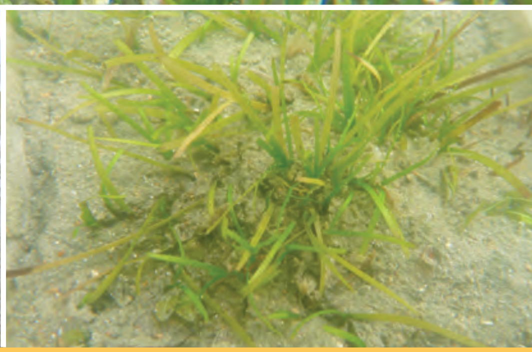
National Environmental Research Program
TROPICAL ECOSYSTEMS hub

Final Report

Final report on thresholds and indicators of declining water quality as tools for tropical seagrass management



Catherine J. Collier, Michelle Devlin, Lucas Langlois, Len J. McKenzie, Caroline Petus, Eduardo Teixeira da Silva, Kathryn McMahon, Matthew Adams, Kate O'Brien, John Statton, and Michelle Waycott

Australian Government
Department of the Environment

Reef & Rainforest RESEARCH CENTRE

Final report on thresholds and indicators of declining water quality as tools for tropical seagrass management

A summary of findings from Project 5.3 Vulnerability of seagrass habitats in the GBR to flood plume impacts: light, nutrients and salinity

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Australian Government

Department of the Environment

Supported by the Australian Government's
National Environmental Research Program

National Library of Australia Cataloguing-in-Publication entry:

978-1-925088-50-2

This report should be cited as:

Collier, C., Devlin, M., Langlois, L., Petus, C., McKenzie, L. Petus, C, Texeira da Silva, E., McMahon, K, Adams, M, O'Brien, K., Statton, J. and Waycott, M. (2014) *Thresholds and indicators of declining water quality as tools for tropical seagrass management.* Report to the National Environmental Research Program. Reef and Rainforest Research Centre Limited, Cairns (46pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's National Environmental Research Program (NERP) Tropical Ecosystems (TE) Hub.

The Tropical Ecosystems Hub is part of the Australian Government's Commonwealth National Environmental Research Program. The NERP TE Hub is administered in North Queensland by the Reef and Rainforest Research Centre Limited (RRRC). The NERP Tropical Ecosystem Hub addresses issues of concern for the management, conservation and sustainable use of the World Heritage listed Great Barrier Reef (GBR) and its catchments, tropical rainforests including the Wet Tropics World Heritage Area (WTWHA), and the terrestrial and marine assets underpinning resilient communities in the Torres Strait, through the generation and transfer of world-class research and shared knowledge.

Cover photographs: Catherine Collier, James Cook University

This report is available for download from the NERP Tropical Ecosystems Hub website:

http://www.nerptropical.edu.au/research

December 2014

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Acronyms Used In This Report

DoE .... Department of the Environment

GBR .... Great Barrier Reef

NERP .... National Environmental Research Program

RRRC .... Reef and Rainforest Research Centre Limited

RS .... Remote sensing

WQ .... Water Quality

C .... Carbon

N .... Nitrogen

Abbreviations Used In This Report

AIMS .... Australian Institute of Marine Science

C .... Carbon

C:N .... Carbon:Nitrogen

CDOM .... Coloured Dissolved Organic Matter

Chl a .... Chlorophyll a

DIN .... Dissolved inorganic nitrogen

DIP .... Dissolved inorganic phosphorus

FRP .... Filterable Reactive Phosphorus

GBR .... Great Barrier Reef

GBRMP .... Great Barrier Reef Marine Park

GBRMPA ...... Great Barrier Reef Marine Park Authority

JCU .... James Cook University

K_d .... Light attenuation coefficient

N .... Nitrogen

NASA .... National Aeronautics and Space Administration

NH_4^+ .... Ammonium

NO_3^- .... Nitrate

NRM .... Natural Resource Management

NTU .... Nephelometric Turbidity Units

OACs .... Optically Active Compounds

PAR .... Photosynthetically Active Radiation

PSU .... Practical Salinity Units

QLD .... Queensland

RS .... Remote Sensing

RRMMP .... Reef Rescue Marine Monitoring Program

SD .... Standard Deviation

SE .... Standard Error

SPM .... Suspended particulate matter

WQ................ Water Quality

Acknowledgements

We would like to thank our partners at the Great Barrier Reef Marine Park Authority (GBRMPA) for providing guidance on project direction and environmental management needs, in particular we thank Katherine Martin and Carol Honchin. There were many people who assisted with experimental work some of whom are included as authors in the relevant scientific publications, including Kyvely Vlahkis, Cecilia Villacorta-Rath, Miwa Takahashi, Adam Wilkinson, Paul Lavery. A number of people have also contributed to the development of remote sensing tools for detecting flood plume impacts on seagrasses and we thank Jorge Alvarez Romero. Data from the Reef Rescue Marine Monitoring Program was used for detecting the effects of flood plume impacts on seagrass abundance and composition, as well as the derivation of light thresholds during seagrass loss. A number of people have contributed to the inshore seagrass Reef Rescue MMP data set and we would like to thank Naomi Smith, Rudi Yoshida, Miwa Takahashi and Ana Giraldo Ospina.

Synthesis

Background

The broad aims of this study were to test the vulnerability of seagrasses to declining water quality, in particular, changes associated with flooding. This project was established in response to extensive seagrass loss that occurred from 2009 to 2011 in the Great Barrier Reef when there was above average run-off for multiple wet seasons, which culminated in the passage of cyclone Yasi through the northern GBR in 2011. Dugong, which are seagrass specialists, also suffered record levels of mortality in 2011 and had low calving rates in the southern GBR following the unprecendented levels of seagrass loss. In 2014, there were signs that seagrass meadows were recovering. This project has been designed to help interpret the effects of flood water on seagrass as well as improve our capacity to detect and respond to other water quality related impacts (e.g. dredging).

Flood plumes are low in salinity (hypo-saline), have high nutrient concentrations (triggering blooms of phytoplankton) and both dissolved (e.g. CDOM) and particulate matter (e.g. suspended sediments) that create low light conditions. Floodwaters may also contain toxic levels of contaminants, such as herbicides. This was a 2-year project that included desktop analyses, analysis of in situ light logger data, analysis of remote sensing-derived water quality, a review of the literature and a number of experiments to test seagrass responses to salinity, light and nutrients and to identify thresholds associated with loss.

The objectives of this project were to determine:

- The level of exposure of seagrass meadows to broad scale and long-term changes in water quality associated with flood plumes in coastal regions of the GBR
- The influence of light, nutrients and salinity on seagrass condition
- Refined thresholds of concern for light, nutrients and salinity
- Indicators of seagrass condition to report on status
- Future trajectories for GBR ecosystems

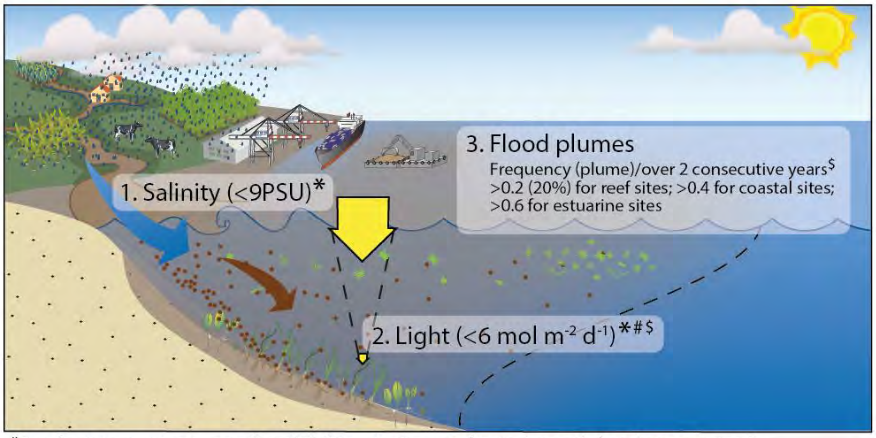
Science summary

Plumes of floodwaters were detected using satellite imagery. Seagrass meadows in coastal and estuarine regions of the GBR were exposed to plumes of variable water quality conditions during the wet season months (Nov-April). Ocean colour information derived from remote sensing was used to develop water quality thresholds that occur when seagrasses have experienced greater than 50% loss in abundance. Different permutations of ocean colour conditions have been extracted for the four main seagrass habitats. The derived water quality thresholds all relate to the constituents (TSS, chl-a, CDOM) that influence the light attenuation. Therefore, in situ data and aquarium-based experiments were used to test seagrass responses to salinity, light and nutrients to identify which aspect of flood plumes have the greatest effect on meadow health.

The response of seagrasses to hypo-salinity was tested from 3 PSU (almost freshwater) to 36 PSU (seawater). GBR seagrasses had broad hypo-salinity tolerance with thresholds (associated with mortality) occurring at <3 PSU for Zostera muelleri and <9 PSU for Halophila ovalis and Halodule uninervis after 10 weeks (Figure 1). There was a stress-induced morphometric response at low-moderate salinities (9 – 15 PSU) whereby shoot density proliferated in response to hypo-salinity. Given the broad salinity tolerance it is highly unlikely that low salinity was the primary cause of seagrass losses associated with flooding. We did not prioritse hypo-salinity for further interactive experimental testing.

Seagrass abundance at Magnetic Island and Dunk Island was correlated to in situ light levels using data from the Reef Rescue MMP. High and significant ($p<0.05$) correlations between seagrass loss and low light, suggests that low light contributed to seagrass loss from 2009 to

2011. Therefore, effects of low light were prioritized for further experimental work, including the interactive effects of elevated nutrients and seasonal variations in water temperature. Four seagrass species were grown at two temperatures, warm (~27°C) and cool water (~22°C), and were exposed to light levels ranging from 0 to 70% of full sunlight (0-23 mol m^{-2} d^{-1}) in aquaria experiments for 3 months. All species suffered faster mortality (declines in seagrass) in warm compared to cooler water, and H. ovalis and Z. muelleri were more sensitive to low light levels than C. serrulata and H. uninervis. From this study, light thresholds for any chosen level of seagrass decline (e.g. 10, 20, 50% decline) could be calculated. 50% loss occurred at 3 to 6 mol m^{-2} d^{-1} after 14 weeks exposure depending on species and water temperature (Figure 1), and 20% loss occurred at 7.4 to 10.4 mol m^{-2} d^{-1}. This experimental approach revealed a very similar light threshold for H. uninervis from Magnetic Island derived using in situ decline and in situ daily light (both approximately 4 mol m^{-2} d^{-1} for 50% loss after 3 months in warm water). The similarity has increased confidence in thresholds derived from experimental work for other species and verified the conclusion that low light was a large contributor to recent in situ seagrass loss in the GBR.



*for short-term exposure, varies with time of exposure (up to 3 months) and among species
#affected by temperature $threshold is established for seagrass loss of greater than 50%

Figure 1. Summary of salinity, light and flood plume thresholds identified in this study.

Indicators of light stress were also tested. Firstly, a review of global literature identified robust indicators of light stress. Secondly, some of these sub-lethal (i.e. detectable before mortality) indicators (tissue nutrients, $\delta^{13}C$ and rhizome carbohydrates) were tested using two aquaria-based experiments: light only and light × nutrients. Results demonstrated that the combination of indicators (C/N, $\delta^{13}C$ and rhizome carbohydrates) provide the most powerful interpretation of light and/or nutrient stress. C/N was highly sensitive to light and nutrients except at high nutrient concentration when C/N ratios did not respond to light. Rhizome carbohydrates or leaf $\delta^{13}C$ are robust complimentary early-warning indicators of light availability with the most sensitive of these indicators varying among species.

This study has and will contribute to the following management outcomes:

- Identified seagrass meadows at high risk of exposure to flood waters when certain conditions, defined by the frequency of colour classes, are experienced over two consecutive years.
- Colour class frequency represents an exposure to water types experienced over the wet season.
- Different permutations of ocean colour information can provide information that can be used to develop guidelines on habitat scale seagrass loss.

- Developed new environmental thresholds (light), which will be incorporated into seagrass guidelines for protection of GBR seagrasses.
- Measured new salinity thresholds, which occur at low salinities.
- Confirmed metric selection (sub-lethal indicators) and scoring for Reef Rescue MMP reporting.

1. Introduction

There have been chronic declines in inshore water quality in the Great Barrier Reef (GBR) since European settlement, which have led to dramatic ecological shifts (De'ath and Fabricius, 2010; Roff et al., 2013). Intensive use of the GBR catchments for agriculture, grazing, as well as establishment of urban centers and marine based commercial activity such as ports, have placed high pressure on GBR ecosystems (Brodie et al., 2013b). Rivers discharging into the GBR lagoon are the main land-based source of key pollutants (including TSS, dissolved inorganic nitrogen (DIN) and photosystem II-inhibiting herbicides (PSII herbicides) in the coastal and marine environment (Figure 2). The levels of TSS, Colored Dissolved Organic Matters (CDOM) and chlorophyll-a (chl-a) associated with plume waters decrease from the inshore to the offshore boundaries of the River plumes. The relative concentrations of these three Optically Active components (OACs) affect the light attenuation properties of the water types (Devlin et al., 2008, 2009) and the diffuse attenuation coefficient of photosynthetically active radiation (K_d(PAR)) decrease from the inshore to the offshore boundaries of the River plumes (Devlin and Schaffelke, 2009; Devlin et al., 2012a, 2013a, b; Petus et al., a, b). Thirty major rivers drain into the GBR, all of which vary considerably in length, catchment area, and flow frequency and intensity. River plumes are driven by high river flow conditions, which in the GBR are the periods in the monsoonal season that are typically associated with the passage of cyclones or low pressure systems, i.e., from about December to April (Devlin and Brodie, 2005). Level of exposure of coastal to marine ecosystems (including seagrass meadows) to river plumes and land sourced pollutants is spatially and temporally dependant of the different land-uses in the GBR catchments, the local transports of pollutants, and the distance of respective ecosystems to the river mouths. Nearly all of the GBR rivers experienced a high degree of flooding during the 2010-2011 wet season due to the very strong 'La Nina' beginning early in the season in mid-2010 and three cyclones (Tasha in December 2010, Anthony in January 2011 and the most damaging: Yasi in February 2011) that crossed the North Queensland coast over a period of three months (Devlin et al., 2012b; Logan et al., 2013). The predominantly inshore distribution of seagrass meadows in the GBR makes them particularly susceptible to the direct effects of flood plumes as well as chronic water quality decline generally.

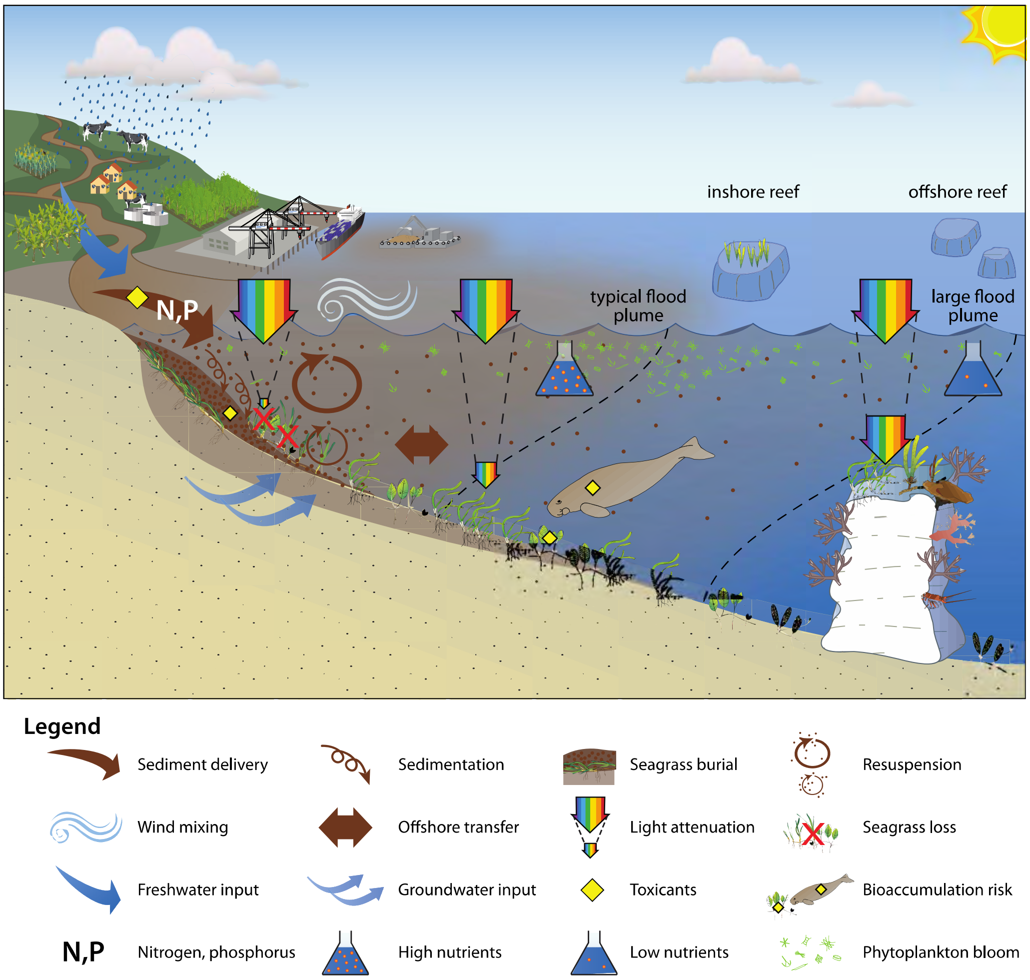


Figure 2. Conceptual understanding of flood water impacts on seagrasses

Seagrasses are marine flowering plants with approximately 70 species distributed globally except in polar regions (Short et al., 2011). The ecosystem services provided by seagrass meadows makes them a high conservation priority (Cullen-Unsworth and Unsworth, 2013). For example, nutrient cycling in seagrass meadows makes them one of the most economically valuable ecosystems in the world (Costanza et al., 1997). Furthermore, in the tropics, seagrass meadows support populations of turtles and dugongs, which are seagrass specialists (Marsh et al., 2011) as well as commercial (e.g. prawns) and subsistence (e.g. holothurians) fisheries (Coles et al., 1993; Cullen-Unsworth and Unsworth, 2013). They also support threatened species, with ray-finned fish including seahorses and pipefish, being the most affected group of threatened species (Hughes et al., 2008). Seagrass meadows also incorporate and retain carbon within their tissues and in the sediments, which can affect local pH and increase calcification of coral reefs, and contribute to what has become known as 'Blue Carbon' or marine carbon sequestration (Fourqurean et al., 2012; Unsworth et al., 2012).

The Reef Rescue Marine Monitoring Program has established that seagrass meadows along the GBR were in decline in 2011 (McKenzie et al., 2012). The indicators of this decline were: 73% of sites declined in abundance (below the seagrass guidelines) from 2010-2011 and 80% showed a declining long-term trend (5-10 years); 55% of sites exhibited shrinking meadow area, majority of sites had few seeds that would enable recovery. The trends in seagrass decline were the result of changing water quality, particularly caused by flood plumes, as well as the direct impacts of cyclones in localized areas (Figure 1). Specifically, there were signs that there was an excess of nutrients and low light availability at many sites. Low salinity and herbicides entering the GBR through floodwater may also have contributed to seagrass declines. The decline in seagrass meadow abundance and area was also associated with record dugong and turtle mortality in 2011 (Meager and Limpus, 2012).

Seagrasses indicate changing water quality at a range of scales

As seagrasses are highly sensitive to changing water quality, they are considered “sentinels” of coastal degradation (Dennison et al., 1993; Orth et al., 2006) and, as such, they are frequently incorporated into assessments of estuarine and coastal integrity (e.g. Borja et al., 2008; Fourqurean et al., 1997; Romero et al., 2007). In addition to being good bioindicators of changing water quality, changes in seagrass health indicate likely ecological and economic flow-on effects. The advantage of measuring seagrasses as bioindicators, in addition to water quality, is that they integrate a temporal component, reflecting both the past and current environmental condition. Good bioindicators should be scientifically defensible, and the cause-effect pathway, as well as trigger levels leading to their change should be predictable and repeatable (McMahon et al., 2013). There is a plethora of potential bioindicators but ecological health assessments need to be based on simple and scientifically tested indicators (Borja et al., 2008).

One of the key causes of seagrass decline is light reduction (Waycott et al., 2009). They are particularly sensitive to light stress: many species have high light requirements and frequently occur in shallow estuarine or coastal regions, which are readily impacted by flood waters. The ways in which seagrasses can respond to changing light are reasonably well documented (Figure 2) (McMahon et al., 2013; Ralph et al., 2007). Even in the case of light stress, reliability and repeatability remains a limitation of indicator selection when developing robust monitoring programs. Indicator selection becomes even more complicated when designing programs that need to report on multiple water quality, and even climate related stressors such as the Reef Rescue Marine Monitoring Program (MMP).

There are many scales at which indicators respond, ranging from sub-lethal (physiological), through to meadow-scale (or state change) losses (Figure 3, Table 1). These indicators also respond at different temporal scales, with sublethal, physiological indicators able to respond from seconds to months, while the meadow-scale effects usually take many months to be detectable. A robust monitoring program will benefit from having a suite of indicators that can indicate sub-lethal stress that forewarns of imminent loss, as well as indicators of meadow-scale changes, which are necessary for interpreting broad ecological impacts. Many of the indicators listed in Figure 2 and Table 1 remain untested for GBR seagrasses or the environmental thresholds corresponding to their changes are not yet quantified for many indicators. This limits our ability to interpret results of monitoring.

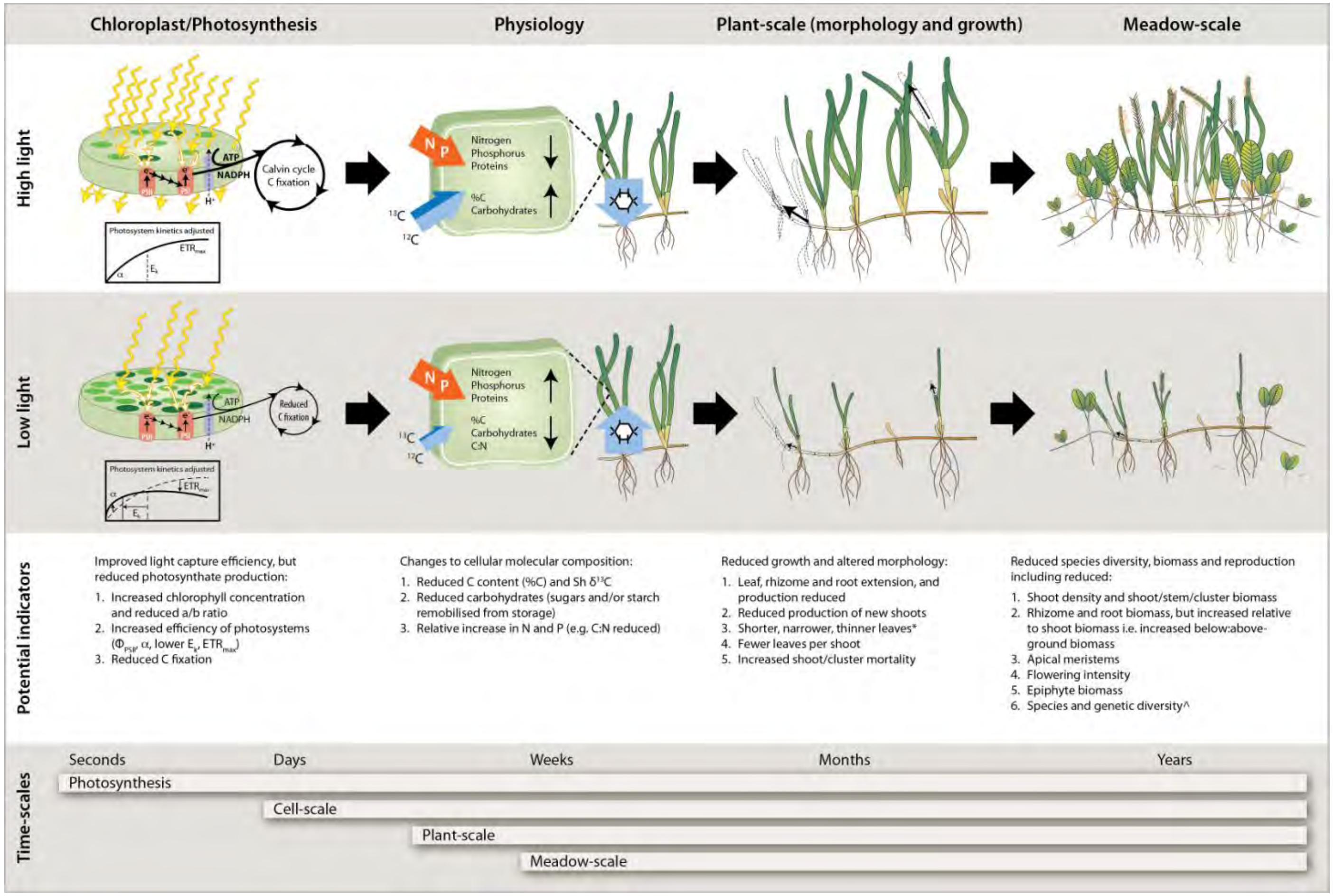


Figure 3. Conceptual diagram of the current understanding of the of seagrass response pathway under low light conditions separated by photosynthetic, other physiological, plant-scale (growth and morphology) and meadow-scale variables. The timescales at which the responses to light reduction generally occur are indicated at the base of the diagram. Potential bioindicators are highlighted. (McMahon et al., 2013)

Table 1. Response stages of seagrass meadows to external stressors and the indicator responses observed in Great Barrier Reef monitored seagrass meadows (adapted from Waycott and McKenzie 2010). * measures were utilised in Paddock to Reef reporting (McKenzie et al., 2013).

Indicator	***Sub-lethal*** (ecophysiological)	***State change*** (whole plant and population scale)	***Population decline*** (whole meadow scale)
A. Tissue nutrients	Ratios of key macronutrients change to indicate relative excesses (e.g. C:N*, C:P, N:P, $\delta^{13}C$)	Limited by species variable upper threshold	-
B. Chlorophyll concentrations	Rapid short term changes observed	Limited by species variable upper threshold	-
C. Production of reproductive structures	-	Reduced flowering and fruiting, loss of seeds for meadow recovery seen as high variability among sites*	Threshold reached where no reproduction occurs
D. Change in plant morphology	-	Change in meadow LAI: reduction in leaf area	Threshold where reduction in leaf area is incapable of meeting respiration demand
E. Community structure	-	Change in species composition	Loss of species due to the threshold being reached
F. Change in species abundance (population structure)	-	Change in abundance of species (i.e. % cover)* or the number of individuals in each population	Reduction in effective population size
G. Change in meadow area	-	-	Reduction in total meadow area (habitat loss)
H. Recovery time from loss	Limited or no change	Measurably delayed	Potentially no recovery if threshold reached

Guidelines and reporting

Water quality guidelines

Water quality guidelines for the GBR have been developed based on correlations between coral health and water quality through long-term monitoring (De'ath and Fabricius, 2010; GBRMPA, 2009). These guidelines can be used to set targets for water quality and trigger management actions where guidelines are exceeded. The Reef Rescue Marine Monitoring Program (RRMMP) is one of the flagship programs in the GBR that can be used to detect breaches of guidelines, and identify the ecological effects of breaches, or improvements in water quality. There are currently no specific guidelines for seagrass meadows of the GBR due largely to a lack of data to support their development and identification of potential targets for detecting significant change.

Reef Rescue MMP Report card

The RRMMP aims to report on changes in water quality and ecosystem responses to these changes, including inshore corals and seagrasses.

Figure 4. Seagrass abundance monitoring is carried out as part of the Reef Rescue Marine Monitoring Program, and it is used together with tissue nutrients and reproductive output to score seagrass meadow health on an annual basis.

An annual report card is generated for the status of seagrass each year for the GBR and each of the NRMs (Figure 5). The methodology used in the MMP is described in an annually updated Quality Assurance/Quality Control document (GBRMPA, 2014). The scoring for these report cards is generated from annual monitoring and the indicators listed below (McKenzie et al., 2013).

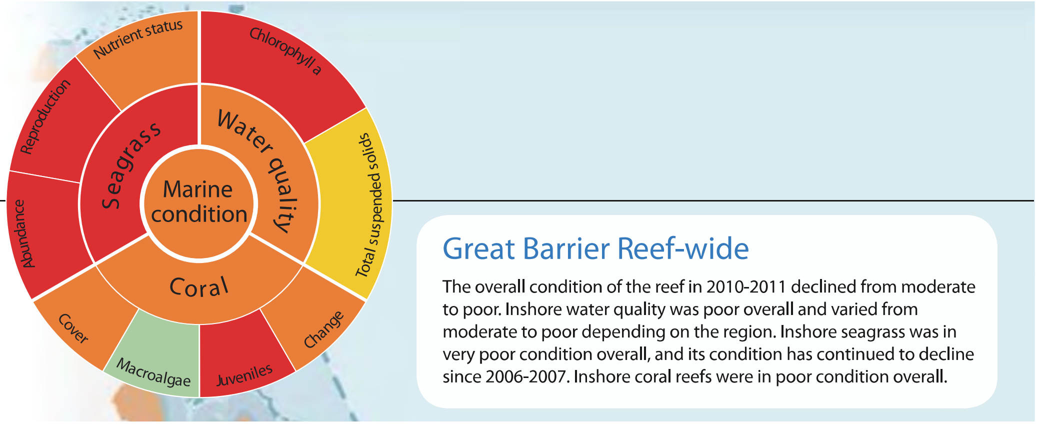


Figure 5. Excerpt from the 2010-2011 Great Barrier Reef Report Card from the Reef Water Quality Protection Plan showing the incorporation of three metrics (Abundance, Reproduction and Nutrient status) in the report card scoring for seagrasses.

Three indicators were selected for the report card using advice from expert working groups, by the GBRMPA, the Paddock to Reef Integration technical advisory group (McKenzie et al., 2013), as well as available evidence in the literature on their suitability for identifying changes in water quality (Fourqurean et al., 1997; McMahon et al., 2013). Seagrass abundance is used to indicate the state of the seagrass, reproductive effort to indicate the potential for the seagrass to recover from loss, and the nutrient status to indicate the condition of the environment in which the seagrass are growing in recognition of seagrass' role as a bioindicator. These indicators are scored for calculation of a seagrass status and trend metric (Table 2, Table 3) (McKenzie et al., 2013). The status of seagrass abundance was determined using the regionally-specific seagrass abundance guidelines developed by McKenzie (2009), while tissue nutrient ratios are scored using globally-derived values that have not yet been tested in the GBR. The third metric, reproduction, is not explored extensively in this project and is not as well developed in terms of thresholds. These indicators were tested in this project to verify their response to light, nutrients and salinity.

Table 2. Scoring threshold table to determine seagrass abundance status.

description	category	score	status
very good	75-100	100	80 - 100
good	50-75	75	60 - <80
moderate	low-50	50	40 - <60
poor	<low	25	20 - <40
very poor	<low by >20%	0	0 - <20

Table 3. Scores for leaf tissue C:N against guideline to determine light and nutrient availability.

description	C:N ratio range	value	score	status
very good	C:N ratio >30*	30	100	80 - 100
good	C:N ratio 25-30	25	75	60 - <80
moderate	C:N ratio 20-25	20	50	40 - <60
poor	C:N ratio 15-20	15	25	20 - <40
very poor	C:N ratio <15*		0	0 - <20

**C:N ratios >35 were scored as 100, and C:N ratios <10 were scored as 0*

2 Summary of approach

Goals of the NERP program

"The NERP Tropical Ecosystems Hub will address issues of concern for the management, conservation and sustainable use of the World Heritage listed Great Barrier Reef (GBR) and its catchments, tropical rainforests including the Wet Tropics World Heritage Area (WTWHA), and the terrestrial and marine assets underpinning resilient communities in the Torres Strait, through the generation and transfer of world-class research and shared knowledge. This research will be highly relevant, influential in policy, planning and management, publicly available, and value for money."

This study is part of the NERP TE hub, Theme 2, Understanding Ecosystem Function and Cumulative pressures.

"Theme 2 builds on research undertaken through the MTSRF and other programs that have identified many of the primary risks and threats to the environmental assets of North Queensland. These pressures do not occur in isolation to each other and it is clear that a greater understanding of the cumulative and synergistic impact of these pressures is required for improved management. These pressures are not static, therefore predicting and preparing for change is a significant challenge for environmental decisions makers charged with stewardship of Queensland's natural environment. Changing climates, extreme natural events, changes in natural resource use and population growth are some of the pressures facing these ecosystems. Theme 2 is comprised of four Programs that will increase the understanding of ecosystem function and the impact of synergistic and cumulative pressures on the system. This understanding is essential in developing effective management responses that promote ecosystem resilience."

Theme 2, Program 5 Cumulative impacts on benthic biodiversity" including the Great Barrier Reef, Torres Strait and adjacent catchments (Figure 6).

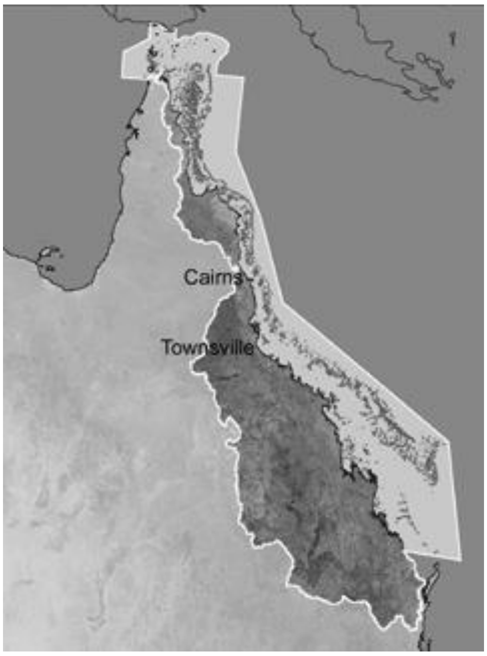


Figure 6. NERP TE program region including the Great Barrier Reef, Torres Strait and adjacent catchments.

Project 5.3 deliverables

- The level of exposure of seagrass meadows to broad scale and long-term changes in water quality associated with flood plumes in coastal regions of the GBR
- The influence of light, nutrients and salinity on seagrass condition
- Refined thresholds of concern for light, nutrients and salinity
- Indicators of seagrass condition to report on status
- Future trajectories for GBR ecosystems

We adopted a multi-tiered approach to achieving these goals (Figure 7):

1. Flood plume exposure mapping of in-situ data (a)
2. Analysis of existing in-situ light and seagras abundance data and review of the literature (b,c)
3. Original experimental research to test for the effects of salinity, light and nutrients. We experimentally tested combinations of salinity, light and nutrients with experimental combinations being dependant on: 1. previous knowledge; 2, management priorities; 3. research objectives; and, 4. logistical constraints (d, e, f, g).

Indicators of seagrass status were tested throughout this project and these indicators ranged from sub-lethal (physiological) through to population level (meadow-scale) indicators (Table 4). Abundance and growth were tested the most frequently owing to their ease of measurement and their importance in ecological functioning (e.g. as habitat, sediment stability); however in some projects changes in these indicators were not targeted. More specifically, sub-lethal indicators were the focus of two experiments (d,e) and changes in growth and abundance were not expected, and in fact were even avoided in order to capture the "sub-lethal" response phase. The flood plume mapping work was related to changes in seagrass abundance and species composition from the Reef Rescue Marine Monitoring Program (RRMMP). This report focuses on results that are most relevant for improved management of seagrass meadows of the GBR and all other results will be available through targeted scientific publications.

Table outlining project 5.3 sub-components

<table>
<tr><th></th><th>Flood plumes</th><th colspan="2">Thresholds</th><th colspan="3">Sub-lethal indicators</th><th>Total</th></tr>
<tr><td>Light</td><td rowspan="3">a. Flood plume exposure analysis

Destop analysis of In situ data</td><td>c. Light thresholds-seagrass loss* Desktop</td><td>f. light x temp (season) Experiment</td><td>b. Sub-lethal indicators-review Desktop</td><td>d. Light Experiment</td><td rowspan="2">e. Light x nutrients Experiment</td><td>6</td></tr>
<tr><td>Nutrients</td><td></td><td></td><td></td><td></td><td>2</td></tr>
<tr><td>Salinity</td><td></td><td>g. Salinity experiment</td><td></td><td></td><td></td><td>2</td></tr>
</table>

*In-situ data generated through the reef Rescue MMP, anlysis of data in this project was a desktop analysis

Figure 7. Summary of NERP project 5.3 sub-components showing breakdown among in-situ (flood plume analysis), desk-top analyses and aquarium-based experimental work.

Table 4. Summary of the indicators tested in each of the sub-components of Project 5.3

				Thresholds			Sub-lethal indicators		
Level	**Parameter grouping**	Parameter	**a. Flood plumes**	**b. Salinity**	**c. *In-situ* thresholds**	**d. Light x temperature**	e. Review	f. Light	g. Light x nutrients
Physiological (sub-lethal)	Leaf tissue nutrients	%C					🗐	🗐	🗐
		%N					🗐	🗐	🗐
		C/N					🗐	🗐	🗐
		$Del^{13}C$					🗐	🗐	🗐
	Energy reserves	Rhizome carbohydrates					🗐	🗐	🗐
	Photosynthesis	PAM				🗐	🗐	🗐	🗐
		O_2 production				🗐	🗐		🗐
Plant-scale (state change)	Growth	Leaf		🗐		🗐	🗐	🗐	🗐
		Rhizome				🗐	🗐		
	Morphology	Morphology		🗐		🗐	🗐		
	Sexual reproduction	Sexual reproduction		🗐			🗐		
Meadow-scale (population level)	Abundance	Shoot density		🗐		🗐	🗐	🗐	🗐
		Percent cover	🗐		🗐				
		Biomass		🗐		🗐	🗐	🗐	🗐
	Species composition	Species composition	🗐				🗐		

This project extends across a large proportion of the GBR south of Cooktown for the flood plume exposure analysis (a), in situ assessment of light and seagrass loss (c) was from wet tropics and Burdekin Dry Tropics sites in the northern GBR, and collection of seagrasses for experimental work (b,d,f,g) also included collections from Green Island off Cairns (Wet Tropics NRM) down to Gladstone Harbour (Fitzroy NRM), with different species occurring at each site (Table 5 Figure 8).

The remainder of this report has been structured around the objectives listed above. Additional detail on each of the components can be found in associated publications, and these are listed, where relevant.

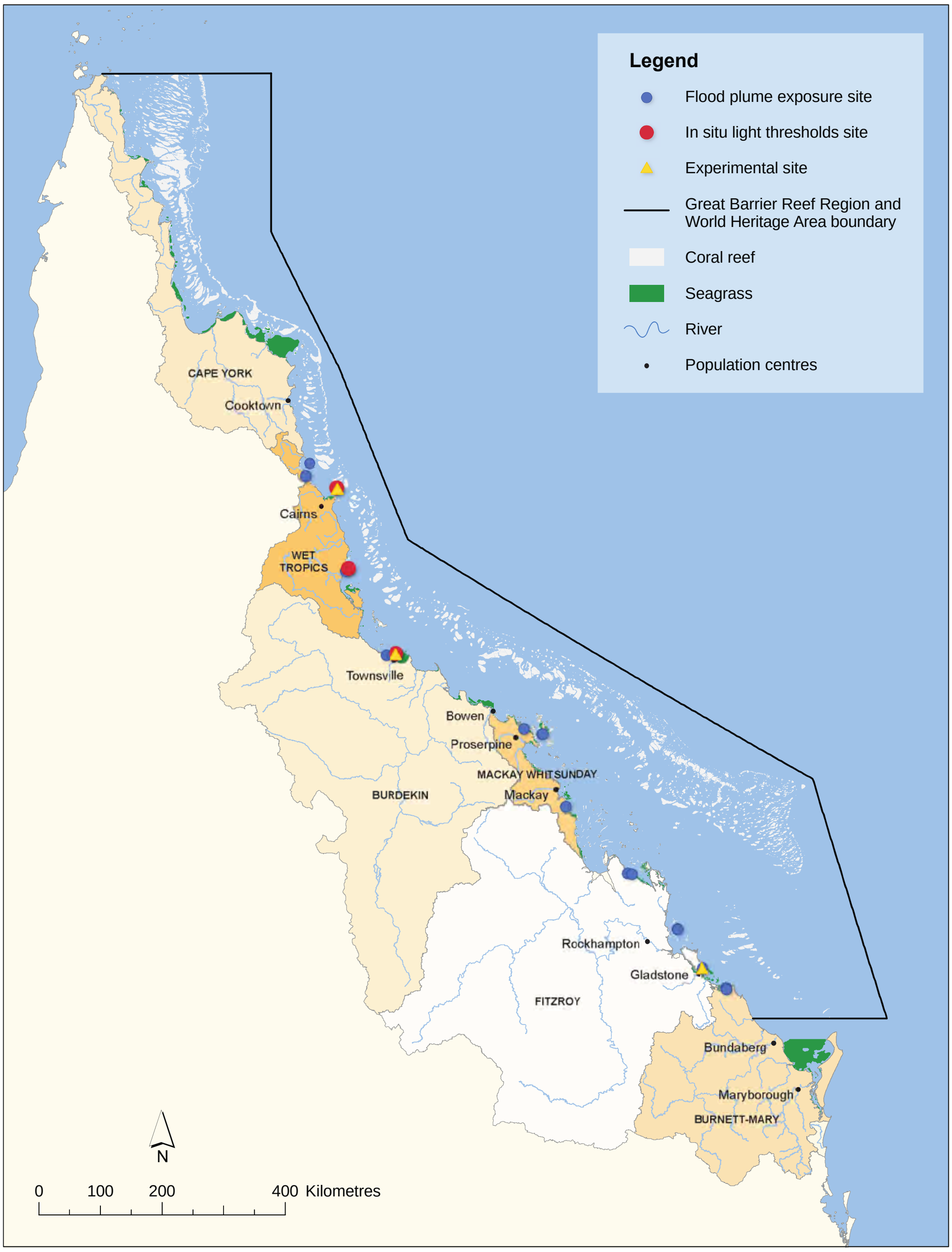


Figure 8. Map of the seagrass sampling sites referred to in this report.

Table 5. Sites referred to in this report (also see Figure 8).

NRM region (*Board*)	**Location**	**Site**		**Seagrass community type**
Wet Tropics (*Terrain NRM*)	Low Isles *reef*	LI1*	Low Isles	*H.ovalis/H.uninervis*
		LI2^	Low Isles	*H.ovalis/H.uninervis*
	Cairns *coastal*	YP1*	Yule Point	*H. uninervis* with *H. ovalis*
		YP2*	Yule Point	*H. uninervis* with *H. ovalis*
	Green Island *reef*	GI1*	Green Island	*C. rotundata/T. hemprichii* with *H. uninervis/H. ovalis*
		GI2*	Green Island	*C. rotundata/T. hemprichii* with *H. uninervis/H. ovalis*
		GI3^	Green Island	*C. rotundata/ H. uninervis/C.serrulata/S.isoetifolium*
	Mission Beach *coastal*	LB1*	Lugger Bay	*H. uninervis*
		LB2*	Lugger Bay	*H. uninervis*
	Dunk Island *reef*	DI1*	Dunk Island	*H. uninervis* with *T. hemprichii/ C. rotundata*
		DI2*	Dunk Island	*H. uninervis* with *T. hemprichii/ C. rotundata*
		DI3^	Dunk Island	*H. uninervis / H. ovalis/H.decipiens/C. serrulata*
Burdekin (*NQ Dry Tropics*)	Magnetic island *reef*	MI1*	Picnic Bay	*H. uninervis* with *H. ovalis & Zostera/T. hemprichii*
		MI2*	Cockle Bay	*C. serrulata/ H. uninervis* with *T. hemprichii/H. ovalis*
		MI3^	Picnic Bay	*H. uninervis* with *H. ovalis & Zostera/T. hemprichii*
	Townsville *coastal*	SB1*	Shelley Beach	*H. uninervis* with *H. ovalis*
		BB1*	Bushland Beach	*H. uninervis* with *H. ovalis*
Mackay Whitsunday (*Reef Catchments*)	Whitsundays *coastal*	PI2*	Pioneer Bay	*H. uninervis/ Zostera* with *H. ovalis*
		PI3*	Pioneer Bay	*H. uninervis* with *Zostera/H. ovalis*
	Whitsundays *reef*	HM1*	Hamilton Island	*H. uninervis* with *H. ovalis*
		HM2*	Hamilton Island	*Z. muelleri* with *H. ovalis/H. uninervis*
	Mackay *estuarine*	SI1*	Sarina Inlet	*Z. muelleri* with *H. ovalis (H. uninervis)*
		SI2*	Sarina Inlet	*Z. muelleri* with *H. ovalis (H. uninervis)*
Fitzroy (*Fitzroy Basin Association*)	Shoalwater Bay *coastal*	RC1*	Ross Creek	*Z. muelleri* with *H. ovalis*
		WH1*	Wheelans Hut	*Z. muelleri* with *H. ovalis*
	Keppel Islands *reef*	GK1*	Great Keppel Is.	*H. uninervis* with *H. ovalis*
		GK2*	Great Keppel Is.	*H. uninervis* with *H. ovalis*
	Gladstone Harbour *estuarine*	GH1*	Gladstone Hbr	*Z. muelleri* with *H. ovalis*
		GH2*	Gladstone Hbr	*Z. muelleri* with *H. ovalis*

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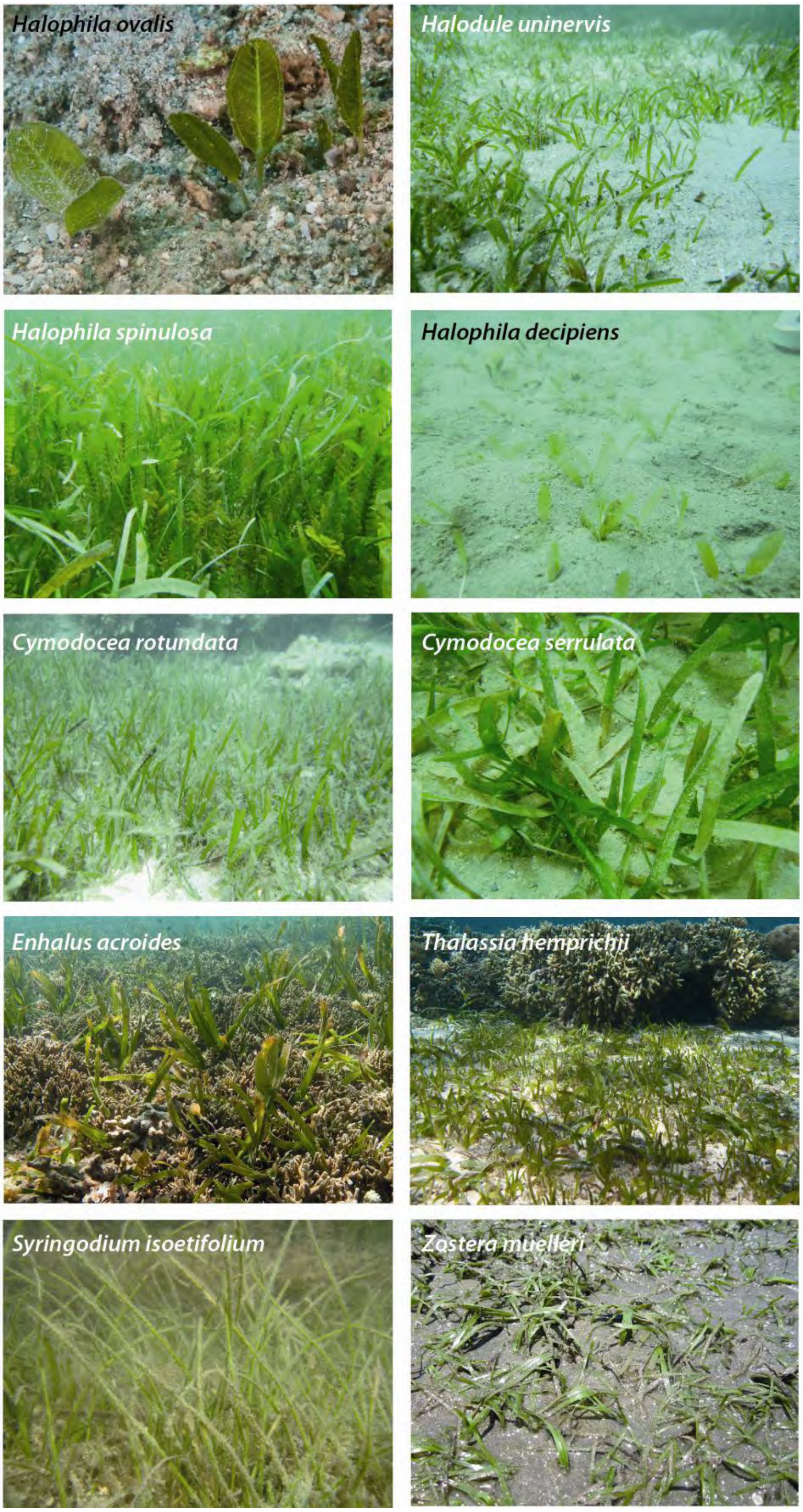

Figure 9. Species described in this report and which are common throughout the Great Barrier Reef.

3 Monitoring large scale water quality impacts on seagrass communities in the Great Barrier Reef utilising MODIS imagery and long term monitoring data

Abstract

We explored the environmental components of wet season conditions, high flow and their effects on seagrass meadow health. This included an assessment of remote sensing-derived ocean colour analysis and identified water quality thresholds associated with loss of seagrass (2007 – 2014) over annual and multi-annual ocean colour measurements derived from remote sensing. Plumes of floodwaters with high concentrations of TSS, chl-a and CDOM were detected using satellite imagery and in-situ data. Decline of seagrass was exacerbated by the consecutive above wet season flow conditions from 2008 to 2011 in the catchments of the Great Barrier Reef leading to widespread flooding. High flow condition and the extent and distribution of flood plumes can help track low salinity conditions, high nutrient concentrations (triggering blooms of phytoplankton) and both dissolved and particulate sediment that drive reductions in light. We found that seagrass meadows in coastal and estuarine regions of the GBR were exposed to flood plumes of high turbidity water for ~20% and green water for ~50% of the wet season months (Nov-April). Declines in habitat-consolidated seagrass % cover were compared with their frequency of exposure to River plume colour classes; each 6CC class being associated with different concentrations and proportion of land-sourced contaminants and light availability. The correlations between colour class, water quality and seagrass health confirmed that MODIS data can be used to explain changes in seagrass health at the seagrass habitat scale and indicated that declines in seagrass areas and biomasses over the monitored period were linked to cumulative exposure to plume waters.

Intermittent exposure to reduced water quality can result in relatively high biomass meadows but slight change in water quality can shift the balance in these seagrass communities. Large scale water quality mapping can help define the type of seagrass communities and identify the main water types which shape and drive seagrass response. Thus long term water quality data, both in-situ and through remote sensing can provide measures of risk relative to the seagrass community health, including measures of seagrass biomass, cover and species.

Introduction

Remote Sensing (RS) data combined with in situ sampling of river plumes has provided an essential source of data related to the movement and composition and frequency of river plumes and land-sourced pollutants in GBR waters (Bainbridge et al., 2012; Brodie et al., 2010; Devlin et al., 2012b; Petus et al., 2014a; Petus et al., 2014b; Schroeder et al., 2012). GBR Plume waters have been described as different river plume water masses from the coast to the offshore boundary of the plume; each being characterized by varying water quality characteristics, light availability, salinity and colours (Devlin et al., 2012b; Petus et al., 2014b). RS data identify areas which may experience acute or chronic high exposure to the river plumes water masses and thus enhance our ability to map the risk to GBR seagrasses from exposure to reduced water quality. Working on the Cleveland bay subset study area, Petus et al. (2014b) have thus shown that strong correlation existed between the changes of biomass and area of individual meadows and exposure of seagrass ecosystems to turbid plume water masses mapped through MODIS images.

Mapping seagrass meadows and associated ecological measurements through remote sensing has been challenging to investigate for both GBR and world-wide systems, due to the water quality type typically found around seagrass meadows. Many seagrass meadows are found in shallow, coastal waters, which are typically Type 2 /optically complex waters where suspended sediment and coloured dissolved organic matter co-occur with phytoplankton. The standard and global bio-optical algorithms used in clear or "oceanic" waters are mostly inaccurate when applied to these coastal waters, although regional parameterization of these algorithms can help increase their accuracies (Brando et al., 2012; Naik et al., 2013). However, utilization of remote sensing imagery provides data across large spatial and temporal scales that would not be possible with traditional in-situ monitoring. To avoid issues with the extraction of Level 2 data, such as chlorophyll and total suspended sediments, we have utilised only MODIS true color images (Level 1b products), which represent water colour as a proxy for the water quality condition.

Multi-scale (temporal and spatial) studies of seagrass species distributions is often the starting point for examining environmental drivers and interpreting responses of seagrass meadows to climate change and decreased water quality (Kendrick et al., 2008; Petus et al., 2014b). The main objective of this study was to test if relationships can be established between the frequency of exposure to river plume water masses and changes in seagrass health in the GBR at different spatial and temporal scales. We focused on a 2-year period (2005–2007) of below median rainfall followed by a five-year period (2008–2012) of above-median rainfall and flooding to test seagrass health responses to river plume exposure in the GBR. River plume water masses exposure was assessed through the satellite mapping of GBR plume colour classes; each class being associated with different concentrations and proportion of land-sourced contaminants. Seagrass health was defined in this study by the seagrass percentage cover.

Methods

The frequency and spatial extent of flood plumes is mainly driven by the size and intensity of flow (Devlin et al., 2012b). Flow data was sourced from the Department of Environment and Resource Management (Queensland, http://watermonitoring.derm.qld.gov.au/host.htm). River discharge data from 1975 to 2011 were obtained for the rivers that have the greatest influence over the study sites (Devlin et al., 2013).

Flow is calculated as an annual median for the whole GBR. Timing of sampling against total river flow is described, taking into account; all 35 rivers distributed throughout the GBR and also for Tully and Fitzroy rivers, separately. Two descriptive statistics derived from daily river flow data were used to describe the river flow regimes considering all 35 together: (i) the total annual flow into the GBR lagoon, and (ii) the long-term annual median flow calculated for the period 1970 to 2001.

Satellite mapping of GBR river plumes

Three distinct plume water types have been described within GBR river plumes (from the inshore to the offshore boundary of river plumes) characterized by varying salinity levels, colour, spectral properties and WQ concentrations (Table 6). Flood plumes were mapped in this work using the method presented in Álvarez-Romero et al. (2013). In this method, daily MODIS Level-0 data acquired from the NASA Ocean Colour website (http://oceancolour.gsfc.nasa.gov) are converted into true colour images with a spatial resolution of about 500×500 m using SeaWiFS Data Analysis System (SeaDAS; Baith et al., 2001). True colour images are then spectrally enhanced (from RGB to HSI colour system) and classified into six river plume colour classes (CC1 to CC6) corresponding to six distinct inshore-to-offshore plume water masses through a supervised classification using spectral signature from river plume waters in the GBR.

Numerous recent studies used the method presented in Álvarez-Romero et al. (2013) to describe GBR plume waters and ecosystems exposure to land sourced pollutants (e.g., Devlin et al., 2013; Petus et al., 2014b). All were based on GBR river plume colour classes reclassified into 3 plume