



Marine and Tropical Sciences Research Facility

Drivers of change to seagrass distributions and communities on the Great Barrier Reef: Literature Review and Gaps Analysis



Catherine Collier and
Michelle Waycott



Australian Government
Department of the Environment,
Water, Heritage and the Arts



JAMES COOK
UNIVERSITY
AUSTRALIA



Reef &
Rainforest
RESEARCH CENTRE

Drivers of change to seagrass distributions and communities on the Great Barrier Reef

Literature Review and Gaps Analysis

Catherine Collier and Michelle Waycott

School of Marine and Tropical Biology, James Cook University



Australian Government

**Department of the Environment,
Water, Heritage and the Arts**

Supported by the Australian Government's
Marine and Tropical Sciences Research Facility
Project 1.1.3 Condition, trend and risk in coastal habitats:
Seagrass Indicators, distribution and thresholds of potential concern

© James Cook University

ISBN 9781921359248

This report should be cited as:

Collier, C. and Waycott, M. (2009) *Drivers of change to seagrass distributions and communities on the Great Barrier Reef: Literature Review and Gaps Analysis*. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (55pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's Marine and Tropical Sciences Research Facility.

The Marine and Tropical Sciences Research Facility (MTRSF) is part of the Australian Government's Commonwealth Environment Research Facilities programme. The MTRSF is represented in North Queensland by the Reef and Rainforest Research Centre Limited (RRRC). The aim of the MTRSF is to ensure the health of North Queensland's public environmental assets – particularly the Great Barrier Reef and its catchments, tropical rainforests including the Wet Tropics World Heritage Area, and the Torres Strait – through the generation and transfer of world class research and knowledge sharing.

This publication is copyright. The Copyright Act 1968 permits fair dealing for study, research, information or educational purposes subject to inclusion of a sufficient acknowledgement of the source.

The views and opinions expressed in this publication are those of the authors and do not necessarily reflect those of the Australian Government or the Minister for the Environment, Water, Heritage and The Arts.

While reasonable effort has been made to ensure that the contents of this publication are factually correct, the Commonwealth does not accept responsibility for the accuracy or completeness of the contents, and shall not be liable for any loss or damage that may be occasioned directly or indirectly through the use of, or reliance on, the contents of this publication.

This report is available for download from the Reef and Rainforest Research Centre Limited website:
http://www.rrrc.org.au/publications/research_reports.html



Completed December 2007
Published by the RRRC February 2009
Cover artwork, report layout and editing: Shannon Hogan

Contents

List of Figures.....	ii
List of Tables.....	ii
Acronyms Used In This Report	iii
Acknowledgements	iii
Introduction	1
Seagrass Distribution	3
Broad Habitat Range	3
Many Environmental Drivers.....	7
Light – A dominant driver	7
Nutrients – Elusive yet important	12
Temperature – Most species have broad temperature tolerance	15
Hydrodynamics	17
Sediment.....	18
Salinity.....	18
Temporal Variation to Seagrass Growth.....	19
Seasonal Patterns: Influenced by local climatic conditions	19
Sexual reproduction triggers unknown.....	23
Inter-annual patterns: Influenced by regional-scale climate and recovery	24
Overall Importance as a Driver: Moderate to high.	24
Knowledge gaps.....	24
Disturbance and Its Drivers.....	25
Types of Disturbances: From Centimetres to Kilometres	25
Disturbances: Different Drivers of Change with Common Outcomes	27
Physical disturbance – A dominant disturbance	27
Overall Importance as a Driver: Very high.	28
Knowledge gaps.....	28
Light – Episodic reduction common	28
High light	29
Nutrients – Rarely implicated in disturbance events	31
Temperature – Too hot in shallow waters	32
Burial – Smothering and escape, it’s all about time.....	33
Impacts of Disturbances – Change and Loss	34
Loss.....	34
Recovery and change	35
Potential maximum seagrass biomass and community structure	36
Changes in meadow states: The good, the bad, the ugly	38
Summary of potential disturbances to seagrass meadows in the GBR	40
Disturbance to seagrass meadows in the GBR and issues related to their management	41
References	42

List of Figures

Figure 1:	Generalised life cycle of seagrasses for three common coastal seagrass species in the GBR region
Figure 2:	Latitudinal distribution of seagrass species across the GBR
Figure 3:	Species distribution across the major habitat types in the GBR and their global distribution
Figure 4:	Relative depths for achieving a Minimum Light Requirement (MLR) for a seagrass in turbid versus clear water
Figure 5:	Some of the known responses of GBR seagrasses to light gradients as outlined in the text and identification of unknown responses to changing light regimes
Figure 6:	Nutrient response model for benthic primary producers with site-specific examples from within the GBR
Figure 7:	Plot of sediment nutrient concentration for the Marine Monitoring Program sites in the GBR, 2005-2006
Figure 8:	Generalised conceptual diagram showing seagrass responses to elevated temperature
Figure 9:	Generalised trend in seagrass biomass and long-term climatic variables for the Cairns region
Figure 10:	Generic conceptual diagrams of key drivers of seasonal trends in seagrasses in the Great Barrier Reef region, recognising three seasonal periods
Figure 11:	Seagrass-Watch data for six regions of the Queensland coast showing the general trends in seagrass cover for available data
Figure 12:	Tropical seagrass responses to increasing stress such as reduced light availability
Figure 13:	Models show how seagrass growth is possibly limited for specific drivers, and the combined effect of these drivers
Figure 14:	Changes between natural states of a seagrass meadow
Figure 15:	Changes between the states described in Figure 14 with the added pressure of human mediated changes
Figure 16:	Generalised model depicting seagrass meadows under different disturbance regimes

List of Tables

Table 1:	The minimum light requirements for seagrasses of the GBR ranked in reducing order as well as maximum recorded depth limit and mean depth limit
Table 2:	Major causes of natural disturbance, drivers of change impacts and location observed in GBR seagrass meadows
Table 3:	Major causes of human-mediated disturbance, drivers of change impacts and location observed in GBR seagrass meadows

Acronyms Used In This Report

GBR	Great Barrier Reef
MLR	Minimum light requirement
MTSRF	Marine and Tropical Sciences Research Facility
N	Nitrogen
P	Phosphorus
QDPI&F	Queensland Department of Primary Industries and Fisheries
RWQMP	Reef Water Quality Monitoring Program

Acknowledgements

Funding was provided through the Australian Government's Marine and Tropical Sciences Research Facility (MTSRF) Project 1.1.3 *Condition, trend and risk in coastal habitats: Seagrass indicators, distribution and thresholds of potential concern*.

Data on nutrients and support was provided by the Queensland Department of Primary Industries and Fisheries (QDPI&F) as a partner in MTSRF Project 1.1.3 and through supporting activities in the Great Barrier Reef World Heritage Area Marine Monitoring Program.

Thanks are extended to the following people for discussions, input and advice: Jane Mellors, Len McKenzie, Rob Coles, Michael Rasheed (QDPI&F), Bill Dennison, Ben Longstaff, Tim Carruthers, Jane Thomas (Integration and Application Network, University of Maryland Center for Environmental Studies), Ainsley Calladine, Alana Grech, Helene Marsh, Ivan Lawler, Joe Holtum, Dieter Tracey, Juanita Bité, Catherine Walsh, Kellie Lobb (James Cook University), Kathryn McMahon, Paul Lavery (Edith Cowan University) and Stuart Campbell (Wildlife Conservation Society, Marine Programs, Bogor Indonesia).

Introduction

Seagrass meadows are important for a number of reasons: they act as the foundation of a diverse community with numerous ecological roles; primary production; habitat and food for herbivores (including turtles and dugongs); sediment stabilization; biochemical modification of the local environments; nutrient cycling and hydrodynamic modifiers. Seagrasses are known to be under threat from numerous impacts and also play a role as indicators of coastal ecosystem health (Orth *et al.* 2006). Recent analysis of Great Barrier Reef Ecosystem Health (Great Barrier Reef Marine Monitoring Program Workshop, September 2007) supports this in the GBR region.

The Great Barrier Reef (GBR) supports a high diversity of seagrass species across a broad range of habitat types. Seagrasses are not a taxonomically unified group but are an ecological group, which through pressures imposed by the marine environment have converged in general morphology, i.e. they have photosynthetic leaves and roots and rhizomes to anchor in the sediment and to grow via rhizome extension (Waycott *et al.* 2007). The high seagrass diversity in the GBR is associated with a broad range of seagrass forms and functions (Walker *et al.* 1999). These species respond to environmental drivers in different ways and with different thresholds for tolerance to disturbances. While there are some generalisations that can be drawn across this broad grouping, for many aspects being considered in relation to drivers of change, seagrass species differ. Every effort is made in this review to consider this diversity where there is enough available information to do so.

Seagrass monitoring and research has a rich history in the GBR region and yet there are many key areas of system understanding that are poorly understood. In this review we summarise the understanding of drivers in seagrass meadows. In a recent report (Coles *et al.* 2007), the status and trends of seagrass distribution in the GBR is described. The review here-in describes drivers of change in seagrass meadows and how these influence seagrass distributions, natural cycles in distribution and growth and drivers of disturbances to seagrass meadows. We seek to identify key processes that explain the distribution, variability and limitations to growth, enhancing our ability to recognise ecosystems under stress and when management actions may be required. The overall aim of this review is to highlight significant knowledge gaps that, if fulfilled, will improve our ability to manage seagrasses of the GBR.

To fully describe the processes limiting seagrass growth, an understanding of the manner in which seagrasses grow and survive throughout their life is useful (Figure 1). The life of a seagrass plant is typically dominated by the life-history stage of growth and meadow expansion following seed recruitment. During this stage of plant growth, individuals (from germination of a single seed) may persist for a very long time, forming large, clonal meadows. For all GBR seagrasses the extent of longevity and scale of individual growth remains unknown and requires future studies using genetic and ecological tools. Flowering and seed set provide propagules for seagrass habitats recovery following disturbance. Germination and establishment are rate limiting to habitat recovery and potentially influence the resilience of coastal marine communities. The causes of habitat loss are multitude and are form the basis of this review.

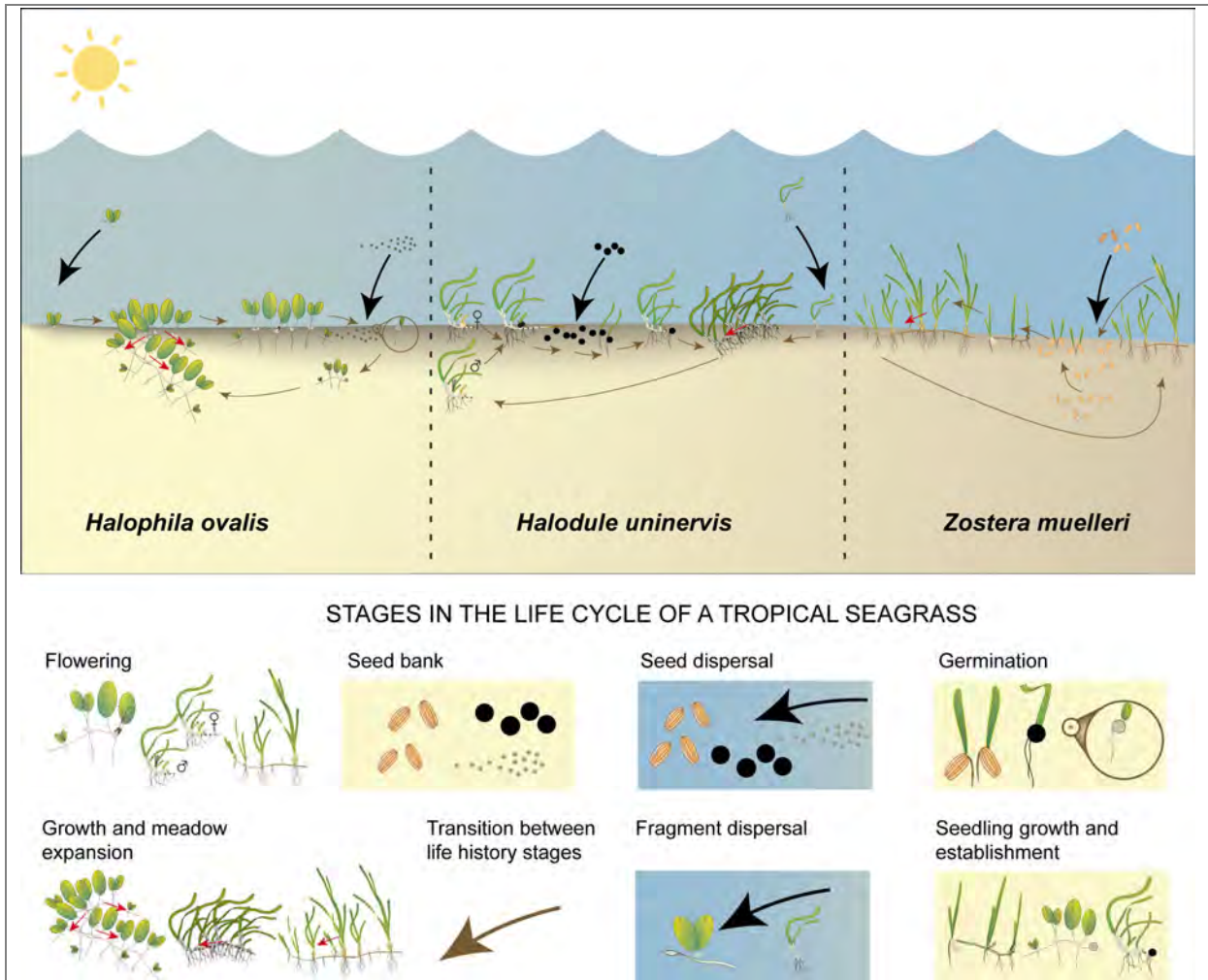


Figure 1: Generalised life cycle of seagrasses for three common coastal seagrass species in the GBR region.

Seagrass Distribution

Broad Habitat Range

Seagrasses occur throughout much of the protected sediment-covered areas of the GBR. The mapped area of seagrass is about 1,741 km². There are also extensive areas of deepwater seagrass that have not been mapped in detail, but including an estimate of this area, seagrasses probably cover up to 5,668 km² (Waycott *et al.* 2007) – more than twice the area of coral reef in the GBR (IAN, 2006).

There are fourteen species of seagrass found in the GBR, with one of these, *Ruppia sp.*, thought to be introduced into Queensland waters (Waycott *et al.* 2007). The latitudinal distribution of these species is varied (Figure 2). Most occur throughout the GBR and are tropical-subtropical in their distributional range with their southern limit in Moreton Bay near Brisbane. Others are constrained to tropical waters north of the Tropic of Capricorn; *Zostera muelleri* (syn. *capricorni*) is more of a temperate species, and although it can be found in estuaries and coastal habitats across the range of the entire GBR, it is more common towards the south, extending across southern Australia to Western Australia and to New Zealand. The tropical species are almost all distributed across the entire Indo-West Pacific region except for three species, *Halophila spinulosa*, *Halophila tricostata* and *Halophila capricorni* (Waycott *et al.* 2004). The latter two species are endemic to the GBR and Coral Sea region, unusual among seagrasses globally which typically have broad oceanic wide distributions.

The seagrass species diversity of the GBR region is amongst the highest in the world, equalled or surpassed only by the Southeast Asian region (Waycott *et al.* 2004) and Southwestern Australia (Carruthers *et al.* 2007). Ongoing controversy surrounding seagrass taxonomic diversity among tropical seagrass species (Waycott *et al.* 2006) has made examining exact species distributional limits difficult and requires further attention (Waycott *et al.* 2006).

The high diversity of seagrass species in the Great Barrier Reef corresponds with their broad range of habitats. The key seagrass habitats have been classified as *rivers* and *inlets*, *coastal*, *reef* and *deepwater* habitats (Carruthers *et al.* 2002). These have been defined according to the dominant processes and impacts acting on seagrasses in the habitats: terrigenous runoff, physical disturbance, low nutrients and low light respectively (Carruthers *et al.* 2002). Uniquely, seagrasses also occupy habitats that are both permanently submerged – subtidal – and those that are intermittently exposed to the air – intertidal; each of these also having their own unique environmental characteristics and key processes. As such these habitats have been further divided in a recent review into *Coastal intertidal* and *subtidal* and *Reef intertidal* and *subtidal* (Waycott *et al.* 2007).

These later classifications are used here to describe the distribution of GBR species across different habitats (Figure 3). The greatest number of species can be found in subtidal coastal and reef habitats. River estuaries are dominated by *Zostera muelleri* in the south and often *Enhalus acoroides* to the north. Intertidal habitats are dominated by *Halodule uninervis* and *Halophila ovalis*, as these can develop a small stature that enables them to lay on the sediment surface and minimise desiccation.

Only species of the genus *Halophila* occupy deepwater habitats, with *Halophila decipiens* being the most dominant. Some seagrasses can reach sixty metres, but at depths of more than 35m their cover becomes very sparse (Coles *et al.* 2000). Some seagrass communities in the GBR have higher species diversity – those with both coastal and reefal influences.

These coastal reef communities thus represent an important ecosystem and may harbour highly diverse faunal communities.

A unique characteristic of tropical meadows is that they often form mixed species meadows (e.g. Birch and Birch 1984; Mellors and Marsh 1993; Rasheed 2004). This differentiates them from their temperate counterparts, which are often dominated by monospecific stands (e.g. Bulthuis 1983; Conacher *et al.* 1994a; Collier *et al.* 2007). Tropical seagrass meadows can comprise a mix of colonising species together with later successional species. Each species has a different threshold for a range of environmental conditions (see next section of this report). The suite of species can, therefore, influence the way a meadow responds to changes in environmental conditions and to disturbances.

Seagrass distribution – Key points

- Seagrasses occur throughout the GBR in a broad range of habitats.
- These habitats have their own key drivers and also susceptibilities.

Knowledge gaps

- Seagrass distribution in the Cape York region.
- Distribution and changes to the distribution of deepwater species, particularly ephemeral meadows.
- Environmental conditions and fluctuations in reef and deepwater habitats.
- Interactions within mixed species meadows.
- Biodiversity associated with different seagrass communities.

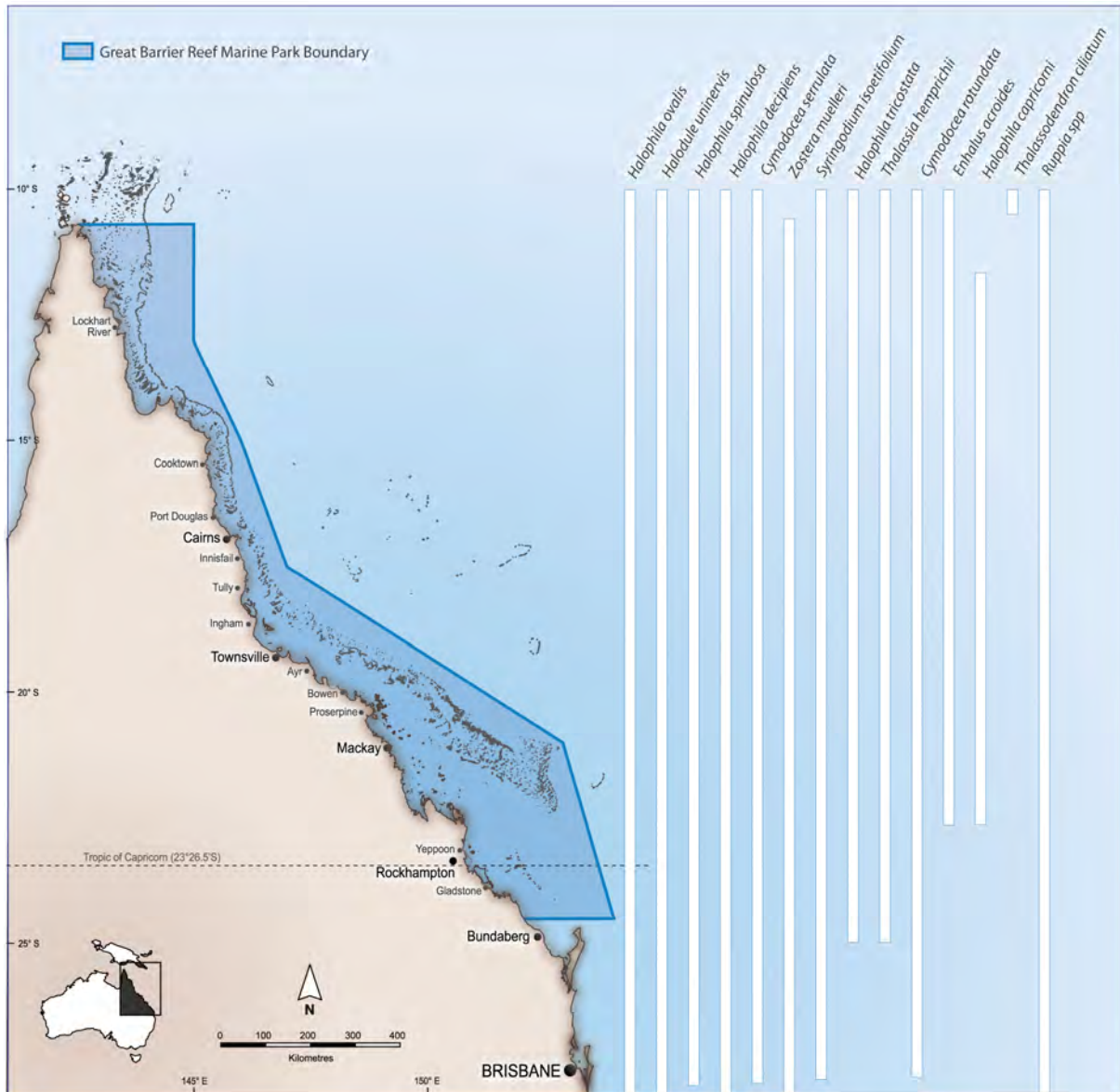


Figure 2: Latitudinal distribution of seagrass species across the GBR (white bars).

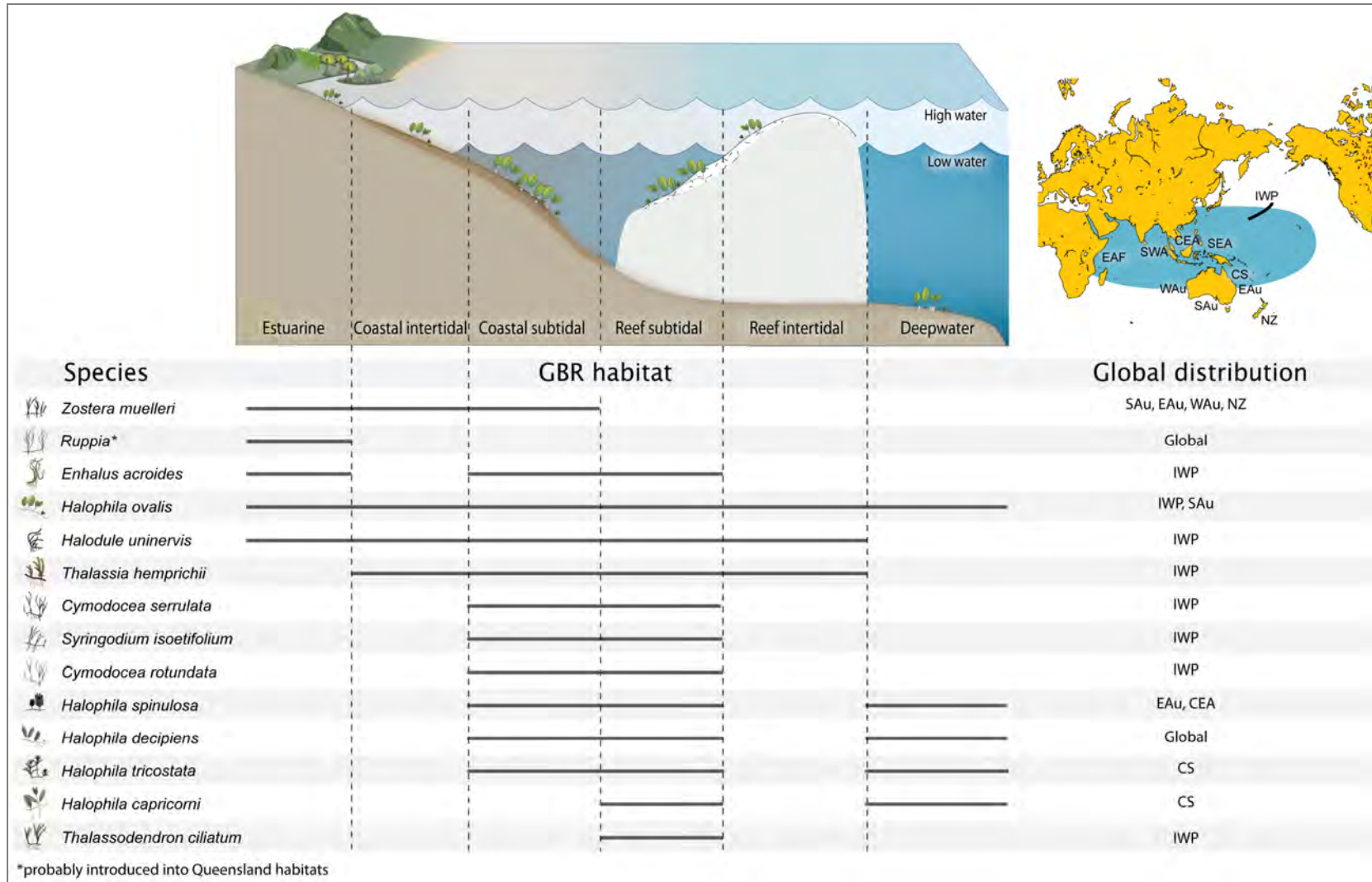


Figure 3: Species distribution across the major habitat types in the GBR and their global distribution. EAF = East Africa; SWA = Southwest Asia; CEA = Central East Asia; WAu = West Australia; SAu = South Australia; Eau = East Australia; CS = Coral Sea; IWP = Indo West Pacific.

Many Environmental Drivers

Seagrass distributions, as well as intra- and inter-annual cycles, are driven by key environmental parameters. While a single dominant process acting on seagrasses in each habitat has been previously defined (Carruthers *et al.* 2002), there are a range of drivers in each environment that exert an influence on species composition and their overall health (such as growth, biomass, reproductive output). It is important to understand what drives seagrass distributions and variability as it also affects the way various disturbances can affect seagrass meadows.

Light – A dominant driver

Light availability is probably the dominant overriding factor driving seagrass distributions in the GBR. It is a strong selective pressure for species composition and often defines the boundary of seagrass meadows, in particular the deep edge of the meadow.

Minimum light requirements

Light is a critical determinant of seagrass or any plant's growth. It is important to know the minimum light requirements (MLRs) for seagrasses, as their MLR can define seagrass distributional boundaries. Furthermore, extended periods at below MLR can lead to seagrass loss (Longstaff and Dennison, 1999). The global range for seagrass MLRs is 4-29% of sub-surface (just below the water's surface) (Dennison *et al.* 1993); the variability being due primarily to species-specific differences. Using MLRs (and other habitat requirements) it is possible to predict how changes in water quality will affect species distributions (Fourqurean *et al.* 2003) or responses to low light events.

MLRs have been quantified for only three of the fourteen seagrass species that occur in the GBR, and these assessments were made in localities other than the GBR. Longstaff (2003) determined that *Zostera muelleri* requires 31-36% of surface light to survive based on studies undertaken in Moreton Bay. This is at the higher end of the global MLR range for seagrasses (Dennison *et al.* 1993). Despite its high minimum light requirements, it is common in estuarine habitats of the GBR, which are often characterised by low light availability. To survive in this habitat, it often grows in very shallow water and is successful because of its tolerance to sediment deposition (Carruthers *et al.* 2002). *Halodule uninervis* (syn. *pinifolia*) in the Gulf of Carpentaria has a quantitatively lower MLR, just 14-19% of surface irradiance (Longstaff and Dennison 1999). Estimates of light availability in *Halophila spinulosa* meadows in Moreton Bay indicate that it can survive at light intensities of less than six percent surface irradiance (Udy and Levy 2002). The MLR for *Ruppia* was also estimated as 24% based on secchi disc depth readings taken in Wilson Inlet in south-western Australia (Carruthers and Walker 1999). *Halophila decipiens* in Florida Bay required 0-5% of surface light (Fourqurean *et al.* 2003).

MLRs for other GBR seagrass species can be estimated based on their distributional patterns and the MLR of related species (Table 1). It is reasonable to assume that *Halophila* species, which can be found growing in deepwater habitats up to sixty metres, have a much lower MLR than coastal and reef seagrasses. Deepwater *Halophila* species probably have light requirements in the same range as that for *Halophila spinulosa* (<6%) as they frequently occur in similar habitats. Species that are found more commonly in reef habitats with high light, including *Thalassia*, *Syringodium* and *Thalassodendron*, probably have much higher MLRs.

Based on studies from other regions, we can infer that the MLR for this group of reef-based seagrasses is 24-37% (Kenworthy and Fonesca 1996; Fourqurean *et al.* 2003). The amount of light required for sexual reproduction may be higher than the MLR for vegetative growth

due to the high additional energy investment required for flower and seed production (Rollon *et al.* 2003) but the MLR for successful sexual reproduction has not been determined for any GBR species.

The maximum depth limits of seagrasses are affected to a large extent by their MLR however the depth limit in turbid water will be shallow compared with clear water (Figure 4). Species with broad tolerances to available light, i.e. those that can grow in either a high light or a low light environment have the broadest range of depths over which they can grow. The depth limits of GBR seagrasses (Table 1) have been indirectly documented through survey and mapping studies (Lee Long *et al.* 1993; McKenzie *et al.* 1997; Coles *et al.* 2001). Interestingly, deepwater seagrasses (*Halophila spp.*) are also those found in shallow turbid waters. However, *Enhalus* has a shallow depth limit of less than two metres, though it is unknown whether this relates to its MLR or to the fact that it needs to reach the surface for sexual reproduction (den Hartog 1970).

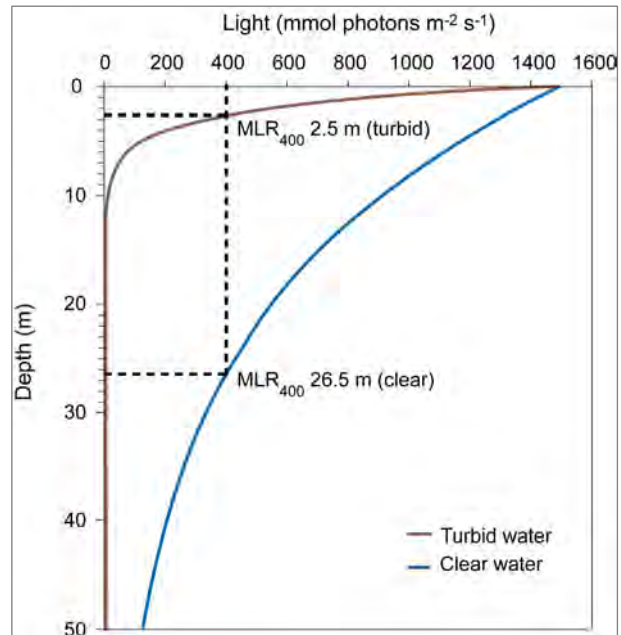


Figure 4: Relative depths for achieving a Minimum Light Requirement (MLR) for a seagrass in turbid versus clear water.

Table 1: The minimum light requirements (MLRs) for seagrasses of the GBR ranked in reducing order as well as maximum recorded depth limit and mean depth limit.

Species	MLR (% surface)	Location for MLR measurements	Max. depth limit
<i>Zostera muelleri</i>	31-36 ^a	Moreton Bay	6 ⁱ
<i>Enhalus acoroides</i>	?		2 ⁱ
<i>Thalassia hemprichii</i>	Estimate 20-37 ^{bcd}	22%; <i>Thalassia testudinum</i> Tampa Bay, Florida	4 ⁱ
<i>Thalassodendron ciliatum</i>			?
<i>Cymodocea rotundata</i>			4.5 ⁱ
<i>Cymodocea serrulata</i>			18 ⁱ
<i>Syringodium isoetifolium</i>		24-37%; <i>Syringodium filiforme</i> , Indian River Lagoon, Florida. 20-35% Florida Bay	11 ^{ij}
<i>Ruppia spp.</i>	24 ^e	Wilson Inlet, WA	
<i>Halodule uninervis</i>	14-19 ^f	Gulf of Carpentaria	11 ^{ij}
<i>Halophila ovalis</i>	1-6 ^{gh}		28 ⁱ
<i>Halophila tricostata</i>			22 ^j
<i>Halophila capricorni</i>			21 ^j
<i>Halophila spinulosa</i>		<6%; Moreton Bay	28 ⁱ
<i>Halophila decipiens</i>		0-5%; Florida Bay	56 ⁱ

* Mean from one site only. ^a (Longstaff 2003), ^b (Kenworthy and Fonesca 1996), ^c (Fourqurean *et al.* 2003), ^d (Dixon and Leverone 1995), ^e (Carruthers and Walker 1999), ^f (Longstaff and Dennison 1999), ^g (Udy and Levy 2002), ^h (Fourqurean *et al.* 2003), ⁱ (Lee Long *et al.* 1996), ^j (McKenzie *et al.* 1997).

Light gradients

Gradients in light availability occur throughout the GBR. Light attenuation by the water column reduces light with increasing depth (Kirk 1994) resulting in gradients in light intensity from shallow through to deepwater seagrass habitats. Gradients in light intensity also result from differences in water quality, with water containing suspended materials or dissolved substances attenuating light more strongly than clear water (Kirk 1994). Therefore, there are differences in light penetration amongst seagrass habitat types as turbidity levels are generally higher in near-shore environments including estuaries and coasts (Furnas 2003). Seagrass composition, distribution and their characteristics are influenced by these light gradients.

Seagrasses are capable of responding to gradients in light availability in order to maximise their light use efficiency and to maintain an overall carbon balance (Dennison and Alberte 1985; Ralph *et al.* 2007). These responses can be broadly categorised as physiological, morphological and meadow or population-scale responses (Olesen *et al.* 2002; Waycott *et al.* 2005). The seagrass species that can be found in the GBR are putatively sensitive to short-term changes in light availability (Longstaff and Dennison 1999), but the longer-term impacts of reduced irradiance are not as well understood.

Ecophysiological responses across depth-related light gradients occur. Shallow water plants have photosynthetic characteristics that are suited to high light environments while deeper plants (ten metres; 90% less light) have photosynthetic characteristics typical of low light environments (Bité *et al.* 2007; Campbell *et al.* 2007). Photosynthetic adaptations were also observed across habitat types that feature differences in their light climate: seagrass in estuarine and deepwater habitats have photosynthetic characteristics indicative of low light plants when compared to coastal and reef sites (Campbell *et al.* 2007). Longstaff and Dennison (1999) also found that plants of *Halodule pinifolia* (syn. *uninervis*) in the Gulf of Carpentaria that were growing deeper adjust their pigment ratios at deeper sites. Experimental studies have also shown that nutrient content and isotope ratios can be affected by light intensity (Abal *et al.* 1994; Grice *et al.* 1996).

Few studies have quantified morphological differences across light gradients in the GBR with most of our understanding being qualitative. The transition from intertidal to subtidal is often associated with an increase in biomass (Sheppard *et al.* 2007) as intertidal meadows exposed to the air assume a small stature enabling them to keep moist and minimise desiccation (Bridges *et al.* 1983). Amongst subtidal seagrass meadows, as irradiance declines seagrass meadows can reduce their biomass. In some seagrass species, a reduction in biomass or other related metric, such as shoot density, is the most reliable indication of changes in light intensity (Olesen *et al.* 2002; Collier *et al.* 2007; Collier *et al.* 2008). However, biomass is highly dependant on species composition. In the GBR, species composition is stratified with depth (and therefore light intensity) (Table 1) and can be variable over small spatial scales (e.g. Taylor *et al.* 2006). Based on studies in other regions, other morphological changes that are likely to reflect the light environment include leaf dimension (length, width, area), leaves per shoot, branching structure and rhizome internode length (Abal *et al.* 1994).

The way that seagrasses respond to gradients in light is species specific (Czerny and Dunton 1995; Grice *et al.* 1996; Olesen *et al.* 2002) and not well characterised for most seagrass species in the GBR. At present we lack an understanding of seagrass responses to *in situ* light transitions and gradients. Changes in these characteristics could be used in monitoring programs as a complement to current monitoring tools. If characteristics that are known to respond to light can be detected, using them will strengthen the ability to identify the cause-effect pathway of any observed changes to seagrasses.

High light

Unlike temperate seagrasses, which are typically low-light limited, tropical seagrasses are often exposed to very high light intensities at their upper depth limit, particularly intertidally and in the shallow subtidal. The ability to cope with these very high light intensities is one of the key pre-requisites for survival in the intertidal habitat. GBR seagrasses are capable of some adaptation to high light by down-regulation of their photosynthetic efficiency (Campbell *et al.* 2007). Despite these adaptations, light in the intertidal can be in excess of requirements and excess light can cause temporary photo damage (Ralph and Burchett 1995). Studies in Zanzibar have indicated that for intertidal plants, it is exposure to air that can inhibit photosynthesis during low tide exposure, rather than high light (Beer *et al.* 2006), however this requires further investigation. Interestingly, *Halophila ovalis*, which can tolerate very low light intensities, can also occupy the intertidal zone in very high light. How it adapts across this light gradient is not yet known. Tolerance of this extreme environment constrains upper tidal limits and species diversity.

Temporal changes in light

Light available to seagrasses can also vary over temporal scales due to seasonal and tidal cycles. Changes associated with seasons are discussed later. The GBR has tidal cycles that range from 1.7-6.2 m (Lovelock and Ellison 2007). The change in depth associated with these tidal cycles can affect diurnal changes in light availability (McKenzie *et al.* 2007) with seagrasses experiencing days of very high light, followed by days of very low light. These cycles are likely to have implications for seagrass growth and survival. The relationship is unlikely to be straightforward. As seagrasses can be inhibited by very high-light tidal cycles that expose seagrasses to midday full sun may be detrimental to seagrass growth. Maximum rates of photosynthesis may occur in just a short window either side of this high light exposure. This is an area requiring further investigation.

Light – Key points

- Seagrass distribution and species assemblages are sometimes dictated by light penetration, i.e. seagrasses may be light limited in a significant number of locations.
- MLRs are species-specific, may be very broad and are as yet not defined for many species that occur in the GBR.
- MLRs have not been determined at all within the GBR.
- Seagrasses adapt to gradients in light availability. Some photosynthetic and morphological responses have been demonstrated but most responses are not well characterised in GBR species.
- GBR seagrasses experience temporal changes in light associated with tidal cycles and very high light in intertidal meadows.

Overall Importance as a Driver: Very high for subtidal and deepwater seagrasses.

Knowledge gaps

- MLR for GBR seagrass species and populations.
- Comprehensive analysis of depth limits for GBR species – by region and habitat.
- Predicted spatial distribution and depth limit of seagrass meadows based on light requirements.
- Characteristics of GBR seagrasses that change with gradients in light.
- The role of high light in exposure stress in intertidal meadows.
- The role of temporal changes in light (seasons and tides).

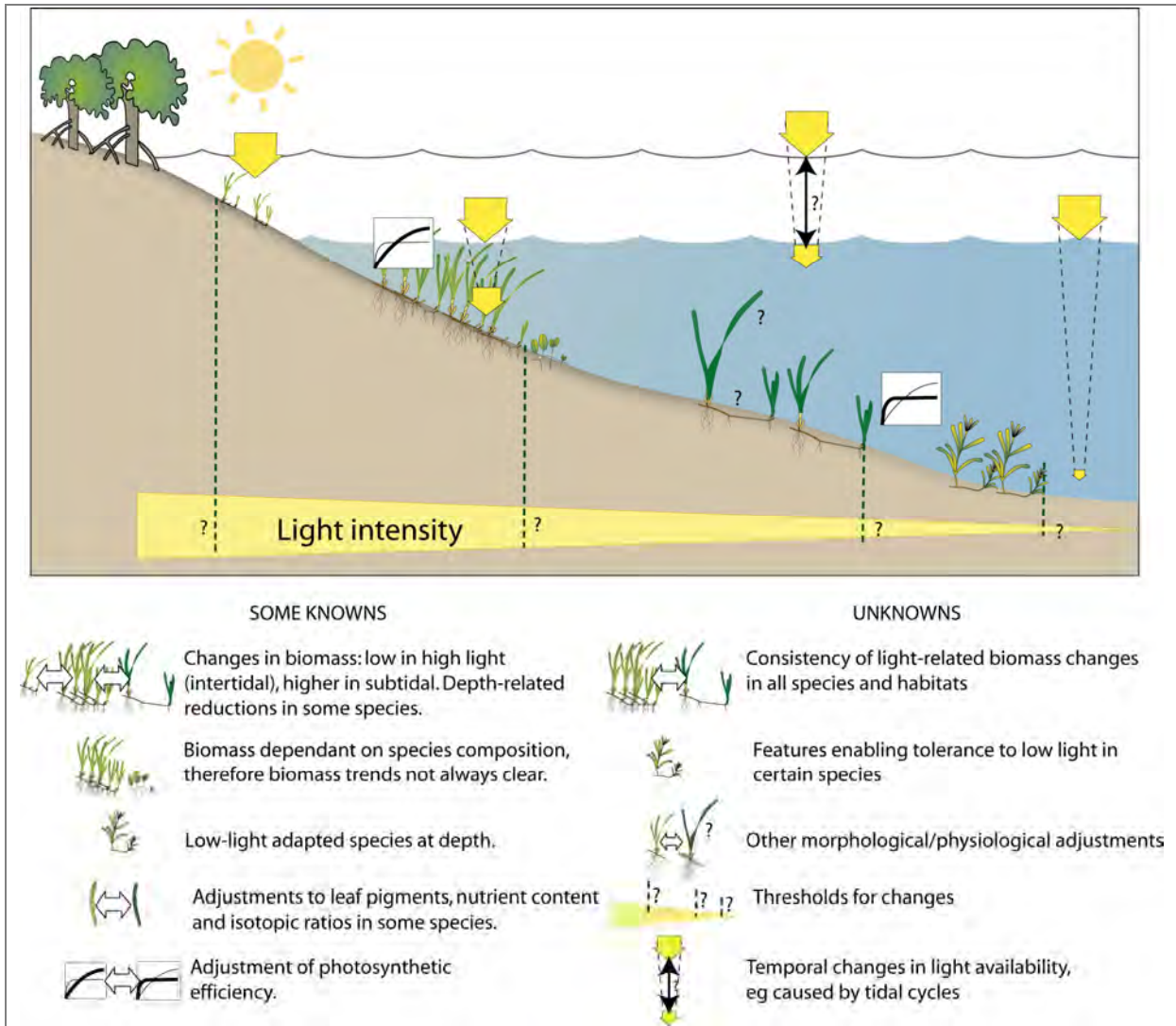


Figure 5: Some of the known responses of GBR seagrasses to light gradients as outlined in the text and identification of unknown responses to changing light regimes.

Nutrients – Elusive yet important

Seagrasses of the GBR have been shown experimentally to be nutrient limited. Two key nutrients are typically limiting, nitrogen (N) and phosphorous (P), and seagrasses appear to be primarily limited by nitrogen and, then secondarily by phosphorus (Udy *et al.* 1999; Mellors 2003; McKenzie *et al.* 2007). When sediments are very high in carbonates, seagrasses may be primarily phosphorous limited (Mellors 2003). Among intertidal seagrasses, nitrogen and phosphorus tissue nutrient concentration indicate a balanced supply of the two nutrients for some species (McKenzie *et al.* 2007). The tissue nutrient concentrations of central GBR seagrasses are higher than average for global seagrasses and frequently exceed a global threshold that indicates nutrient saturation (Mellors 2003). However, this global threshold was developed by Duarte (1990) from available data with a disproportionately large number of large bodied temperate species that have a greater investment into low nutrient structural material.

The structurally smaller species typical of many habitats in the GBR might be expected to have a maximum value for percent tissue nutrients that are higher than structurally large seagrasses due to the reduced proportions of structural carbon in smaller, more herbaceous plants. As a result, they are expected to possess a higher N:P ratio, representing a transition from nutrient limitation to nutrient saturation. For example, based on nutrient data collected for the Reef Water Quality Monitoring Program (RWQMP), the median %N and %P values are 2.3% and 0.47% for *Halophila ovalis* and 2.2 and 0.18% for *Halodule uninervis* (data courtesy RWQMP/QDPI&F), compared to a global median of 1.8 and 0.2% (Duarte 1990). These values need to be revised specifically for GBR species (Schaffelke *et al.* 2005). Nutrient availability is believed to influence the distribution of seagrasses in the GBR. For example, subtidal deepwater (more than fifteen metres) seagrasses have the highest density in areas near high catchment runoff in the Wet Tropics in the northern GBR (Coles *et al.* 2000). In contrast, very low seagrass density is found in deepwater in the far northern GBR, north of Cooktown, where there is very low runoff and very little disturbance from humans. It has also been proposed that the low seagrass distribution on reefs around the southern GBR is due to relatively low nutrient inputs from catchment runoff in that region (Udy *et al.* 1999).

GBR seagrass meadows have some assimilative capacity for nutrients when not limited by other resources, such as light. Therefore, their nutrient status is thought to be indicative of nutrient availability and nutrient content (ratios) is used in local long-term monitoring. The addition of nutrients can favour seagrass growth and lead to increases in tissue nutrients (Udy and Dennison 1997; Mellors 2003). At Green Island, increases in nutrient availability from human impacts have led to the expansion of seagrass meadows (Udy *et al.* 1999).

Nutrient availability interacts with other potentially limiting factors. For example, studies at Magnetic Island demonstrated that responsiveness to nutrient addition can vary depending on the season: after nutrient addition, a growth response was detected in the growing season when the demand for nutrients was greater while during the senescent season tissue nutrients increased in concentration and may have even become toxic (leaf size reduced in high nutrient treatments) (Mellors 2003). Experimental tests of nutrient enrichment on seagrasses in aquaria also found no response in winter, when cool temperatures were thought to limit the assimilative capacity by the seagrass (Walsh 2006). Furthermore, light can inhibit responsiveness to nutrient availability and may be the cause for minor seagrass declines in areas where nutrient availability is thought to be adequate (McKenzie *et al.* 2007).

Nutrient availability probably acts secondarily to other site-specific limitations to seagrass growth (McKenzie *et al.* 2007). As most of the GBR is relatively nutrient limited (left-hand side) other resources probably limit growth (Figure 6).

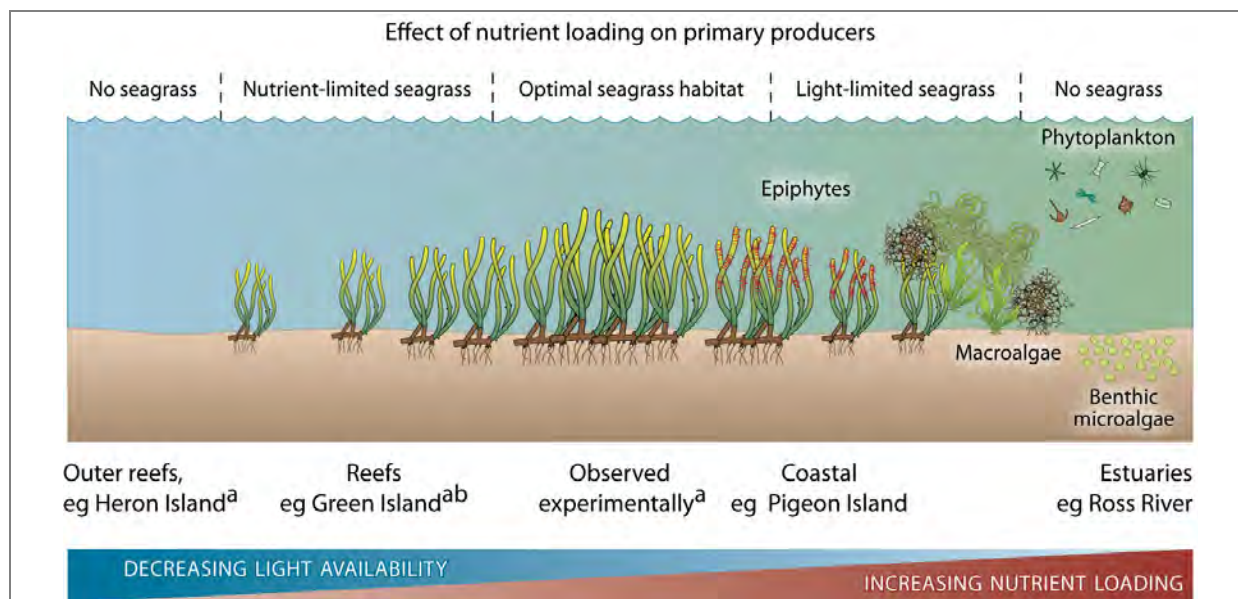


Figure 6: Nutrient response model for benthic primary producers with site-specific examples from within the GBR.

The roles that nutrient availability plays on seagrasses at a site-scale are multifaceted. Monitoring has shown that there is no clear trend between seagrass biomass and nutrient availability in the sediment for intertidal GBR seagrasses (Figure 7). Responsiveness is associated with the ability of plants to utilise nutrients, dependent on local sediment geochemistry. Bioavailability of nutrients is dependent on particle size and type. For example, clay content influences sediment adsorptive capacity – the more clays the greater the absorptive capacity – and calcium carbonate binds phosphorus, limiting its bioavailability. Furthermore, other environmental drivers such as light can affect nutrient uptake and the manner in which they are utilised by seagrass plants (Fourqurean and Rutten 2003). Because of these and other interacting factors, long-term monitoring in the GBR has identified site-specific differences in the responsiveness of seagrass to sediment nutrient concentrations (McKenzie *et al.* 2007). On small scales, the comparison between sites demonstrates that the specific role of nutrients as a driver remains elusive. Habitat-level assessments, which separate sites based on key drivers in the habitat, are likely to provide more insight. For example, reef and coastal seagrasses are distinguishable based on their nutrient content (McKenzie *et al.* 2007), the former having lower tissue nutrients.

Nutrients – Key points

- Seagrasses in the GBR are generally nutrient limited, particularly nutrient limited in offshore low nutrient locations (e.g. outer reefs).
- Responsiveness to nutrient availability depends on the primary limiting factor such as light.

Overall Importance as a Driver: Moderate for GBR-wide distributions but variable for individual sites.

- Knowledge gaps
- Nutrient thresholds that indicate transition from nutrient limitation to nutrient saturated and toxicity.
- Predicted spatial distribution and species composition based on nutrient availability.
- Long-term trend analysis and linkage to environmental parameters.
- The role of interacting factors on nutrient uptake and limitation.

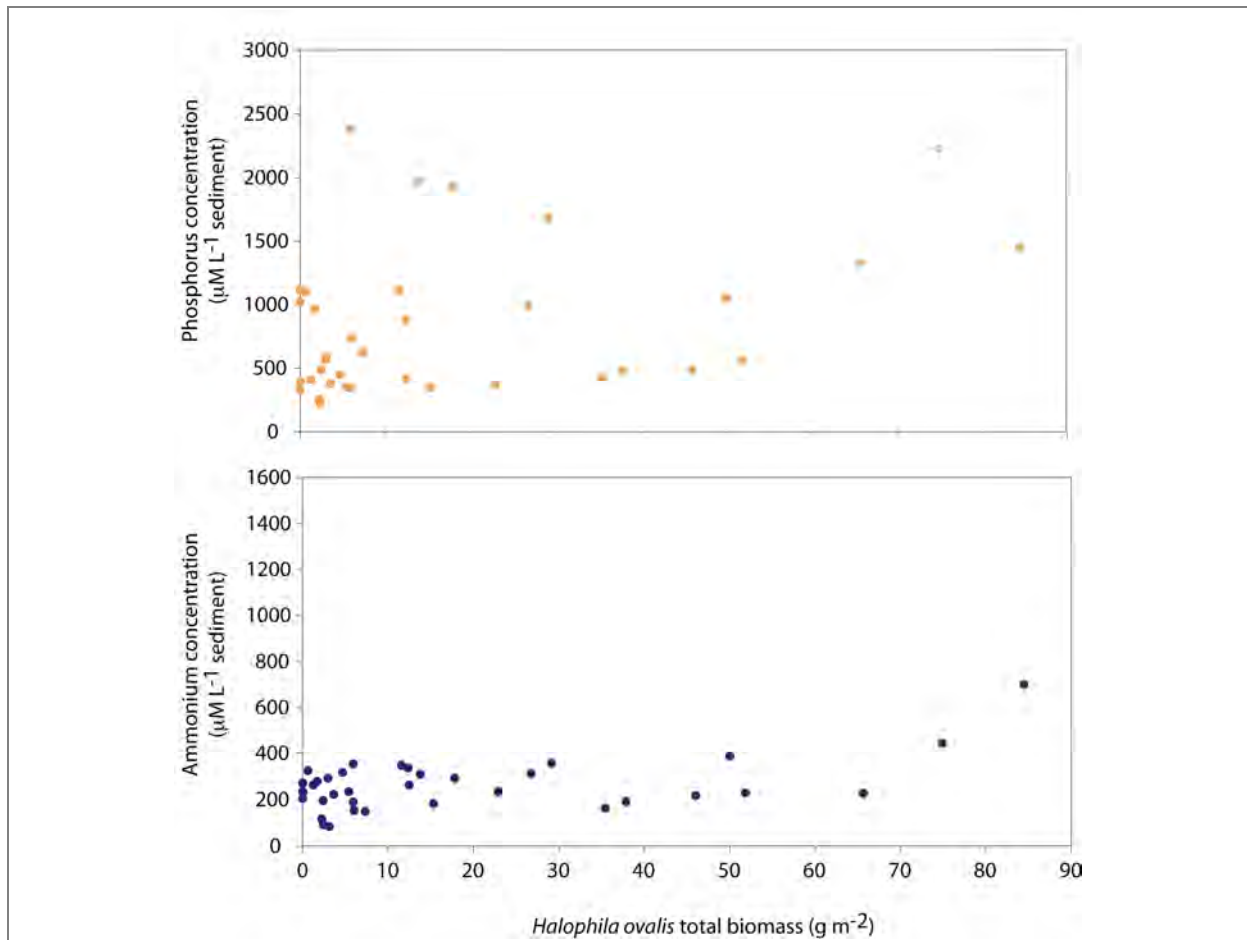


Figure 7: Plot of sediment nutrient concentration (top, phosphorus; bottom, ammonium) for the Marine Monitoring Program sites in the GBR, 2005-2006. Adapted from data contained in McKenzie *et al.* 2007.

Temperature – Most species have broad temperature tolerance

The more than 2,000 km length of the GBR extends through tropical and sub-tropical waters and represents a considerable temperature gradient. Most seagrass species inhabit the full length of the GBR and are therefore tolerant of this temperature range. However species vary in their dominance across this range for example *Enhalus*, is more common towards the north. It is not known whether this distributional limitation is temperature dependant or recruitment limitation (dispersal limited). Sea surface temperatures are forecasted to increase (Lough 2007), and seagrass in the northern GBR where water temperatures are highest may be at risk (Waycott *et al.* 2007). The upper temperature limits for both short term and long term plant survival are not known for any seagrass species. Two species, *Zostera muelleri* and *Halophila ovalis* are also common in temperate waters and therefore appear to have a much lower temperature limit than other GBR species. Thermal stress may also influence the biogeographical distribution of seagrasses. Very shallow and intertidal meadows frequently experiencing temperatures in excess of 40°C will exhibit a narrowing of their depth range and loss of biomass (Figure 8). Tolerance to these extremes is species-specific, with those species restricted to a tropical-subtropical distributions having the greatest tolerance to temperature extremes (Campbell *et al.* 2006). Increases in temperature can result in 'burn-off'. These observations however are correlative at best and require empirical testing to refine our understanding of thermal limits which are unknown for any seagrass species globally.

Temperature – Key points

- The GBR supports species with broad thermal tolerances.
- Temperatures above thermal limits in shallow water can restrict the upper limit of seagrass distributions.

Overall Importance as a Driver: Moderate.

Knowledge gaps

- Thermal tolerance limits (thresholds) for seagrass species, particularly upper temperature thresholds.
- Thermal limits to species distributions.
- Temperature influences on seagrass morphological and physiological characteristics.

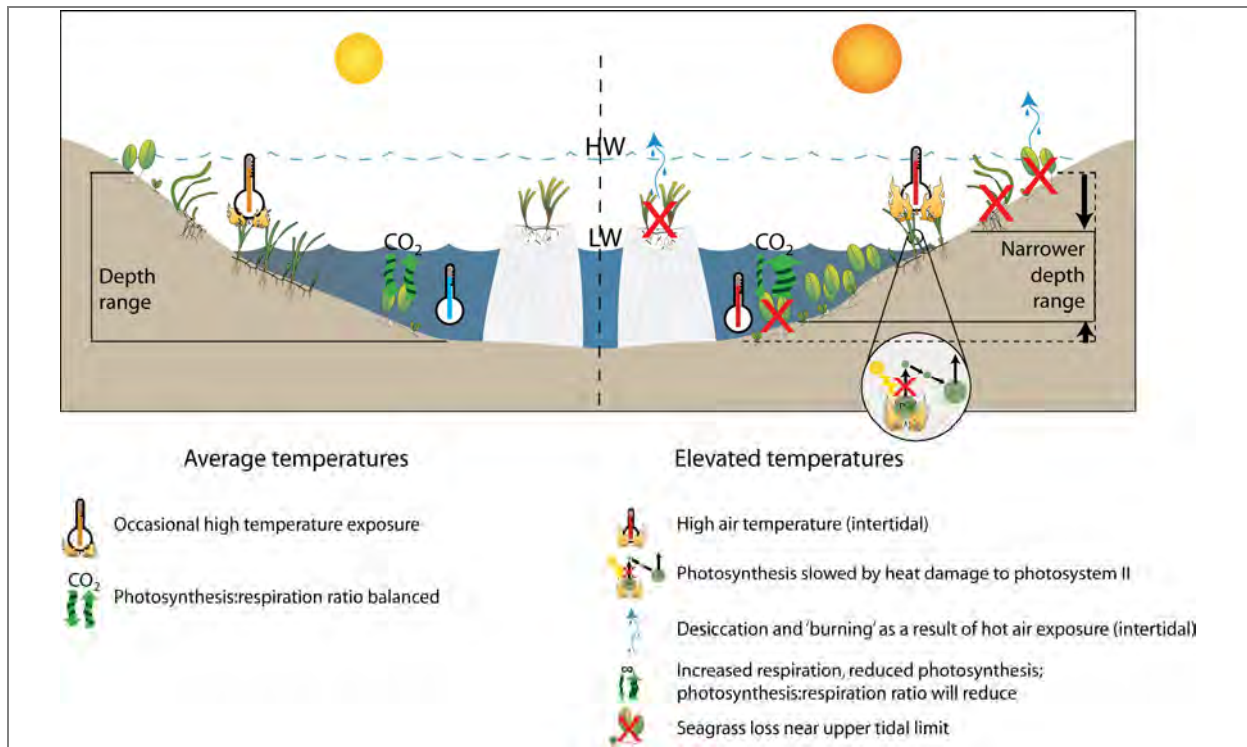


Figure 8: Generalised conceptual diagram showing seagrass responses to elevated temperature (from Waycott *et al.* 2007).

Hydrodynamics

Hydrodynamic processes occur across a broad space-time continuum (Steinberg 2007). Seagrass recruitment can be affected at all scales of these processes (Koch *et al.* 2006). On the smallest scale turbulent mixing influences photosynthesis and pollination. In principle large-scale processes are likely to affect the dispersal of seagrass propagules and play an important role on the current distribution of seagrasses. Currents also carry nutrients, sediments and potential toxicants. High current velocities can affect the stature of seagrasses but little is known about the role of hydrodynamics in GBR seagrass meadows (Waycott *et al.* 2007). Oceanic swells, tides and mixing can influence turbidity, limiting light and water temperatures and affecting growth rates. Waves that reach the sea floor can resuspend sediments leading to high turbidity levels. Seagrass habitats that are exposed to extended periods of wind-generated waves can show signs of reduced light availability, such as reduced biomass (Mellors *et al.* 1993). On a broad scale, seagrasses in the GBR are also predominantly found in north-east facing embayments, protected from the direct effects of high wave energies associated with the predominant south-easterly winds. Inference suggests seagrass distributions are affected by larger scale oceanographic processes, such as tidal range, as some species are less common north of Princess Charlotte Bay and south of Mackay where tidal velocities are high (Coles *et al.* 2000). However, few studies have investigated these processes directly and so our understanding of the influence of hydrodynamics is limited to a few case studies, mostly on temperate species (Koch *et al.* 2006).

Hydrodynamics – Key points

- Higher energy environments have poor colonisation ability for seagrasses.

Overall Importance as a Driver: Moderate where high energy limits survival or dispersal is limited.

Knowledge gaps

- The importance of oceanographic processes for seagrass dispersal and distribution patterns.
- The influence of current velocities on seagrass characteristics.

Sediment

The physical nature of sediment can be a major limiting factor to the ability of seagrasses to grow and survive in particular locations (Koch 2001). There are also many biogeochemical characteristics of sediment that can affect seagrasses including nutrient content / binding capacity, organic content and oxygen levels (Mellors 2003). These sedimentary characteristics are likely to influence seagrass growth dynamics (Marbà *et al.* 2006). Seagrasses are unable to grow in sediments of high organic content (Koch 2001). In seagrass meadows composed of larger species, seagrasses can influence the hydrodynamics and sedimentary conditions (Koch 2001), however in GBR meadows, the small seagrass stature does not appear to exert a strong influence of the sedimentary conditions (Mellors *et al.* 2002).

The depth and mobility of sediments can also influence seagrass composition. Some seagrasses such as *Cymodocea spp.* prefer deeper sediments while others can tolerate a broad range of sediment depths (Birch and Birch 1984). Colonising seagrasses such as *Halophila spp.* and *Halodule uninervis* are better suited to mobile sediments than larger climax species (Bridges *et al.* 1983). *Halophila*, however, can be damaged by burial under sediments while the rhizomes of other seagrasses can survive shallow burial and recover by vertical rhizome extension through the deposited sediment (Campey 1995). Sediment type can also influence sediment re-suspension processes, with finer sediments remaining suspended in the water column for longer (Larcombe *et al.* 1995).

Sediment – Key points

- Sediment type may affect seagrass distribution.

Overall Importance as a Driver: Moderate.

Knowledge gaps

- Influence of sediment biogeochemical characteristics on seagrasses.
- Sediment burial rates and the ability of seagrasses to recover.

Salinity

Little is known about the salinity tolerance of GBR seagrasses though we can infer from their distributions that species that are found in estuarine and coastal habitats are more tolerant of changes in salinity than reef-based and deep-water seagrasses. Studies in other tropical regions have confirmed experimentally that tropical species vary in their tolerance to variations in salinity (Dawes *et al.* 1989; Lirman and Cropper 2003). Salinity thresholds are not known for GBR seagrasses. With predicted increases in storm intensity (Lough 2007), seagrasses may in the future be exposed to lower salinities and for longer periods resulting in species shifts and habitat loss as has been proposed for Florida Bay (Fourqurean *et al.* 2003).

Salinity – Key points

- Changes in salinity will mostly influence coastal and estuarine seagrasses exposed to floods.

Overall Importance as a Driver: Low-Moderate, localised.

Knowledge gaps

- Salinity thresholds for GBR seagrasses.

Temporal Variation to Seagrass Growth

Long-term monitoring of seagrasses in the GBR is demonstrating significant natural variations in seagrass distribution and biomass (McKenzie *et al.* 2007). Some of these can be explained by natural cycles in climate.

Seasonal Patterns: Influenced by local climatic conditions

Seagrasses in the GBR have been shown demonstrate strong seasonal patterns in growth and biomass (Mellors *et al.* 1993; McKenzie 1994; Rasheed 2004). This is in contrast to commonly held concepts of seasonality in tropical seagrasses that suggests the lack of a strong seasonal temperature gradient will result in limited seasonal growth responses. However the amplitude of seasonal growth patterns may be suppressed by the stage of meadow recovery from a recent significant disturbance (McMahon 2005), where plants are colonising and so have atypical growth rates and form. Thus seasonal patterns of growth have the potential to influence the ability of seagrass meadows to recover from disturbances and should be considered in any framework for understanding disturbance responses.

Seasonal patterns in seagrass meadows are commonly unimodal with a single peak and trough, often defined as the growing and senescent seasons respectively. Detailed seasonal studies in the Cairns region have shown that seagrass biomass peaks in late spring to early summer, with the minimum in June/July (Mellors *et al.* 1993; McKenzie 1994; Rasheed 2004). This pattern has been corroborated at Townsville (Lanyon and Marsh 1995; Mellors 2003) and Moreton Bay (Conacher *et al.* 1994b) though the timing and key drivers of seasonality may vary at other locations. Ongoing data collection by Seagrass-Watch volunteers is currently expanding the database of temporal changes in seagrass cover, which will enable longer-term analyses of seasonality. In contrast to tropical meadows, in temperate regions, the same species can show biomass peaks later in summer (Larkum *et al.* 1984) or even in autumn (Hillman *et al.* 1995). Biomass exhibits the greatest seasonal trends whereas shoot density tends to remain fairly constant throughout the year for some persistent species such as *Zostera* (Conacher *et al.* 1994b; Rasheed 2004).

Growth and biomass of temperate seagrass meadows are typically correlated with water temperature and solar irradiance (Lee *et al.* 2007) but the drivers of seasonal variability in tropical meadows are more varied. For example, seasonal peaks and troughs in tropical seagrasses can be solely driven by tidal exposure causing 'burning' to leaves or by water currents (Erftemeijer and Herman 1994). Water temperature can correlate with growth at sub-optimal temperatures, but in summer, very high water temperatures can be detrimental, therefore peaks in water temperature can correspond to seagrass loss (Lee *et al.* 2007). Furthermore, in the tropics, seasonal increases in solar irradiance can be eclipsed by summer peaks in cloud cover and reduced water clarity (for example, caused by wind-driven re-suspension and riverine runoff).

Seagrass biomass and a range of environmental drivers in the Cairns region are illustrated in Figure 9 as a case study of drivers in GBR seasonal patterns. Because of distinct seasonal changes in the environmental parameters, it is possible to differentiate three seasons relevant to seagrass growth and reproduction (Figure 9). Biomass increases in the growing season from June to November as water becomes warmer and light intensity increases (longer day length, increasing irradiance, low cloud cover, low turbidity) (Figure 9). Biomass quickly peaks in spring and early summer. Later in summer at the onset of the wet season, temperatures continue to climb, however, these can become detrimental and even slow growth (McKenzie 1994) and may even lead to burn-off, particularly for intertidal or very shallow meadows (Erftemeijer and Herman 1994). At very high temperatures, compensation irradiance (the light level at which photosynthesis equals respiration) increases and more

light is required to maintain a positive carbon balance (Bulthuis 1987). However, these periods of very high temperature also coincide with the onset of the wet season when cloudiness and elevated turbidity, caused by runoff, lead to reduced light availability. High levels of physical disturbance such as scouring and sediment deposition can also increase in the wet season. After the wet season, tidal amplitudes increase and the lowest tides fall in the middle of the day. This can lead to desiccation of exposed meadows, particularly when combined with strong wind. Wind-driven resuspension can also lead to high turbidity (Anthony *et al.* 2004), and windiness can be correlated with declines in biomass (Mellors and Marsh 1993) and probably contribute to low growth biomass in the post-wet senescent season. These seasonal patterns are further illustrated in Figure 10.

These seasonal patterns are not always clearly detectable. High disturbance regimes throughout the GBR can overshadow seasonal cycles with patterns of large-scale loss and recovery being more dominant. Furthermore, some meadows, such as deepwater *Halophila* spp. are ephemeral and the role of seasonal weather patterns is not well known.

Seasonal variation – Key points

- Tropical seagrass meadows of the GBR demonstrate seasonal trends in biomass and cover.
- Seasonal trends are not correlated with temperature and solar irradiance alone; the drivers are varied and linked to other environmental drivers.
- The season can also affect their responsiveness to disturbances.

Knowledge gaps

- Long-term detailed seasonal analyses to identify inter-annual variation in seasonal trends.
- Drivers of seasonal variability in a range of GBR regions.
- Seasonal changes in characteristics other than percent cover and biomass, particularly growth and physiological characteristics.

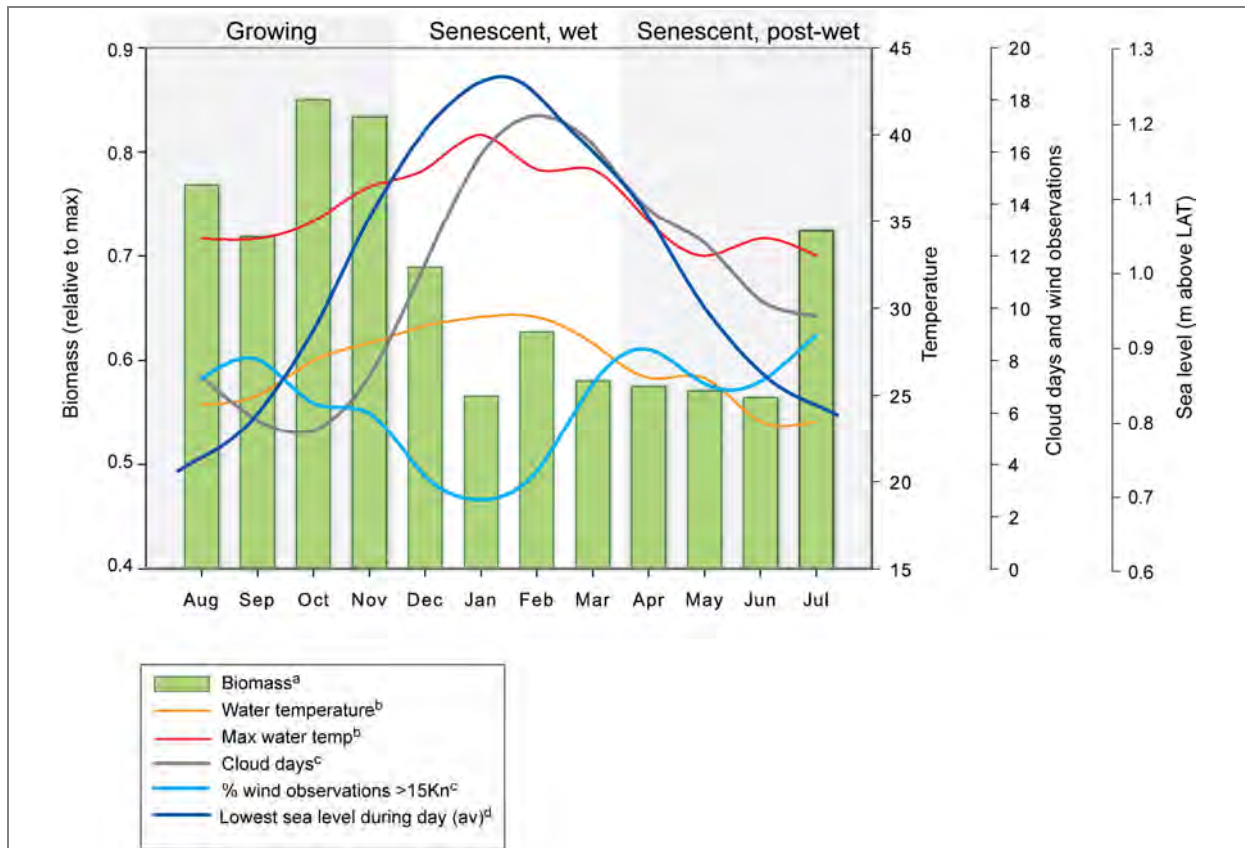


Figure 9: Generalised trend in seagrass biomass and long-term climatic variables for the Cairns region. ^a Biomass converted to relative value mean of Mellors *et al.* 1993; McKenzie 1994; Rasheed 2004); ^b Seagrass-Watch 2003-2004; ^c Bureau of Meteorology average of 66-year data; ^d Maritime Safety Queensland average of 66-year data.

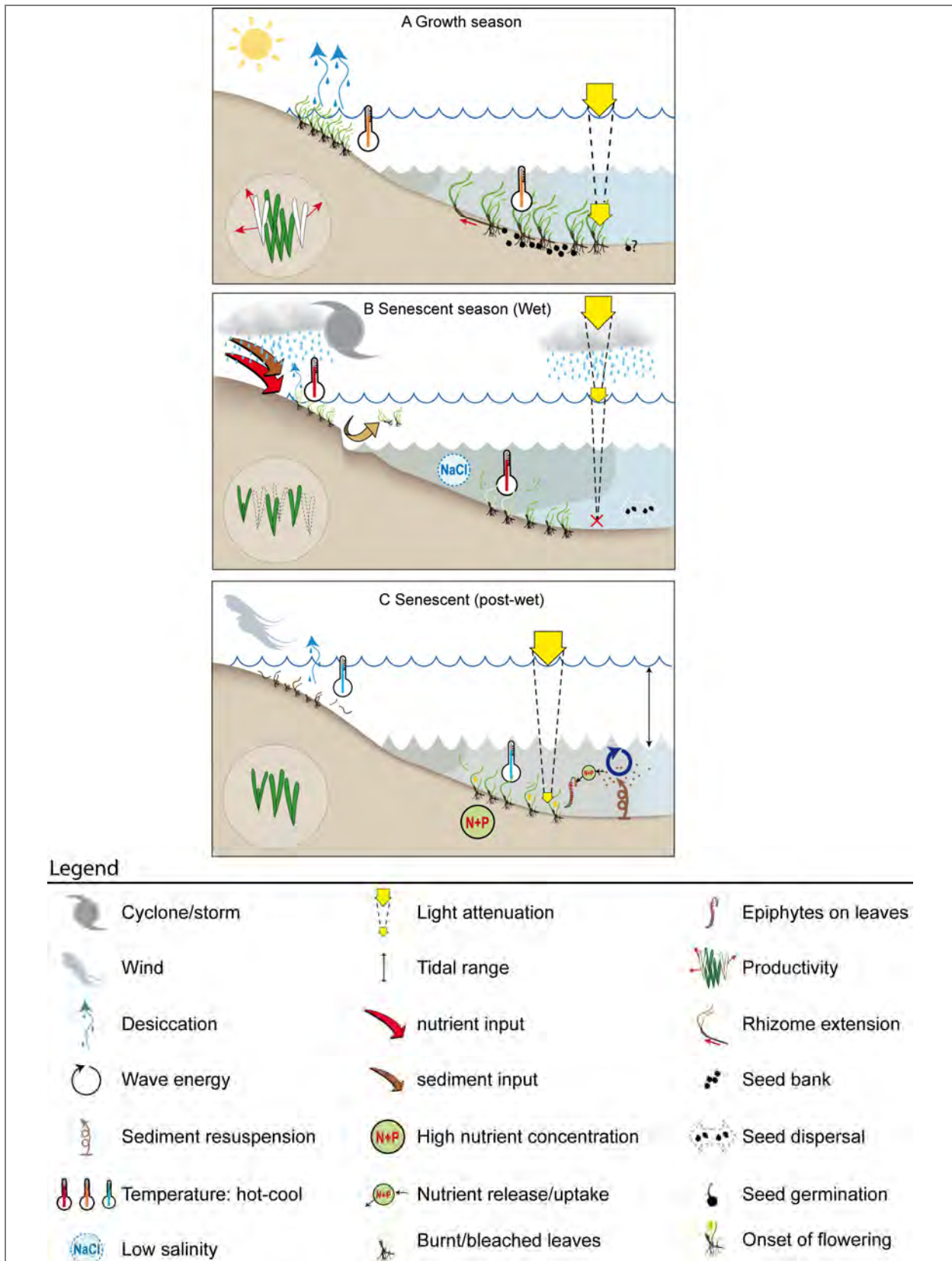


Figure 10: Generic conceptual diagrams of key drivers of seasonal trends in seagrasses in the Great Barrier Reef region, recognising three seasonal periods.

Sexual reproduction triggers unknown

Sexual reproduction is important in the population dynamics of seagrasses, and seed banks may be particularly important as a mechanism for recovery following widespread seagrass loss. Evidence is accumulating that seasonality occurs also in the production of flowers and fruits (McMahon 2005). The timing of sexual reproduction is most likely to be species-specific (Rasheed 2004; Waycott *et al.* 2004; McKenzie *et al.* 2007) although a number of species can be seen concurrently setting seed in the period August to October. The triggers for the initiation and/or limitations to flowering are not known although in temperate seagrasses low temperatures are correlated with the initiation of flowering (McComb *et al.* 1981). Flowering in some species, e.g. *Halophila ovalis*, appear opportunistic when resources are available (Waycott *et al.* 2004; McMahon 2005). Seagrass responses to stressors such as short term elevated temperatures may also induce flowering as is observed in some terrestrial plant species (Balasubramanian *et al.* 2006).

Seed germination can be affected by temperature, salinity and anoxia in *Zostera muelleri* (Brenchley and Probert 1998) but the main triggers for germination in natural conditions are also not known for any GBR species. Seedling recruitment can be more successful after disturbance creates gaps in the established adult population (Rasheed 2004). The trigger for germination may be exposure to high light after sediments are removed (Inglis 2000b), however, successful establishment of seedlings in gaps may also be related to the lack of competition with established adults. The prevalence of recruitment from seed and the triggers for germination are not well understood. As re-establishment of meadows from seed is likely to be very important for the long-term survival of seagrass meadows, this is an area requiring further investigation.

Sexual reproduction – Key points

- The timing of seed production varies for each species but most flower from August to October.
- The triggers for sexual reproduction are likely to be varied.

Knowledge gaps

- Triggers for the initiation of flowering and seed germination.
- Dispersal patterns and dispersal mechanisms.

Inter-annual patterns: Influenced by regional-scale climate and recovery

Inter-annual differences in seagrass biomass and distribution occur in the GBR and can be attributed to regional-scale changes in climate. Long-term monitoring in Queensland ports by the QDPI&F has identified recent state-wide increases in seagrass biomass hypothesised to be associated with increased rainfall, reduced exposure of intertidal meadows to daytime exposure, lower temperatures and decreased solar irradiance (Dew *et al.* 2007; Rasheed *et al.* 2007; Taylor *et al.* 2007). Prior to this, about five years ago, State-wide reductions in rainfall led to increases in exposure to sunlight and desiccation ultimately leading to considerable seagrass die-off.

Inter-annual variation in seagrass cover assessed by the Seagrass-Watch program (<http://www.seagrasswatch.org/home.html>) has begun to identify local annual variation cycles with evidence that meadow recovery status influences these cycles. No general trend was evident across a selection of the sites from the Queensland coast with strong representative data (Figure 11). Site-specific or local region influences may be of primary importance in dictating these trends in seagrass cover. In addition, some sites, Urangan, Burrum Heads and Shelley Beach (SB) demonstrated a reduced seasonal signal in the period following initial recovery from complete meadow loss. These data highlight the importance of having regional to local knowledge of habitat status and support the concept for monitoring widely and generally rather than in fewer locations with more detailed data collection activity.

Inter-annual variation – Key points

- Regional-scale climate variables can lead to broad-scale changes in seagrasses.

Overall Importance as a Driver: Moderate to high.

Knowledge gaps

- High-level data and statistical analysis.
- Experimental verification of observations.

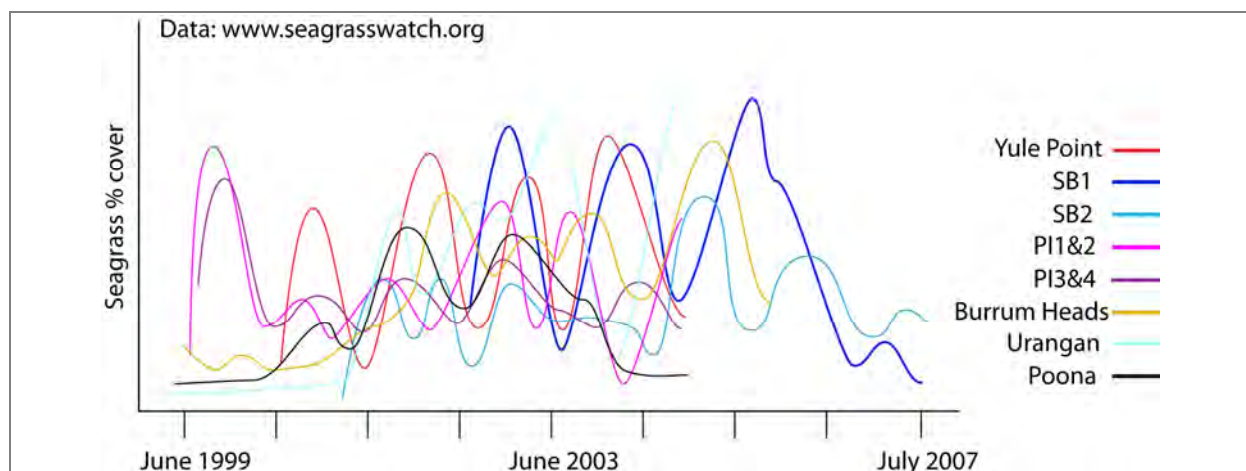


Figure 11: Seagrass-Watch data for six regions of the Queensland coast showing the general trends in seagrass cover for available data (data sourced from <http://www.seagrasswatch.org.au/home.html>, November 2007). Seagrass cover values not scaled equally for each site, so are not comparable but ranged from 0-80%.

Disturbance and Its Drivers

Seagrass meadows of the GBR are characterised by high disturbance regimes (Carruthers *et al.* 2002). This is for the main part due to the prevalence of seagrass in coastal habitats where the presence of readily re-suspended fine sediments, grazing by dugong and green turtle and the influence of cyclones and large flood events are most acutely felt (Carruthers *et al.* 2002; Waycott *et al.* 2004). Such disturbances differentiate tropical seagrass meadows from temperate meadows in Australia and many other parts of the world, the latter tending to be more stable. Stable seagrass meadows do occasionally develop in the GBR such as the seagrass meadows at Green Island, Dunk Island and the Low Isles. However, these locations are influenced regularly by terrestrial runoff (Furnas 2003), and thus are not as nutrient limiting as those regions that do not have terrestrial sourced nutrients delivered. At the same time, these sites are removed from the immediacy of more degenerative coastal inputs such as fine sediments and toxicants. As already suggested, the influence of disturbance-related impacts may suppress distributional and seasonal trends to seagrass abundance and community structure. A more process-oriented understanding of the drivers of change in coastal seagrass habitats is needed to better assess their health and status.

Types of Disturbances: From Centimetres to Kilometres

There are multiplicities of drivers that may affect any seagrass population. Disturbances that change these primary limiting factors may vary in nature but have the same final outcome.

Here we define disturbances as both natural and human-induced processes that modify the structure of seagrass meadows. Change in structure may be a loss of plant density (number of shoots per unit area), biomass (weight of plant tissue per unit area), plant tissue composition (substantive changes in nutrient content) and/or community species composition (seagrass). Disturbances can occur at scales ranging from centimetres – caused by animals living within seagrasses, or small boat damage such as propeller scars – to kilometres – caused by storms and/or cyclones and runoff. Natural disturbance regimes are common in the GBR such as regular grazing by dugongs or cyclones (Table 2). Human-related disturbances are none-the-less common, and in some cases, have the potential to have lasting or even irreversible impacts (Table 3). In addition we classify the types of disturbance to seagrass meadows as either *physical*, which involves the physical disruption of the seagrass plants themselves, or *ecophysiological*, where the environment exerts pressures on the plants, altering the plants in some way. Clearly, there is a continuum possible with these different types and scales of disturbance. The main focus of this analysis is to assess those disturbances which make substantive changes to the structure of the plants, the community structure or the presence of seagrasses.

Physical disturbances include biotic interactions through processes such as grazing or bioturbation or environmental disturbance through the action of waves, sediment scouring or dredging. *Ecophysiological disturbances* include processes such as light limitation, excess nutrients, changes in salinity or temperature stress.

We do not have direct knowledge of all these processes occurring in GBR seagrasses although it is reasonable to assume that all classes of physical and ecophysiological stressors occur in the region.

Table 2: Major causes of natural disturbance, drivers of change impacts and location observed in GBR seagrass meadows.

Type of disturbance	Driver of change	Impact	Example, Location / Date	Reference
1. NATURAL				
Grazing – dugongs, turtles, etc.	Physical disturbance	Increased growth rates, changed species composition, changed chemical composition, increased flowering	Broad and common. Particularly Hervey Bay, Princess Charlotte Bay	Preen, 1995; Aragones and Marsh, 2000; McMahon 2005; Aragones <i>et al.</i> 2006
Cyclones and storms	Physical disturbance, Substrate removal	Seagrass loss, changed species composition and density during recovery, loss of seed bank	Magnetic Island, Port of Mourilyan, Hervey Bay	Birch and Birch 1984; Preen <i>et al.</i> 1995; McKenna <i>et al.</i> 2007
Rainfall / runoff – estuaries	Sediment deposition, Reduced light, Reduced salinity, Increased nutrients	Seagrass loss/reduced biomass, burial of seed bank	Hervey Bay, Cleveland Bay	Preen <i>et al.</i> 1995; Pringle 1989
Sustained wind-generated waves	Reduced light	Many, ultimately biomass reduction, loss	Green Island	Mellors <i>et al.</i> 1993
Burn-off	Elevated temperature	Burnt leaves, leaf biomass loss	Whitsundays, Port of Weipa	McKenzie and Campbell 2004; Chin 2005; McKenzie and Yoshida 2006; Roelofs <i>et al.</i> 2006
Sediment deposition	Physical disturbance, Reduced light	Seagrass loss	Sarina	Bridges <i>et al.</i> 1983

Table 3: Major causes of human-mediated disturbance, drivers of change impacts and location observed in GBR seagrass meadows.

Type of disturbance	Driver of change	Impact	Example, Location / Date	Reference
2. INDIRECT, HUMAN-RELATED				
Water quality decline	Reduced light	Many, ultimately biomass reduction or loss	Moreton Bay	Dennison and Abal 1999
High nutrient levels	Increased nutrients-reduced light-reduced DO	Increased biomass and area or reduced biomass	Green Island, Whitsundays, Hervey Bay	Preen and Marsh 1995; Udy <i>et al.</i> 1999; Campbell <i>et al.</i> 2002
Toxicants	Toxicity	No recorded impacts		McMahon <i>et al.</i> 2005
3. DIRECT, HUMAN-RELATED				
Dredging e.g. ports / marinas	Physical disturbance, Reduced light	Biomass reduction, loss	Oyster Point, Cleveland Bay	Lee Long <i>et al.</i> 2001; Pringle 1989
Anchors	Physical disturbance	Biomass reduction, loss, scarring	Lizard island, Whitsundays	McKenzie <i>et al.</i> 1997; Campbell <i>et al.</i> 2002

Disturbances: Different Drivers of Change with Common Outcomes

Disturbances may cause seagrass loss or, through subsequent recovery processes, disturbance can lead to changes in seagrass species and structural composition. The major causes of disturbances in GBR seagrass meadows are becoming reasonably well understood, although there is limited understanding of how seagrasses are impacted and their recovery processes (Waycott *et al.* 2005). These causes, or drivers, of change may occur at numerous spatial and temporal scales such that impacts from some disturbances may not be immediately apparent.

Physical disturbance – A dominant disturbance

Physical disturbance is a common driver in tropical seagrass meadows and has multiple causes including herbivore grazing, storms, and dredging and anchor damage (Tables 2 and 3). The impacts of physical disturbance are dependant on the scale, magnitude and repetition of the event. Physical disturbance can uproot whole plants, and depending on the scale of the disturbance, whole meadows and their seed banks can be removed. However, not all physical disturbances remove the whole plant. Grazing, for example, can also involve cropping of the leaves, with the consequences being a loss of biomass and little impact on the ability of the plant to continue growing (Aragones *et al.* 2006). Grazing disturbance is usually repetitive and involves adaptation of the meadow to the disturbance, while storm and cyclone damage is stochastic and can lead to catastrophic losses of seagrass (Birch and Birch 1984). Other stressors, such as reduced salinity and high turbidity associated with run-off, can also compound storm disturbance (Waycott *et al.* 2007). The main mechanism for coping with ongoing exposure to physical disturbance is through processes that occur in the recovery phase (i.e. species shifts).

Grazing

Considerable research has been conducted on the grazing of seagrasses by dugongs and green turtles in the GBR (Lanyon *et al.* 1989). Dugongs, the dominant macro-herbivore grazer in the GBR region who rely on seagrass as their sole food source, prefer the smaller colonising species of seagrass (Marsh *et al.* 1999) that have a higher nutritional quality (Lanyon *et al.* 1989; Aragones and Marsh 2000). The method dugongs use to graze seagrass involves ripping up the whole plants, or where this is not possible removing above-ground parts of the plant (Marsh *et al.* 1999). When dugongs graze in large herds they remove the bulk of all plant biomass of a seagrass meadow (Preen 1995). The effects of such intense grazing is to maintain seagrass populations in a high disturbance state as smaller structured seagrass meadows (Preen 1995; McMahon 2005). In Moreton Bay, *Halophila ovalis* meadows can recover as fast as within one month to pre-grazing density following heavy grazing (McMahon 2005). Recovery involves both seed recruitment and vegetative growth (McMahon 2005). Grazing by dugongs removes just small patches of seagrass at a time and can stimulate growth rates and increase biomass as shown in grazing simulation experiments (Aragones and Marsh 2000) and in natural gradients in grazing intensity (McMahon 2005). Grazing can maintain seagrass populations in a state of high disturbance where dugong populations are large, or where grazing is frequent.

Green turtles, in contrast, do not graze exclusively on seagrass, and crop the seagrass leaves rather than ripping up whole plants (Lanyon *et al.* 1989), thus primarily influencing seagrass meadows through loss of biomass rather than changing communities.

Storms and cyclones

The influence of storms and cyclones provide three main sources of physical disturbance; high energy wave action, sediment scouring, and sediment deposition. All of these influences will physically disrupt the seagrass meadow on small (a few plants) and large (whole meadows) scales. Recovery from large events such as a physically disruptive cycle may take decades (Birch and Birch 1984), or may be rapid (Mellors and Waycott *pers. obs.* 1999-2000, Shelley Beach). With such large-scale disturbances as those caused by cyclones, complete meadow loss can follow physical removal of seagrass plants (Birch and Birch 1984). The seed bank may also be removed or even buried by deposited sediments (e.g. Preen *et al.* 1995; Campbell and McKenzie 2004). The loss of the seedbank has important implications for recovery potential. Anecdotal accounts of seagrass being 'buried' by sediments have been recorded, however data on burial rates and depths and sources remain unknown.

Physical disturbance – Key points

- Physical disturbance is a major driver in GBR seagrasses with natural and human-related causes.
- There is a large range of disturbance regimes.
- Recovery processes are key disturbance coping mechanisms.

Overall Importance as a Driver: Very high.

Knowledge gaps

- Recovery strategies for different scales and types of physical disturbance.
- Adaptability of different Seagrass habitats to different disturbance regimes.
- Contribution of grazing to changing seagrass population structure.

Light – Episodic reduction common

Episodes of reduced light intensity are frequently linked to seagrass loss (Walker and McComb 1992). In low light, photosynthesis is greatly reduced and the plants must rely on stored reserves for growth and respiration (Lee and Dunton 1997). Limited supplies mean that seagrasses can not tolerate extended periods without light. Reduced light intensity can follow episodic runoff, dredging and wind-driven resuspension caused by suspended sediment, phytoplankton or dissolved substances (Pringle 1989; Mellors *et al.* 1993; Campbell and McKenzie 2004). If light intensity is driven to levels below the minimum light requirements (MLRs) for seagrasses, and is persistent, it can result in complete seagrass die-off (Longstaff 2003; Campbell and McKenzie 2004). Light-related impacts to seagrasses can include localised and small-scale or very extensive wide-spread impacts. Wide-spread impacts from light reduction events can have major ecological consequences such as drastic declines in seagrass populations (Preen *et al.* 1995). Turbidity-related light reduction events can be prolonged as continual re-suspension often maintains turbidity levels beyond the life of the original plume (Furnas 2003). Wave-driven resuspension is a more frequent cause of turbid conditions than flood plumes (Furnas 2003). Wind-driven re-suspension follows seasonal patterns in wind regimes, but because it can be extreme and unpredictable it is included here as a disturbance. Another cause of episodic light reduction may be nutrients associated loss of water quality (Dennison *et al.* 1993). Excess nutrients may cause algal blooms as the algae can uptake water column nutrients more readily than seagrasses, which rely, at least in part, on nutrients in sediments. Algal blooms shade the benthic plants, which consequently become light limited (Dennison *et al.* 1993) (Figure 6).

Epiphyte and algal bloom associated impacts on seagrasses have been observed in locations exposed to industrial waste such as fertiliser production (Cambridge *et al.* 1986).

There are no reported cases for the long-term loss of seagrass in the GBR as a result of reductions in light availability, as even after large-scale seagrass loss they have, to date, been able to recover (Campbell and McKenzie 2004; McMahon 2005). However, events that reduce light are predicted to increase in intensity and frequency making it a key priority to understand thresholds of tolerance and impacts.

Based on findings from a range of studies, Waycott *et al.* (2005) developed a seagrass stress model (Figure 12) that describes the transitions that occur in a seagrass meadow with increasing stress such as reduced light (either intensity or duration). When light availability is reduced from an optimum level, a number of ecophysiological changes occur. These physiological responses can alleviate light stress in the short term (hours to weeks) but may also persist in the long term (Abal *et al.* 1994; Grice *et al.* 1996). If the period of light reduction is persistent or extreme, then in the next phase, morphological changes can also occur. These are generally slower in onset. At the final stage, the population structure of the meadow is limited to plants specifically adapted to the very low light levels. This model can also be applied to stress caused by a range of drivers. Some of the ecophysiological and morphological responses to reductions in light intensity are common amongst seagrass species – such as biomass and growth, which will usually reduce if light reduction is persistent (Abal *et al.* 1994; Longstaff and Dennison 1999; Hall *et al.* 2001; Walsh 2006) – but the nature of most other responses can vary greatly. As these responses can be used as indicators of a change in water quality and the seagrass light environment, understanding them is important for seagrass monitoring programs.

Eventually, if light becomes limiting to growth, then seagrass loss results. The known MLRs for GBR seagrasses are presented in Table 1. Prolonged periods below the MLRs will eventually lead to seagrass die-off. The duration of light reduction that will lead to loss is species-specific and has been investigated for only two GBR seagrasses – *Halophila ovalis* and *Halodule uninervis* which survived in zero light for 38 and ~100 days, respectively (Longstaff and Dennison 1999; Hall *et al.* 2001). Larger bodied species in other regions can survive an impact of longer duration due to their capacity to store more reserves and adjust to the impact (Lee and Dunton 1997; Collier 2006) but tolerance to light deprivation has not been investigated in similarly large bodied GBR species. The duration of light reduction that seagrasses can tolerate is also dependant on a number of interacting factors, in particular the timing of the event (Hall *et al.* 2001).

High light

Intertidal and shallow sub-tidal meadows can be exposed to very high light (full sunlight) when the tide has receded and how this affects the distribution of seagrasses is discussed in a previous section (page 1). Periods of prolonged exposure to sunlight are dependant on tidal cycles and the timing of low tides. Therefore periodic exposure can also be considered a disturbance stress. Although seagrasses can photosynthesise during emersion, high light is known to cause photoinhibition in some seagrasses and may lead to photodamage (Ralph and Burchett 1995). The photosystems can rapidly repair themselves, however, (Beer *et al.* 2006) and not all seagrasses are susceptible to photoinhibition (e.g. Pollard and Greenway 1993). Prolonged emersion is known to be damaging to seagrass tissues (Erftemeijer and Herman 1994) but there are many potential causes of this including desiccation, elevated pH (Beer *et al.* 2006) and temperature extremes. The role of high light in damage to seagrass leaves during emersion is not known. However relief from light stress in fully subtidal seagrass (i.e. no emersion effects) led to increased growth rates in *Syringodium isoetifolium* when artificially shaded, indicating that high light was causing reduced growth rates (Fokeera-Wahedally and Bhikajee 2005). The role of high light stress in seagrasses requires further investigation.

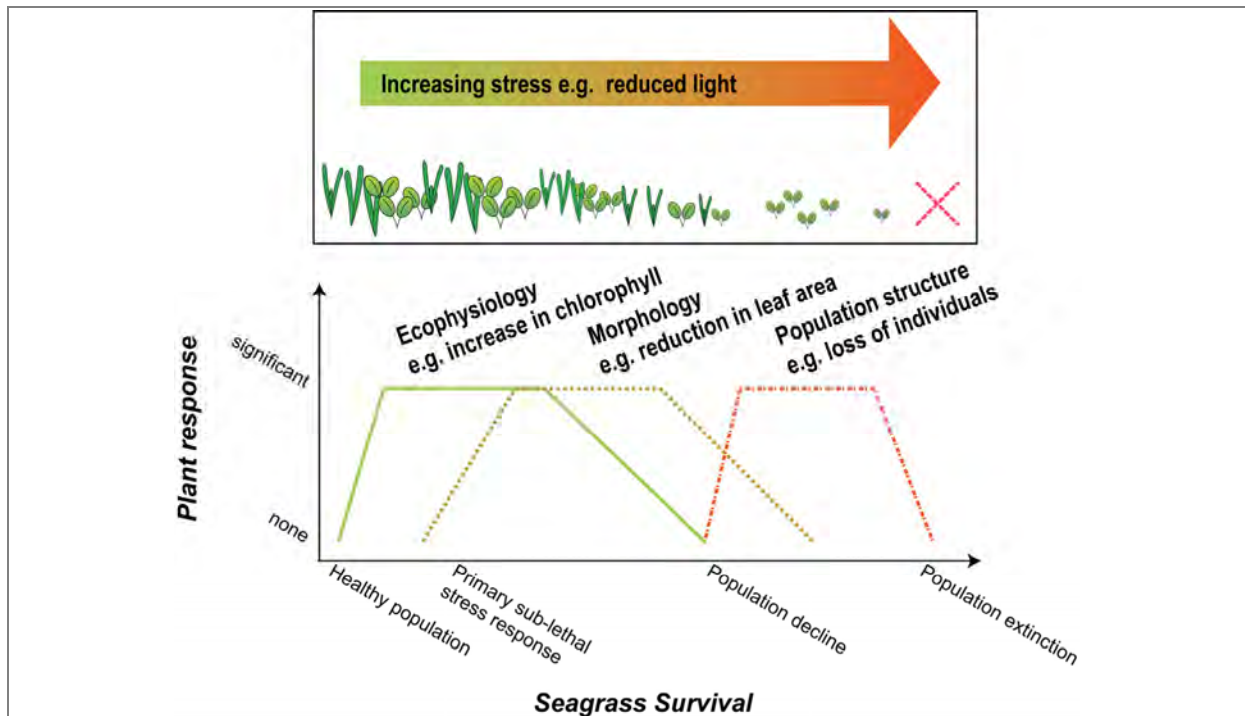


Figure 12: Tropical seagrass responses to increasing stress such as reduced light availability (Waycott *et al.* 2005).

Light-related disturbance – Key points

- Seagrasses cannot tolerate extended periods below their MLRs; the tolerance threshold for surviving in zero light is species-specific ranging from about 38 days upwards
- Seagrasses can adapt to reduced light in various ways, such as reduced biomass, and these changes can be used as sublethal indicators of light reduction though responses for most GBR species are not known.
- Very high light can also impact seagrasses and this is likely to occur during emersion in the middle of the day.

Overall Importance as a Disturbance Driver: Very high.

Knowledge gaps

- Thresholds for tolerance to light reduction (MLRs and duration of tolerance).
- Sublethal response indicators.
- Influence of interacting factors.
- Importance of high light stress.

Nutrients – Rarely implicated in disturbance events

Pulses of nutrients entering coastal systems can cause algal overgrowth followed by periods of anoxia. Nutrient over-enrichment leading to seagrass loss is more common in temperate systems than in tropical systems (e.g. Cambridge *et al.* 1986). Excess nutrients stimulate growth of macrophytes, particularly algae, which shade seagrasses and when decomposing can lead to anoxia (Nixon 1995). The impacts can be catastrophic because of the difficulties and time delay in restoring the system. Nutrient-related impacts on seagrass have been observed in the GBR (Campbell *et al.* 2002) but there are no reported cases of prolonged nutrient-related impacts to seagrasses in the GBR. Nutrients delivered to the reef in runoff, the main source of nutrients to the reef, are rapidly incorporated by bacteria and phytoplankton so seagrass habitats rarely experience excess pulsed nutrient supplies (Furnas 2003).

Nutrient-related disturbance – Key points

- Nutrient over-enrichment is potentially devastating to seagrass meadows but lasting nutrient-related impacts have not occurred in the GBR.

Overall Importance as a Disturbance Driver: Moderate.

Knowledge gaps

- See earlier section on nutrients.

Temperature – Too hot in shallow waters

As water temperatures rise, increasing photorespiration causes a reduction in photosynthetic efficiency. In GBR seagrasses, the temperature thresholds leading to photodamage are species-specific with tropical / subtropical species more tolerant of temperatures above 40°C (Campbell *et al.* 2006). Above about 38-42°C proteins are destroyed and irreparable damage to tissues follows (Waycott *et al.* 2007). Seagrass burnoff has been reported in GBR seagrasses following periods of high water temperature (Chin 2005; Roelofs *et al.* 2006). Temperature in very shallow coastal waters can be up to ten degrees higher than adjacent waters and reach well above 40°C in summer (McKenzie and Campbell 2004; McKenzie and Yoshida 2006).

The temperature threshold that results in tissue damage in seagrasses is not known. In reef corals it is a combination of temperature and duration of exposure that can determine susceptibility to coral bleaching. Whether duration plays an important role in seagrass burn-off is unclear. Temperature stress can also be less evident, with declining growth rates or reproductive success (Roelofs *et al.* 2006; Waycott *et al.* 2007) and the thresholds leading to such changes are likely to be much lower but are not known. Due to human-related climate change, the frequency of extreme temperature events is likely to increase in the future (Lough 2007), making this a priority research area. Ongoing temperature monitoring at a range of Seagrass-Watch sites will provide considerable insight into thresholds and the effects of elevated temperature on intertidal seagrass meadows.

Temperature-related disturbance – Key points

- Temperatures above about 40°C can lead to photodamage and burnoff.
- Seagrasses can also be impacted at much lower temperatures with declining growth rates.

Overall Importance as a Disturbance Driver: Moderate to high in shallow waters.

Knowledge gaps

- Temperature thresholds for seagrass burn-off and other impacts (e.g. growth).
- The effects of prolonged or repetitive exposure to elevated temperatures (e.g. reproductive output).

Burial – Smothering and escape, it's all about time...

Given their broad-scale distribution in estuaries and coastal environments, seagrasses are periodically exposed to major sediment deposition events. Changes to land-use patterns have probably increased the load of sediments from GBR catchments (Furnas 2003), making seagrasses increasingly susceptible to burial. This can result in the complete burial of seagrass plants and their seedbanks (Waycott *et al.* 2007). Experimental burial has shown that *Halodule uninervis* will suffer reduced biomass after burial, but if connected to nearby shoots that are not buried, the impact will be lessened (Campey 1995), however major burial events usually result in burial of an entire meadow. Shoots that survive can elongate their vertical rhizomes to grow out of their buried state in experimental studies (Campey 1995) but there is no evidence for this having occurred in the natural environment. Because of its large stature, *Enhalus* is thought to be more tolerant of burial (Bridges *et al.* 1983).

Burial-related disturbance – Key points

- Burial will result in initially a decline in productivity and if prolonged, seagrass death.

Overall Importance as a Disturbance Driver: Low to moderate.

Knowledge gaps

- Species-specific tolerance to burial.
- Prevalence of burial of seagrass beds in the GBR.

Impacts of Disturbances – Change and Loss

Loss

Persistent disturbances steer seagrasses on a trajectory of declining biomass and growth. The responses occur in stages and typically follow the model described in Figure 12. Experimental studies have shown that these responses can occur in a time-course. For example, following experimental light reduction, physiological changes begin:

1. Sugars stored in rhizomes and leaves are rapidly depleted to support growth and respiration;
2. Pigment concentrations increase to facilitate increased light absorption; and
3. Photosynthetic efficiency increases (Longstaff and Dennison, 1999; Longstaff *et al.* 1999; Bité *et al.* 2007).

Following this, morphological responses occur, including changes to plant morphological characteristics and biomass (Abal *et al.* 1994; Grice *et al.* 1996; Longstaff and Dennison 1999; Longstaff *et al.* 1999; Hall *et al.* 2001; Walsh 2006). Responses are expected to be species-specific and are not well documented for most seagrass species in the GBR. Eventually, complete seagrass loss can occur (e.g. Figure 12); resulting in change in population structure. Seagrass loss has resulted from light reduction caused by turbid flood plumes in Hervey Bay (Preen *et al.* 1995; Longstaff 2003). Responses to highly elevated nutrient concentrations can be similar. Following an increase in what was thought to be sewage-derived nutrients, filamentous algae increased in abundance and seagrass density subsequently declined (Campbell *et al.* 2002).

These responses may be able to be used as early indicators that there is an impact on the meadow, and as such are frequently adopted in current monitoring programs. Timing can play a crucial role in the impact that disturbances have on the meadow. During the senescent or growth season, the impacts are likely to be less than during the growing season.

Species differ in their ability to withstand disturbances. Sediment deposition can smother intertidal seagrasses such as *Halophila* and *Halodule*, which have a small stature (Campbell and McKenzie 2004) while the larger *Zostera* and *Enhalus* can tolerate sediment deposition (Bridges *et al.* 1983). Exposure to air and high temperatures in the intertidal zones are tolerated by the small *Halodule* and *Halophila*, which can lie on sediment or in very shallow pools to keep moist while larger seagrasses cannot.

In response to light reduction, *Halophila ovalis* will be completely lost after thirty days of light deprivation, whereas *Halodule uninervis* and *Halophila spinulosa* can survive much longer periods, which may be partially due to their ability to store more reserves (Longstaff and Dennison 1999; Hall *et al.* 2001; Longstaff 2003). Reef-based seagrasses with a larger stature, thicker rhizome and therefore greater ability to store reserves may be able to endure temporary light reduction for even longer according to studies on other, related, species (Czerny and Dunton 1995), despite their higher MLRs.

Seagrass species also differ in their ability to adapt to disturbances that change their environment. For example, *Halodule* and *Halophila* respond to reduced light availability by altering physiological and morphological characteristics (Longstaff and Dennison 1999; Longstaff *et al.* 1999). The adaptive capacity of other GBR seagrasses has not been investigated, but based on studies in other regions, larger and more persistent species can be less responsive to disturbances such as light reduction with their strategy being to withstand the disturbance rather than adapt to it (Collier 2006). *Halodule uninervis* can firstly

withstand short periods of burial under sediments and adapt by elongating their vertical rhizomes (Campey 1995). This enables them to grow through the sediment and reach light. Species with slower elongation rates, lower energy reserves, or those more easily damaged may be affected to a greater extent (e.g. *Halophila* spp.).

Because of the varied responsiveness of seagrass species to disturbances, disturbance regimes can play a key role in shaping seagrass distribution and species composition. Estuaries are dominated by *Zostera* and *Enhalus* which can tolerate periodic sediment dumping. Intertidal areas are dominated by seagrasses with a small stature that can cope with exposure to air. Subtidal areas are dominated by species that can endure periods of low light. Or it may be dominated by species that can recover well.

Recovery and change

Seagrasses can recover from loss caused by disturbances by two mechanisms: vegetative growth or localised growth of the plant on site, and recruitment from propagules able to be dispersed which include seeds generated by sexual reproduction or plant fragments that remain viable and can colonise new locations.

Recovery by vegetative growth is particularly important when disturbances are small or patchy in nature (Rasheed 2004). The seagrass then grows into a new area by adding new plant parts (shoots or leaf pairs) from existing vegetative fragments containing growing meristems. When recolonising new areas, seagrasses may adopt different morphological characteristics that favour rapid extension over bare substrate (e.g. long internodes, small shoots) (McMahon 2005) or through deposited sediment (Campey 1995). In these intensively grazed systems where up to 65% of biomass is removed, recovery can occur within one month in meadows adapted to this disturbance regime (McMahon 2005). Such rapid recovery may be facilitated by the presence of an 'ungrazeable reserve' which is not easily accessible for dugong feeding (Preen 1995). In meadows that are generally more stable, recovery from small-scale disturbance can take more than two years (Rasheed 2004). Recolonisation by drifting vegetative fragments can probably occur, but only at very low frequencies (Rasheed 2004).

Sexual reproduction is particularly important when there is complete removal of plants. In these cases the seed bank can remain in the sediment with germination occurring when conditions are favourable (Campbell and McKenzie 2004). It is thought that seed can continuously germinate at low rates in seagrass meadows, but they are generally out-competed by vegetative growth and only become dominant when vegetative cover is very low (Inglis 2000a). Low genetic variability among isolated seagrass meadows in post-cyclone and flood-related studies in Hervey Bay indicated that dispersal of seeds between meadows may also be important for recovery (McMahon 2005). Sexual reproduction is also important in much smaller-scale disturbances such as dugong grazing (McMahon 2005). Many species in the GBR are thought to have an 'initial seed recruitment' strategy, whereby germination by seeds is important in the early stage of meadow development, but from there on vegetative propagation dominates (Rasheed 2005).

Early successional species that can rapidly respond to disturbances include *Halophila* and *Halodule*. They can rapidly colonise new substrate. McMahon (2005) suggested that species adapted to these disturbance regimes have a number of features in common: 'genotypically diverse meadows; fast-growth; flexible clonal reproduction; regular and flexible sexual reproduction and breeding system; and a persistent, abundant seed bank'. Larger seagrasses such as *Cymodocea* and *Zostera* can be out-competed in these circumstances (Aragones and Marsh 2000). These latter successional species will move in more gradually as the habitat becomes more stable. In areas in which disturbances are common, the meadow can remain in a constant stage of early successional species with these species

dominating in environments characterised by high disturbance, e.g. shifting sediments (Bridges *et al.* 1983), and dugong grazing termed 'grazing optimisation' (Aragones and Marsh 2000).

There is concern that if disturbance regimes are disrupted significantly, for example if dugong numbers were reduced, there may be significant ecological consequences resulting in a shift in species composition (Aragones *et al.* 2006). Similarly, changing storm regimes, as predicted for the future in climate change scenarios, could also affect species distributions (Waycott *et al.* 2007).

Impacts of disturbances – Key points

- Frequent low level disturbance (e.g. dugong grazing) can stimulate growth but most disturbances have a negative impact causing a range of changes in the plants and eventually leading to reduced growth rates and biomass, eventually species composition or seagrass loss.
- Seagrass recovery requires colonising material, either as vegetative fragments or seeds. A lack of these eliminates potential to recover.

Potential maximum seagrass biomass and community structure

The multiplicity of potential causes of disturbance means that more than one may be in operation at any one time. Given that, at present we have limited information available about each of the major drivers – independent of each other – we have virtually no direct knowledge of synergistic impacting factors. For example, where coastal developments are prevalent, high turbidity (light reduction) and nutrient levels are likely to occur. To progress our understanding of what seagrass growth is possible under different combined conditions, knowledge of the growth of seagrasses under independent conditions may be used to predict maximum potential growth under a combined set of impacts (Figure 13).

All six drivers are typically limiting in some way. That is to say, it is rare to encounter high water clarity, optimum temperatures, low water movement, good sediments and adequate nutrients all at once. The maximum biomass that can form at a particular site will, therefore, be considerably lower than the theoretical maximum. In the models provided (Figure 13), each disturbance factor has an individual impact on the possible growth of a seagrass. So where light is low, biomass will be low, irrespective of how many nutrients are available or how good the sediment is. When physical disturbance is high, seagrass growth will be limited and when there are very high nutrients, seagrass growth will be severely limited. The models presented offer a method by which we might estimate seagrass biomass at a particular site. At present, there is a concept that it is possible for a climax, high biomass seagrass meadow to occur in many places where the combination of local conditions will limit this potential.

Maximum seagrass biomass – Key points

- The possible maximum biomass of a seagrass meadow is the cumulation of the limiting factors for growth and the various disturbance regimes.

Knowledge gaps

- Quantitative data for the theoretical curves.

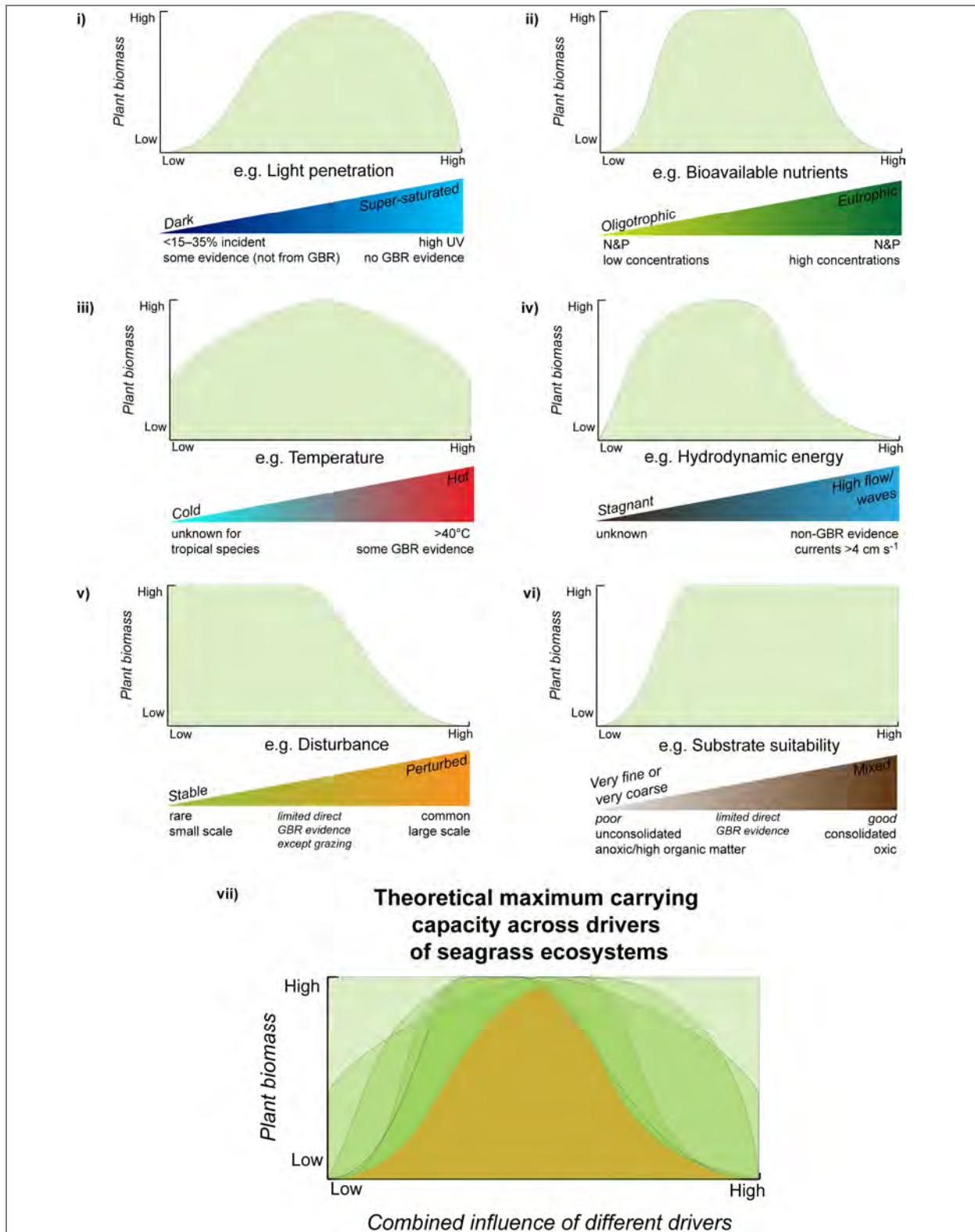


Figure 13: Models show how seagrass growth is possibly limited for specific drivers, and the combined effect of these drivers. Each model is scaled to the range over which plant biomass (= growth) is affected by the driver. The scale for each driver is likely to differ for species, habitats or bioregion. Maximum plant biomass is assumed equivalent (i.e. 100%) for all drivers. Shaded areas are those where seagrass growth is possible. i) Light penetration; ii) bioavailable nutrients; iii) temperature; iv) hydrodynamic regime; v) physical disturbance; vi) substrate suitability; and vii) combined, the orange shaded area is the maximum potential growth under the influence of all drivers.

Changes in meadow states: The good, the bad, the ugly

The idea that there is an 'optimal' seagrass meadow can be further challenged. Tropical seagrass meadows can change from a stable, high biomass meadow, typical of a protected and relatively nutrient rich, high light, low grazing seagrass meadow (e.g. Green Island, near Cairns in the northern GBR) to a low biomass, high turnover seagrass meadow that is heavily grazed or regularly exposed to wave action from storms (e.g. Shelley Beach, near Townsville in the central GBR). The transition between these meadow types or states can also be explained in a successional manner. We have already seen a series of changes proposed due to single drivers such as increasing nutrients or decreasing light (see earlier sections on pages 28-31). The transition from a stable, high biomass meadow to a dynamic meadow responsive to regular disturbances can be caused by a single large impact (i.e. meadow loss then recovery by colonising species) or by numerous small, compounding impacts (Figure 14).

Additional pressures on dynamic seagrass ecosystems will force the direction of change more rapidly. Thus in areas of seagrass under pressure from high disturbance regimes, we expect to see a greater proportion of the seagrass community as 'disturbed' seagrass beds, i.e. those dominated by colonising or high turnover species (*Halophila* and *Halodule*). These are found in sites with high tidal ranges (around Mackay), heavy sediment loads (around Townsville) and in many areas with regular dredging (Coles *et al.* 2007). The model illustrated in Figure 14 suggests that small and perhaps apparently innocuous impacts, on their own, may be of limited concern, however as a compounding impact are of considerable concern.

In order to interpret observed changes in the state at which a seagrass meadow is functioning at any point in time, an understanding of the inherent natural cycles of change in seagrass ecosystems of the GBR is required. It is the diverse and variable nature of this system that provides perhaps the greatest challenge to managing the resource for the future.

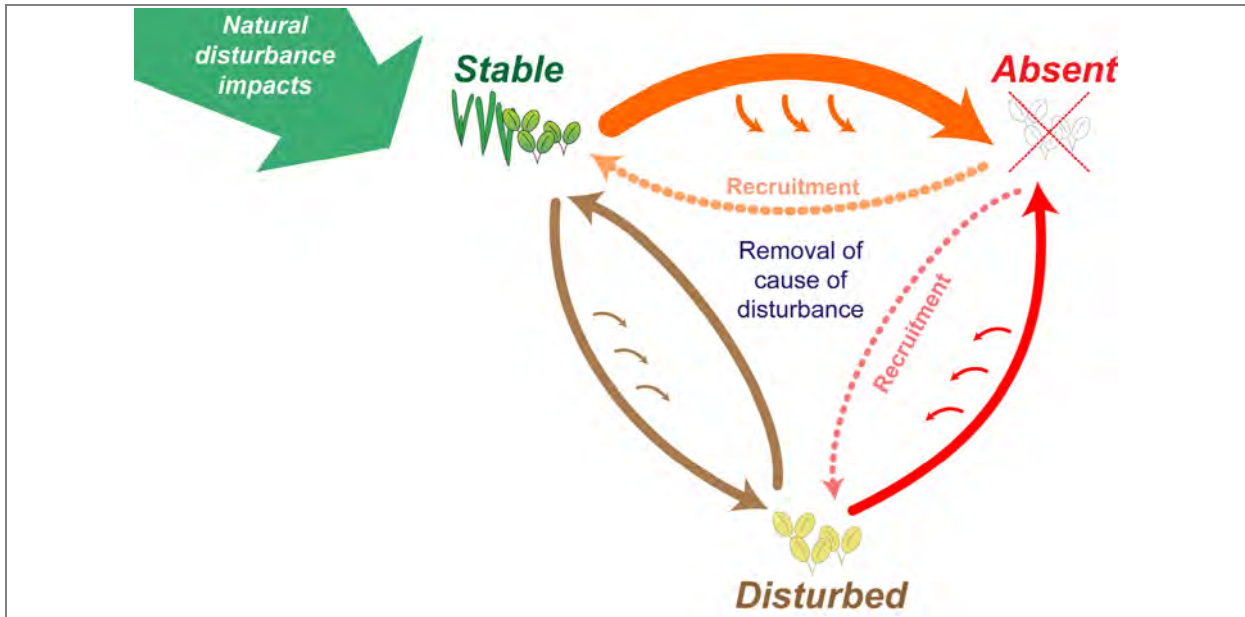


Figure 14: Changes between natural states of a seagrass meadow: **Stable** representing seagrass species and community structure expected to occur perennially barring major system change; **Disturbed** representing seagrass meadows able to respond to frequent or regular impacts but readily recover; **Absent** is where, at a point in time, there is no seagrass meadow but a meadow has been or will be there. Reversal of a state change requires recruitment for a meadow to recover following loss, along with removal of the cause of disturbance. Drivers of change may be large, depicted by the bold, single arrow between states or small and compounding.

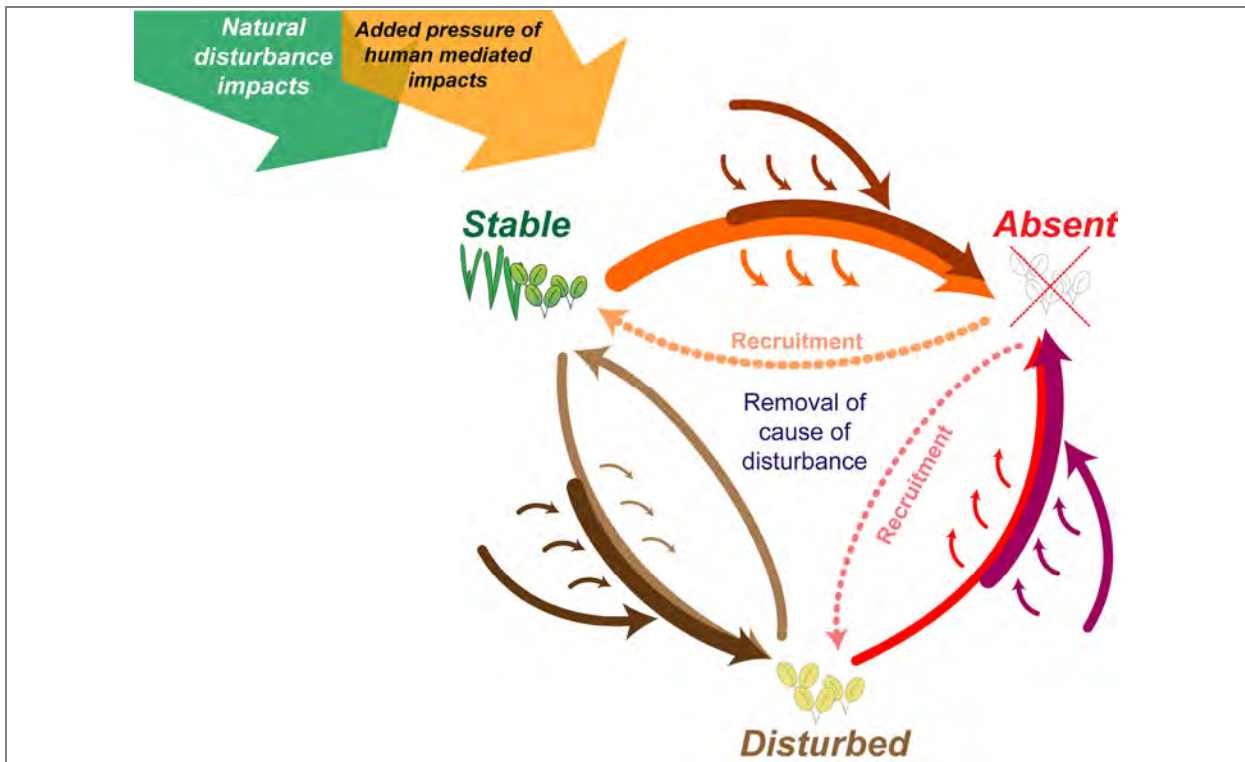


Figure 15: Changes between the states described in Figure 14 with the added pressure of human mediated changes.

Summary of potential disturbances to seagrass meadows in the GBR

Seagrasses of the GBR are exposed to frequent natural disturbances and they appear to be well adapted to cope with this disturbance regime at present (Figure 15). The multiple different disturbances to which seagrasses in different habitats are exposed will result in a cycle between stable and disturbed habitats, in some cases the absence of seagrass altogether (Figure 14). Different locations will experience different drivers of these changes as we have outlined, and at present we have significant knowledge gaps in our understanding of these drivers and how they influence seagrass growth and survival of communities.

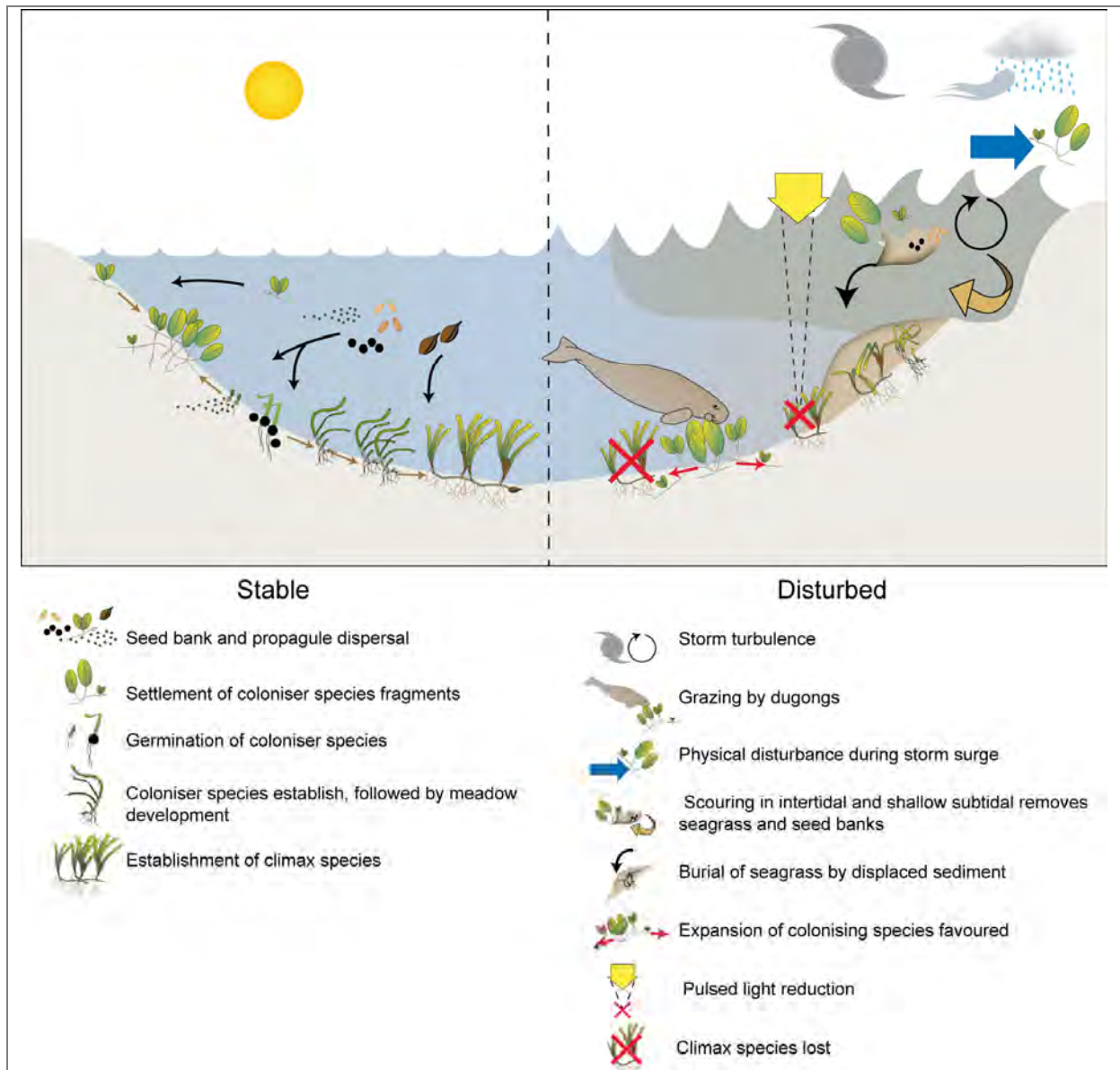


Figure 16: Generalised model depicting seagrass meadows under different disturbance regimes: **Stable** where seagrass meadow succession can develop following recovery; and **Disturbed** where drivers of change select for maintaining the seagrass meadow in colonising species state.

Disturbance to seagrass meadows in the GBR and issues related to their management

Seagrasses of the GBR are diverse and distributed widely across habitats and environmental conditions. Despite this, they are constrained by the need for strict environmental conditions to survive and their distribution, composition and health are controlled by these factors. Disturbance-related events that lead to an imbalance of these environmental requirements can impact seagrass meadows. Seagrasses of the GBR are exposed to frequent natural disturbances as well as increasing and compounding influences from human related impacts. Seagrasses are highly sensitive to changes in their environment and they can therefore be used as sentinels of change in coastal systems (e.g. Great Barrier Reef World Heritage Area Marine Monitoring Program). In order to identify the causes of change in seagrasses and to manage the causes, we need to improve our understanding of how drivers affect seagrass meadows. There are many gaps in our state of knowledge noted throughout this document that currently inhibit our ability to interpret change. Coastal seagrasses are a priority as they represent the greatest area of GBR seagrass habitat, and they are most at risk due to their susceptibility to disturbances including runoff, declining water quality and dredging.

The ongoing impact of coastal development, climate change and human-related uses of the coastal zone present significant challenges to managing seagrass habitats. As seagrass meadows are the buffer between the coral reefs of the GBR and the majority of human activities on the coast, they are critical habitats to monitor and protect both as fisheries habitat and for the general ecosystem health values they promote. Effective management requires evidence-based analysis of how seagrasses will respond to change. Clearly, we have a long way to go in the GBR in this respect. For example, although we have some reasonable data available for seagrass survival thresholds with respect to limited light availability, virtually none has been determined in the GBR. Other key knowledge gaps are highlighted throughout this document.

Currently we recognise that light limitation and physical disturbance have the greatest impact on seagrass meadows in the GBR. Reductions in water quality in particular are of great concern because of the large scale at which it can impact and the difficulty in reversing such an impact. The risk of long-term seagrass loss from reduced light availability elevate the urgency with which we need to improve our understanding of seagrass light thresholds and indicators of change. Physical disturbance is the dominant disturbance in GBR seagrass meadows and has a wide range of causes. It is the capacity for seagrass meadows to recover from physical disturbance that is of greatest interest, as recovery processes dictate the long-term impact that disturbances have. Vulnerability to physical disturbance is greatest in those meadows that lack a reservoir (or nearby source) of seeds or other recovery propagules (fragments).

Climate change is adding to the uncertainty in how seagrasses will cope with future impacts. Already increasing temperatures, possibly associated with human-related climate change, appears to be impacting seagrass meadows (Waycott *et al.* 2007). The dynamic nature of seagrass meadows and our limited understanding of both natural change and heightened impacts inhibit our ability to confidently detect and attribute cause to change.

References

- Abal EG, Loneragan NR, Bowen P, Perry CJ, Udy JW and Dennison WC (1994) Physiological and morphological responses of the seagrass *Zostera capricorni* Aschers. to light intensity. *Journal of Experimental Marine Biology and Ecology* 178: 113-129.
- Anthony KRN, Ridd PV, Orpin A, Larcombe P and Lough JM (2004) Temporal variation in light availability in coastal benthic habitats: effects of clouds, turbidity and tides. *Limnology and Oceanography* 49: 2201-2211.
- Aragones L, Lawler I, Foley W and Marsh H (2006) Dugong grazing and turtle cropping: grazing optimization in tropical seagrass systems? *Oecologia* 149(4): 635-647.
- Aragones L and Marsh H (2000) Impact of dugong grazing and turtle cropping on tropical seagrass communities. *Pacific Conservation Biology* 5(4): 277-288.
- Balasubramanian S, Sureshkumar S, Lempe J and Weigel D (2006) Potent induction of *Arabidopsis thaliana* flowering by elevated growth temperature. *PLoS Genetics* 2(7): e106.
- Beer S, Mtolera M, Lyimo T and Bjork M (2006) The photosynthetic performance of the tropical seagrass *Halophila ovalis* in the upper intertidal. *Aquatic Botany* 84(4): 367-371.
- Birch WR and Birch M (1984) Succession and pattern of tropical intertidal seagrasses in Cockle Bay, Queensland, Australia: A decade of observations. *Aquatic Botany* 19: 343-367.
- Bité JS, Campbell SJ, McKenzie LJ and Coles RG (2007) Chlorophyll fluorescence measures of seagrasses *Halophila ovalis* and *Zostera capricorni* reveal differences in response to experimental shading. *Marine Biology* 152: 405-414.
- Brenchley JL and Probert RJ (1998) Seed germination responses to some environmental factors in the seagrass *Zostera capricorni* from eastern Australia. *Aquatic Botany* 62(3): 177-188.
- Bridges KW, Phillips RC and Young PC (1983) Patterns of some seagrass distribution in the Torres Strait, Queensland. *Australian Journal of Marine and Freshwater Research* 33(2): 273-283.
- Bulthuis DA (1983) Effects of *in situ* light reduction on density and growth of the seagrass *Heterozostera tasmanica* (Martens ex Aschers.) Den Hartog in Western Port, Victoria, Australia. *Journal of Experimental Marine Biology and Ecology* 67(1): 91-103.
- Bulthuis DA (1987) Effects of temperature on photosynthesis and growth of seagrasses. *Aquatic Botany* 27(1): 27-40.
- Cambridge ML, Chiffings AW, Brittain C, Moore L and McComb AJ (1986) The loss of seagrass in Cockburn Sound, Western Australia. II. Possible causes of seagrass decline. *Aquatic Botany* 24: 269-285.
- Campbell SJ and McKenzie LJ (2004) Flood related loss and recovery of intertidal seagrass meadows in southern Queensland, Australia. *Estuarine Coastal and Shelf Science* 60(3): 477-490.

Campbell SJ, McKenzie LJ and Kerville SP (2006) Photosynthetic responses of seven tropical seagrasses to elevated seawater temperature. *Journal of Experimental Marine Biology and Ecology* 330(2): 455-468.

Campbell SJ, McKenzie LJ, Kerville SP and Bité JS (2007) Patterns in tropical seagrass photosynthesis in relation to light, depth and habitat. *Estuarine, Coastal and Shelf Science* 73(551-562).

Campbell SJ, Roder CA, McKenzie LJ and Lee Long WJ (2002) *Seagrass resources in the Whitsunday region 1999 and 2000*. DPI&F Information Series QI02043. Cairns: Department of Primary Industries and Fisheries.

Campey ML (1995) *Disturbance and recovery of a tropical seagrass: an experimental analysis*. James Cook University Townsville.

Carruthers TJB, Dennison WC, Kendrick GA, Waycott M, Walker DI and Cambridge ML (2007) Seagrasses of south-west Australia: A conceptual synthesis of the world's most diverse and extensive seagrass meadows. *Journal of Experimental Marine Biology and Ecology* 350(1-2): 21-45.

Carruthers TJB, Dennison WC, Longstaff BJ, Waycott M, Abal EG, McKenzie LJ and Long WJL (2002) Seagrass habitats of northeast Australia: Models of key processes and controls. *Bulletin of Marine Science* 71(3): 1153-1169.

Carruthers TJB and Walker DI (1999) Sensitivity of transects across a depth gradient for measuring changes in aerial coverage and abundance of *Ruppia megacarpa* Mason. *Aquatic Botany* 65: 281-292.

Chin A (2005) Seagrasses. In: Chin A (ed.) *State of the Great Barrier Reef On-Line*. Townsville: Great Barrier Reef Marine Park Authority.

Coles R, Long WL, McKenzie L, Roelofs A and De'ath G (2000) Stratification of seagrasses in the Great Barrier Reef World Heritage Area, northeastern Australia, and the implications for management. *Biologica Marina Mediterranea* 7(2): 345-348.

Coles RG, McKenzie L and Yoshida RL (2001) *Validation and GIS of seagrass surveys between Cape York and Tarrant Point – October/November 1986*. Cairns: Queensland Department of Primary Industries and Fisheries and Queensland Fisheries Service.

Coles RG, McKenzie LJ, Rasheed MA, Mellors JE, Taylor H, Dew K, McKenna S, Sankey T, Carter A and Grech A (2007) Status and trends of seagrass habitats in the Great Barrier Reef World Heritage Area. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (122pp.) (<http://www.rrrc.org.au/publications/downloads/113-QDPI-Coles-et-al-2007-Status-and-Trends.pdf>)

Collier CJ (2006) *Characterising responses of the seagrass *Posidonia sinuosa* to changes in light availability*. PhD thesis, Edith Cowan University, Perth.

Collier CJ, Lavery PS, Masini RJ and Ralph PJ (2007) Morphological, growth and meadow characteristics of the seagrass *Posidonia sinuosa* along a depth-related gradient of light availability. *Marine Ecology Progress Series* 337: 103-115.

Collier CJ, Lavery PS, Ralph PJ and Masini RJ (2008) Physiological characteristics of the seagrass *Posidonia sinuosa* along a depth-related gradient of light availability. *Marine Ecology Progress Series* 353: 65-79.

Conacher CA, Poiner IR, Butler A, Pun S and Tree DJ (1994a) Germination, storage and viability testing of seeds of *Zostera capricorni* Aschers. from a tropical bay in Australia. *Aquatic Botany* 49: 47-58.

Conacher CA, Poiner IR and O'Donohue M (1994b) Morphology, flowering and seed production of *Zostera capricorni* Aschers. in subtropical Australia. *Aquatic Botany* 49(1): 33-46.

Czerny AB and Dunton KH (1995) The effects of in situ light reduction on the growth of two subtropical seagrasses, *Thalassia testudinum* and *Halodule wrightii*. *Estuaries* 18(2): 418-427.

Dawes CJ, Lobban CS and Tomasko DA (1989) A comparison of the physiological ecology of the seagrasses *Halophila decipiens* ostenfeld and *H. Johnsonii* eiseman from Florida. *Aquatic Botany* 33(1-2): 149-154.

den Hartog C (1970) *The sea-grasses of the world*. North-Holland Publishing Co., Amsterdam.

Dennison WC and Abal EG (1999) *Moreton Bay Study: a scientific basis for the healthy waterways campaign*. Brisbane: South East Queensland Regional Water Quality Management Team.

Dennison WC and Alberte RS (1985) Role of daily light period in the depth distribution of *Zostera marina* (eelgrass). *Marine Ecology Progress Series* 25: 51-61.

Dennison WC, Orth RJ, Moore KA, Stevenson CJ, Carter V, Kollar S, Bergstrom PW and Batiuk RA (1993) Assessing water quality with submerged aquatic vegetation. *Bioscience* 43(2): 86-94.

Dew KR, Rasheed MA, Taylor HA and Sankey TL (2007) *Port of Karumba long-term seagrass monitoring, October 2006*. Cairns: Department of Primary Industries and Fisheries, Northern Fisheries Centre.

Dixon LK and Leverone JR (1995) Light requirements of *Thalassia testudinum* in Tampa Bay, Florida. Sarasota, Florida: Mote Marine Laboratory.

Duarte CM (1990) Seagrass nutrient content. *Marine Ecology Progress Series* 67: 201-207.

Erfteemeijer PLA and Herman PMJ (1994) Seasonal changes in environmental variables, biomass, production and nutrient contents in two contrasting tropical intertidal seagrass beds in South Sulawesi, Indonesia. *Oecologia* 99(1): 45-59.

Fokeera-Wahedally SBM and Bhikajee M (2005) The effects of in situ shading on the growth of a seagrass, *Syringodium isoetifolium*. *Estuarine, Coastal and Shelf Science* 64(2-3): 149-155.

Fourqurean JW, Boyer JN, Durako MJ, Hefty LN and Peterson BJ (2003) Forecasting responses of seagrass distributions to changing water quality using monitoring data. *Ecological Applications* 13(2): 474-489.

Fourqurean JW and Rutten LM (2003) Competing goals of spatial and temporal resolution: Monitoring seagrass communities on a regional scale. In: Busch DE and Trexler JC (eds.) *Monitoring ecosystems: Interdisciplinary approaches for evaluating ecological initiatives*. Washington DC: Island Press.

Furnas M (2003) *Catchment and corals: Terrestrial runoff to the Great Barrier Reef*. Townsville Queensland: Australian Institute of Marine Science.

Grice AM, Loneragan NR and Dennison WC (1996) Light intensity and the interactions between physiology, morphology and stable isotope ratios in five species of seagrass. *Journal of Experimental Marine Biology and Ecology* 195: 91-110.

Hall V, Inglis GJ, Boyle M and Tutt K (2001) The complexities associated with managing the relationship between light and tropical seagrasses. Technical report for the Townsville City Council. In. Townsville: CRC Reef Research Centre, James Cook University.

Hillman K, McComb AJ and Walker DI (1995) The distribution, biomass and primary production of the seagrass *Halophila ovalis* in the Swan/Canning Estuary, Western Australia. *Aquatic Botany* 51(1-2): 1-54.

IAN (2006) *Seagrasses: Prairies of the sea*. In. University of Maryland, Cambridge: Integration and Application Network (IAN).

Inglis GJ (2000a) Disturbance-related heterogeneity in the seed banks of a marine angiosperm. *Journal of Ecology* 88(1): 88-99.

Inglis GJ (2000b) Variation in the recruitment behaviour of seagrass seeds: implications for population dynamics and resource management. *Pacific Conservation Biology* 5: 251-259.

Kenworthy WJ and Fonesca MS (1996) Light requirements of seagrasses *Halodule wrightii* and *Syringodium filiforme* derived from the relationship between diffuse light attenuation and maximum depth distribution. *Estuaries* 19(3): 740-750.

Kirk JTO (1994) *Light and photosynthesis in aquatic ecosystems*. Cambridge: Cambridge University Press.

Koch EW (2001) Beyond light: Physical, geological and geochemical parameters as possible submersed aquatic vegetation habitat requirements. *Estuaries* 24: 1-17.

Koch EW, Ackerman JD, Verduin J and van Keulen M (2006) Fluid dynamics in seagrass ecology - from molecules to ecosystems. In: Larkum WD, Orth RJ and Duarte CM (eds.) *Seagrasses: biology, ecology and conservation*. Dordrecht: Springer.

Lanyon JM, Limpus CJ and Marsh H (1989) Dugong and turtles: grazers in the seagrass system. In: Larkum AWD, McComb AJ and Shepherd SA (eds.) *Biology of seagrasses: a treatise on the biology of seagrasses with special reference to the Australian region*. Amsterdam: Elsevier, 610-634.

Lanyon JM and Marsh H (1995) Temporal changes in the abundance of some tropical intertidal seagrasses in North Queensland. *Aquatic Botany* 49(4): 217-237.

Larcombe P, Ridd PV and Wilson B (1995) Factors controlling suspended sediment on inner-shelf coral reefs, Townsville, Australia. *Coral Reefs* 14(3): 163-171.

Larkum AWD, Collett LC and Williams RJ (1984) The standing stock, growth and shoot production of *Zostera capricorni* aschers. Botany Bay, New South Wales, Australia. *Aquatic Botany* 19(3-4): 307-327.

Lee K-S, Park SR and Kim YK (2007) Effects of irradiance, temperature, and nutrients on growth dynamics of seagrasses: A review. *Journal of Experimental Marine Biology and Ecology* 350(1-2): 144-175.

Lee KS and Dunton KH (1997) Effects of *in situ* light reduction on the maintenance, growth, and partitioning of carbon resources in *Thalassia testudinum* Banks ex Konig. *Journal of Experimental Marine Biology and Ecology* 210: 53-73.

Lee Long WJ, Coles RG and McKenzie LJ (1996) Deepwater seagrasses in northeastern Australia: How deep, how meaningful? In: Kuo J, Phillips RC, Walker DI and Kirkman H (eds.) *Seagrass Biology: Proceedings of an international workshop, Rottnest Island, Western Australia, 25-29 January 1996*. Faculty of Sciences, The University of Western Australia, Perth, pp.41-50.

Lee Long WJ, Mellors JE and Coles RG (1993) Seagrasses between Cape York and Hervey Bay, Queensland, Australia. *Australian Journal of Marine and Freshwater Research* 44: 19-31.

Lee Long WJ, Roelofs AJ, Coles RG and McKenzie LJ (2001) *Monitoring Oyster Point Seagrasses – 1995 to 1999*. Report to the Great Barrier Reef Marine Park Authority, Townsville.

Lirman D and Cropper WP (2003) The influence of salinity on seagrass growth, survivorship, and distribution within Biscayne Bay, Florida: Field, experimental, and modeling studies. *Estuaries* 26(1): 131-141.

Longstaff BJ (2003) *Investigations into the light requirements of seagrass in Northeast Australia. PhD Thesis*. Department of Botany: University of Queensland Brisbane.

Longstaff BJ and Dennison WC (1999) Seagrass survival during pulsed turbidity events: the effects of light deprivation on the seagrasses *Halodule pinifolia* and *Halophila ovalis*. *Aquatic Botany* 65(1-4): 105-121.

Longstaff BJ, Loneragan NR, O'Donohue MJ and Dennison WC (1999) Effects of light deprivation on the survival and recovery of the seagrass *Halophila ovalis* (R.Br.) Hook. *Journal of Experimental Marine Biology and Ecology* 234: 1-27.

Lough J (2007) Climate and climate change on the Great Barrier Reef. In: Johnson JE and Marshall PA (eds.) *Climate change and the Great Barrier Reef: A vulnerability assessment*. Townsville: Great Barrier Reef Marine Park Authority and the Australian Greenhouse Office.

Lovelock CE and Ellison J (2007) Vulnerability of mangroves and tidal wetlands of the Great Barrier Reef to climate change. In: Johnson JE and Marshall PA (eds.) *Climate change and the Great Barrier Reef: A vulnerability assessment*. Townsville: Great Barrier Reef Marine Park Authority and the Australian Greenhouse Office.

Marbà N, Holmer M, Gacia E and Barrón C (2006) Seagrass beds and coastal biogeochemistry. In: Larkum WD, Orth RJ and Duarte CM (eds.) *Seagrasses: biology, ecology and conservation*. Dordrecht: Springer.

Marsh H, Eros C, Corkeron P and Breen B (1999) A conservation strategy for dugongs: implications of Australian research. *Marine and Freshwater Research* 50: 979-990.

McComb AJ, Cambridge ML, Kirkman H and Kuo J (1981) The biology of Australian seagrasses. In: Pate JS and McComb AJ (eds.) *The biology of Australian plants*. Perth: University of Western Australia Press, 258-293.

McKenna SA, Rasheed MA and Sankey TL (2007) Long Term Seagrass monitoring in the Port of Mourilyan – November 2006. Department of Primary Industries and Fisheries, Northern Fisheries Centre, Cairns.

McKenzie L and Yoshida R (2006) Temperature Monitoring. In: *Seagrass-Watch News*. Issue 25, April 2006 (<http://www.seagrasswatch.org/newsletters.html>).

McKenzie LJ (1994) Seasonal changes in biomass and shoot characteristics of a *Zostera capricorni* Aschers. dominant meadow in Cairns harbour, northern Queensland. *Australian Journal of Freshwater Research* 45: 1337-1352.

McKenzie LJ and Campbell S (2004) Surviving the summer heat: Seagrass and corals. *Seagrass-Watch News*. Issue 19, February 2004 (<http://www.seagrasswatch.org/newsletters.html>).

McKenzie LJ, Lee Long WJ and Bradshaw EJ (1997) *Distribution of seagrasses in the Lizard Island Group – A reconnaissance survey, October 1995*. CRC Reef Research Technical Report No 14. Cairns: Queensland Department of Primary Industries.

McKenzie LJ, Mellors J and Waycott M (2007) *Great Barrier Reef Water Quality Protection Plan Marine Monitoring Program - Intertidal Seagrass*. Project 1.1.3 Milestone Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns.

McMahon KM (2005) *Recovery of subtropical seagrasses from natural disturbance*. The University of Queensland, Brisbane.

McMahon M, Bengtson Nash S, Eaglesham G, Müller JF, Duke NC and Winderlich S (2005) Herbicide contamination and the potential impact to seagrass meadows in Hervey Bay, Queensland, Australia. *Marine Pollution Bulletin* 51: 325-334.

Mellors JE (2003) *Sediment and nutrient dynamics in coastal intertidal seagrass of north eastern tropical Australia*. PhD Thesis. School of Tropical Environment Studies and Geography: James Cook University, Townsville.

Mellors JE and Marsh H (1993) Relationship between seagrass standing crop and the spatial distribution and abundance of the natantian fauna at Green Island, northern Queensland. *Australian Journal of Marine and Freshwater Research* 44: 183-191.

Mellors JE, Marsh H, Carruthers TJB and Waycott M (2002) Testing the sediment-trapping paradigm of seagrass: Do seagrasses influence nutrient status and sediment structure in tropical intertidal environments? *Bulletin of Marine Science* 71(3): 1215-1226.

Mellors JE, Marsh H and Coles RG (1993) Intra-annual changes in seagrass standing crop, Green Island, Northern Queensland. *Australian Journal of Marine and Freshwater Research* 44(33-41).

Nixon SW (1995) Coastal marine eutrophication: A definition, social causes and future concerns. *Ophelia* 41: 199-219.

Olesen B, Enríquez S, Duarte CM and Sand-Jensen K (2002) Depth-acclimation of photosynthesis, morphology and demography of *Posidonia oceanica* and *Cymodocea nodosa* in the Spanish Mediterranean Sea. *Marine Ecology Progress Series* 236: 89-97.

Orth RJ, Carruthers TJB, Dennison WC, Duarte CM, Fourqurean JW, Heck KL Jr., Hughes AR, Kendrick GA, Kenworthy WJ, Olyarnik S, Short FT, Waycott M and Williams SL (2006) A Global crisis for seagrass ecosystems. *Bioscience* 56(12): 987(910).

Pollard PC and Greenway M (1993) Photosynthetic characteristics of seagrasses (*Cymodocea serrulata*, *Thalassia hemprichii* and *Zostera capricornii*) in a low-light environment, with a comparison of leaf-marking and lacunal-gas measurements of productivity. *Australian Journal of Marine and Freshwater Research* 44(1): 127-139.

Preen A (1995) Impacts of dugong foraging on seagrass habitats: observational and experimental evidence for cultivation grazing. *Marine Ecology Progress Series* 124: 201-213.

Preen A and Marsh H (1995) Response of dugongs to large-scale loss of seagrass from Hervey Bay, Queensland, Australia. *Wildlife Research* 22(4): 507-519.

Preen AR, Long WJL and Coles RG (1995) Flood and cyclone related loss, and partial recovery of more than 1000 km² of seagrass in Hervey Bay. *Aquatic Botany* 52: 3-17.

Pringle AW (1989) The history of dredging in Cleveland Bay, Queensland and its effects on sediment movement and on the growth of mangroves, corals and seagrass. Townsville: Great Barrier Reef Marine Park Authority.

Ralph PJ and Burchett MD (1995) Photosynthetic responses of the seagrass *Halophila ovalis* (R. Br.) Hook. f. to high irradiance stress, using chlorophyll fluorescence. *Aquatic Botany* 51: 55-66.

Ralph PJ, Durako MJ, Enriquez S, Collier CJ and Doblin MA (2007) Impact of light limitation on seagrasses. *Journal of Experimental Marine Biology and Ecology* 350(1-2): 176-193.

Rasheed MA (2004) Recovery and succession in a multi-species tropical seagrass meadow following experimental disturbance: the role of sexual and asexual reproduction. *Journal of Experimental Marine Biology and Ecology* 310(1): 13-45.

Rasheed MA, Dew KR, McKenna SA, Sankey TL, Taylor HA and Carter A (2007) *Long-term seagrass monitoring in Cairns Harbour and Trinity Inlet – December 2006*. Cairns: Department of Primary Industries and Fisheries, Northern Fisheries Centre.

Roelofs A, Rasheed M, Thomas R, McKenna S and Taylor H (2006) *Port of Weipa Long Term seagrass monitoring, 2003-2005*. Ports Corporation of Queensland.

Rollon RN, de Ruyter van Steveninck ED and van Vierssen W (2003) Spatio-temporal variation in sexual reproduction of the tropical seagrass *Enhalus acoroides* (L.f.) Royle in Cape Bolinao, NW Philippines. *Aquatic Botany* 76(4): 339-354.

Schaffelke B, Mellors J and Duke NC (2005) Water quality in the Great Barrier Reef region: responses of mangrove, seagrass and macroalgal communities. *Marine Pollution Bulletin* 51: 279-296.

Sheppard JK, Lawler IR and Marsh H (2007) Seagrass as pasture for seacows: Landscape-level dugong habitat evaluation. *Estuarine, Coastal and Shelf Science* 71: 117-132.

Steinberg C (2007) Impacts of climate change on the physical oceanography of the Great Barrier Reef. In: Johnson JE and Marshall PA (eds.) *Climate Change and the Great Barrier Reef: A vulnerability assessment*. Townsville: Great Barrier Reef Marine Park Authority and the Australian Greenhouse Office.

Taylor HA, Rasheed MA, Dew KR and Sankey TL (2007) *Long term seagrass monitoring in Port Curtis and Rodds Bay, Gladstone – November 2006*. Cairns: Department of Primary Industries and Fisheries, Northern Fisheries Centre.

Taylor HA, Rasheed MA and Sankey TL (2006) *Long term seagrass monitoring in the Port of Thursday Island, March 2006*. DPI&F Publication PR06-2546. Cairns: Department of Primary Industries and Fisheries, Northern Fisheries Centre. 22.

Udy JW and Dennison WC (1997) Growth and physiological responses of three seagrass species to elevated sediment nutrients in Moreton Bay, Australia. *Journal of Experimental Marine Biology and Ecology* 217(2): 253-277.

Udy JW, Dennison WC, Long WJL and McKenzie LJ (1999) Responses of seagrass to nutrients in the Great Barrier Reef, Australia. *Marine Ecology-Progress Series* 185: 257-271.

Udy JW and Levy D (2002) Deep seagrass and coral habitats found in eastern Moreton Bay. Brisbane: The University of Queensland and Tangalooma Wild Dolphin Resort.

Walker D, Dennison WC and Edgar G (1999) Status of Australian seagrass research and knowledge. In: Butler A and Jernakoff P (eds.) *Seagrass in Australia: Strategic review and development of an R & D plan*. Collingswood Victoria: CSIRO Publishing Australia.

Walker DI and McComb AJ (1992) Seagrass degradation in Australian coastal waters. *Marine Pollution Bulletin* 25(5-8): 191-195.

Walsh C (2006) *Growth responses of Halophila ovalis to changes in water quality: an experimental approach*. James Cook University Townsville.

Waycott M, Collier CJ, McMahon K, Ralph P, McKenzie LJ, Udy JW and Grech A (2007) The vulnerability of seagrasses of the Great Barrier Reef to climate change. In: Johnson JE and Marshall PA (eds.) *Climate Change and the Great Barrier Reef: A vulnerability assessment*. Townsville: Great Barrier Reef Marine Park Authority and the Australian Greenhouse Office.

Waycott M, Longstaff BJ and Mellors J (2005) Seagrass population dynamics and water quality in the Great Barrier Reef region: A review and future research directions. *Marine Pollution Bulletin* 51(1-4): 343-350.

Waycott M, McMahon M, Mellors J, Calladine A and Kleine D (2004) *A guide to the tropical seagrasses of the Indo-West Pacific*. Townsville: James Cook University.

Waycott M, Procaccini G, Les DH and Reusch TBH (2006) Seagrass Evolution, Ecology and Conservation: A Genetic Perspective. In: Larkum AWD, Orth RJ and Duarte CM (eds.) *Seagrasses: Biology, Ecology and Conservation*. Dordrecht: Springer.

Further Information

Marine and Tropical Sciences Research Facility
PO Box 1762
CAIRNS QLD 4870

This document is available for download at <http://www.rrrc.org.au/publications>

Credits: Cover photos courtesy of *Catherine Collier*.

