collier *et al.* (2016) and should be reviewed before acute impact guidelines described herein are implemented for management purposes.

A successful light-based management approach for protecting seagrass (*Z. muelleri*) from an acute impact has recently been applied in Gladstone Harbour during a large-scale dredging campaign (Gladstone Ports Corporation 2012). Combined with the species-specific threshold values in this document it provides a template for the application of light thresholds to manage other coastal developments that result in acute impacts to water quality and light.

For further details on the light management thresholds please contact us or see

Collier, C. J., K. Chatrand, C. Honchin, A. Fletcher, and M. Rasheed. 2016. *Light thresholds for seagrasses of the GBR: a synthesis and guiding document*. Reef and Rainforest Research Centre. <www.nesptropical.edu.au>

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