

JCU ePrints

This file is part of the following reference:

**Cooper, Timothy F. (2008) *Coral bioindicators of environmental conditions on coastal coral reefs.*
PhD thesis, James Cook University.**

Access to this file is available from:

<http://eprints.jcu.edu.au/8170>

Coral bioindicators of environmental conditions on coastal coral reefs

Thesis submitted by
Timothy Fraser COOPER B.Sc. (Hons) JCU
in June 2008

for the degree of Doctor of Philosophy
in the School of Marine and Tropical Biology
James Cook University

STATEMENT OF ACCESS

I, the undersigned author of this work, understand that James Cook University will make this thesis available for use within the University Library and, via the Australian Digital Theses network, for use elsewhere.

I understand that, as an unpublished work, a thesis has significant protection under the Copyright Act and;

I do not wish to place any further restriction on access to this work

Signature

Date

ELECTRONIC COPY

I, the undersigned, the author of this work, declare that the electronic copy of this thesis provided to the James Cook University Library, is an accurate copy of the print thesis submitted, within the limits of the technology available.

Signature

Date

STATEMENT ON SOURCES

Declaration

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

.....
(Signature)

.....
(Date)

STATEMENT ON THE CONTRIBUTION OF OTHERS

Chapter 2 is included without abstract and published as Cooper TF, Uthicke S, Humphrey C, Fabricius KE. (2007). Gradients in water column nutrients, sediment parameters, irradiance and coral reef development in the Whitsunday Islands, central Great Barrier Reef. *Estuarine, Coastal and Shelf Science* 74: 458-470. The data was collected by all authors during field work undertaken over a 2-year period from 2004 to 2006. S Uthicke collected, processed and wrote the sediment sections. TF Cooper compiled and analysed the water quality and irradiance data, and wrote the manuscript. The manuscript (and this chapter) was submitted after editorial contributions from all co-authors.

Chapter 3 is included without abstract as Cooper TF, Ulstrup KE. (in review). Mesoscale variation in the photo-physiology of a coastal coral on the Great Barrier Reef. *Marine Biology*. TF Cooper collected and analysed the data, and wrote the manuscript. KE Ulstrup processed the data and derived parameters from the rapid light curves. The manuscript (and this chapter) was submitted after editorial contributions from the co-author.

Chapter 4 is included without abstract as Cooper TF, Slivkoff M. (in prep). Relationship among coral reflectance, chlorophyll *a* concentration and perceived brightness of scleractinian corals. TF Cooper collected and analysed the data, and wrote the manuscript. M Slivkoff processed the spectral reflectance data. TF Cooper and M Slivkoff designed and built the reflectance chamber. The manuscript (and this chapter) has been prepared after editorial contributions from the co-author.

Chapter 6 is included without abstract and published as Cooper TF, Ridd PV, Ulstrup KE, Humphrey C, Slivkoff M, Fabricius KE. (2008). Temporal dynamics in coral bioindicators for water quality on coastal coral reefs of the Great Barrier Reef. *Marine and Freshwater Research* 59: 703-716. TF Cooper collected and analysed the data. PV Ridd and C Humphrey assisted with logger deployment and processing of physical and water quality samples. KE Ulstrup assisted with processing of coral samples and M Slivkoff processed the satellite image. The manuscript (and this chapter) was submitted after editorial contributions from all co-authors.

Chapter 7 is included without abstract and published as Cooper TF, De'ath G, Fabricius KE, Lough JM. (2008). Declining coral calcification in massive *Porites* in two nearshore regions of the northern Great Barrier Reef. *Global Change Biology* 14: 529-538. The samples were collected by TF Cooper and KE Fabricius. TF Cooper processed the coral slices and wrote the manuscript. JM Lough supervised sample processing and extracted the growth variables from the coral slices. The statistical analyses were done by G De'ath. The manuscript (and this chapter) was submitted after editorial contributions from all co-authors.

Acknowledgments

This study was supported by funding from the Australian Institute of Marine Science (AIMS), the Cooperative Research Centre (CRC) for Coral Reefs and CRC Rainforest to the Catchment to Reef Program, and the Reef and Rainforest Research Centre through the Marine and Tropical Sciences Research Facility.

I am grateful to my supervisor Dr Katharina Fabricius for providing the opportunity to undertake this research and for the invaluable guidance and support that made this study possible. I am also grateful for the stimulating discussions with Dr Glenn De'ath that shaped the statistical techniques used in this study. I thank Prof. Michael Kingsford and Dr Ken Anthony at James Cook University (JCU) for advice on various aspects of the study. I was fortunate to work alongside many highly regarded scientists at AIMS and I thank Dr David Barnes, Dr Terry Done, Dr Janice Lough and Dr Eric Wolanski for giving of their time and ideas.

In the Water Quality and Ecosystem Health Team, I thank Craig Humphrey, Dr Anke Klüter, Dr Britta Schaffelke and Dr Sven Uthicke who made my time at AIMS both enjoyable and productive. I thank Dr Peter Ridd at JCU who provided the light and turbidity loggers used in this project. At the CRC Reef, I was grateful for the support of Dr David Williams and Tim Harvey.

For assistance with laboratory techniques, field work and cycling (or combinations thereof), I would like to thank Lewis Anderson, Dr Ray Berkelmans, Stephen Boyle, Neal Cantin, Deborah Frietas, Dr Miles Furnas, Joe Goiffre, Tim Hyndes, Niall Jeeves, Alison Jones, Nadine Koch, the staff and guests of Long Island, Eric Matson, Katharina McGuire, Tony McKenna, Dr David McKinnon, Dr Andrew Negri, Eyvone Sawall, Melanie Shaw, Christopher Shelbourn, Michele Skuza, Matt Slivkoff, Dr Adam Smith, Paola Spicker, Danika Tager, Damian Thomson, Lindsay Trott, Jake van Oosterom, Dr Madeleine van Oppen, Miriam Weber, Margaret Wright and Tracie Wright. Thanks to the crew of the *RV Lady Basten* for logistical support, engineering wisdom and great food in the field.

Thanks to Dr Marcus Lincoln Smith for mentoring me through my early years in science and for continued personal support and encouragement to pursue a PhD. A special thanks to Karin Ulstrup whose constructive comments and encouragement improved the content of this thesis. Finally, I acknowledge the support provided by friends and family over the past few years, in particular Truda Cooper, whose strength in adversity was a source of inspiration throughout this project. This work is dedicated to my grandparents who were instrumental in developing my interest of the ocean.

Publications

Peer-reviewed journal articles associated with this thesis

Cooper TF, Ulstrup KE. (in review). Mesoscale variation in the photo-physiology of a coastal coral on the Great Barrier Reef. *Marine Biology*.

Cooper TF, Ridd PV, Ulstrup KE, Humphrey C, Slivkoff M, Fabricius KE. (2008). Temporal dynamics in coral bioindicators for water quality on coastal coral reefs of the Great Barrier Reef. *Marine and Freshwater Research* 59: 703-716

Cooper TF, De'ath G, Fabricius KE, Lough JM. (2008). Declining coral calcification in massive *Porites* in two nearshore regions of the northern Great Barrier Reef. *Global Change Biology* 14: 529-538

Cooper TF, Uthicke S, Humphrey C, Fabricius KE. (2007). Gradients in water column nutrients, sediment parameters, irradiance and coral reef development in the Whitsunday Islands, central Great Barrier Reef. *Estuarine, Coastal and Shelf Science* 74: 458-470

Peer-reviewed journal articles relevant but not associated with this thesis

Humphrey C, Weber M, Lott C, **Cooper TF**, Fabricius KE. (2008). Effects of different types of sediment, dissolved inorganic nutrients and salinity on fertilisation and embryo development in the coral *Acropora millepora* (Ehrenberg, 1834). *Coral Reefs* doi 10.1007/s00338-008-0408-1

Wolanski E, Fabricius KE, **Cooper TF**, Humphrey C. (2008). Wet season fine sediment dynamics on the inner shelf of the Great Barrier Reef. *Estuarine, Coastal and Shelf Science* 77: 755-762

Fabricius KE, De'ath G, Puotinen ML, Done TJ, **Cooper TF**, Burgess, SC. (2008). Disturbance gradients on inshore and offshore coral reefs caused by a severe tropical cyclone. *Limnology and Oceanography* 53: 690-704

Conference abstracts

Cooper TF, Slivkoff M, Fabricius KE. (2006). Coral colour responds to changes in water quality: validation of a bioindicator using reflectance spectrometry. International Society for Reef Studies: European Meeting, 19 – 22 September 2006, Bremen, Germany.

Conference abstracts contd.

Cooper TF, Slivkoff M, Fabricius KE. (2006). Coral colour responds to changes in water quality: validation of a bioindicator using reflectance spectrometry. Australian Marine Sciences Association, 9 – 13 July 2006, Cairns, Australia. *Ron Kenny Prize for Highly Commended student oral presentation.*

Cooper TF, Fabricius KE, Humphrey C, Neale S. (2005). Coral based indicators of the effects of water quality on nearshore reefs of the Great Barrier Reef. Rainforest meets Reef: Joint conference of CRC Reef and Rainforest CRC, 22 – 24 November 2005, Townsville, Australia.

“I thought of that while riding my bicycle”

— Albert Einstein, on the theory of relativity.

CONTENTS

Contents	i
List of Tables	iv
List of Figures	vi
Abstract	x
Chapter 1.0 General introduction, review of literature and thesis outline	1
1.1 General Introduction	2
1.2 Review of literature	3
1.2.1 Effects of water quality on corals	3
1.2.1.1 Nutrient availability	3
1.2.1.2 Sedimentation	4
1.2.1.3 Turbidity and light attenuation	5
1.2.2 Characteristics of suitable indicators	5
1.2.3 Indicators and indices in other aquatic ecosystems	11
1.2.4 Indicators of the condition of coastal coral reefs	12
1.2.4.1 Colony indicators	12
1.2.4.2 Population indicators	16
1.2.4.3 Community indicators	18
1.3 Thesis outline	21
Chapter 2.0 Gradients in water column nutrients, sediment parameters, irradiance and coral reef development in the Whitsunday Islands, central Great Barrier Reef	27
2.1 Introduction	28
2.2 Materials and methods	29
2.2.1 Study area	29
2.2.2 Water column	30
2.2.3 Sediments	31
2.2.4 Irradiance	32
2.2.5 Maximum depth of coral reef development	33
2.2.6 Statistical analysis	33
2.3 Results	35
2.3.1 Water column	35
2.3.2 Sediments	41
2.3.3 Irradiance	42
2.3.4 Maximum depth of coral reef development	43
2.4 Discussion	48
2.4.1 Water column	48
2.4.2 Sediments	49
2.4.3 Irradiance	50
2.4.4 Maximum depth of coral reef development	50

Chapter 3.0	Spatial variation in the photo-physiology of a coastal coral along an environmental gradient of the Great Barrier Reef	53
3.1	Introduction	54
3.2	Materials and methods	56
3.2.1	Study area and sampling design	56
3.2.2	Environmental gradient	57
3.2.3	Relative PAR-absorptivity	57
3.2.4	Minimum fluorescence and maximum quantum yield	58
3.2.5	Rapid light curves	58
3.2.6	Relative non-photochemical quenching and relative excitation pressure	59
3.2.7	Statistical analyses	60
3.3	Results	61
3.3.1	Environmental gradient	61
3.3.2	Relative PAR-absorptivity	61
3.3.3	Minimum fluorescence and maximum quantum yield	62
3.3.4	Rapid light curves	63
3.3.5	Relative non-photochemical quenching and relative excitation pressure	64
3.4	Discussion	70
3.4.1	Relative PAR-absorptivity	70
3.4.2	Minimum fluorescence and maximum quantum yield	72
3.4.3	Rapid light curves	72
3.4.4	Relative non-photochemical quenching and relative excitation pressure	73
Chapter 4.0	Relationship among coral reflectance, chlorophyll <i>a</i> concentration and perceived brightness of scleractinian corals	75
4.1	Introduction	76
4.2	Materials and methods	77
4.2.1	Reflectance measurements	78
4.2.2	Determination of chlorophyll <i>a</i>	80
4.2.3	Statistical analyses	80
4.3	Results	80
4.4	Discussion	86
Chapter 5.0	Spatial variation of coral bioindicators along an environmental gradient of the Great Barrier Reef	90
5.1	Introduction	91
5.2	Materials and methods	92
5.2.1	Field study area and sampling design	92
5.2.2	Laboratory experiments	93
5.2.3	Field manipulative experiment	94
5.2.4	Physiological analyses	96
5.2.5	Statistical analyses	96
5.3	Results	97
5.3.1	Field study	97
5.3.2	Laboratory experiments	99
5.3.2.1	Experiment 1	100
5.3.2.2	Experiment 2	102

5.3.3	Field manipulative experiment	107
5.4	Discussion	111
Chapter 6.0	Temporal dynamics in coral bioindicators for water quality on a coastal coral reef of the Great Barrier Reef	116
6.1	Introduction	117
6.2	Materials and methods	118
6.2.1	Study area and sampling design	118
6.2.2	Weather data	119
6.2.3	Turbidity and benthic irradiance	120
6.2.4	Water column nutrients	121
6.2.5	Coral indicators	122
6.2.6	Statistical analyses	122
6.3	Results	123
6.3.1	Weather data	123
6.3.2	Turbidity and benthic irradiance	128
6.3.3	Water column nutrients	130
6.3.4	Coral indicators	137
6.4	Discussion	150
Chapter 7.0	Declining coral calcification in massive <i>Porites</i> in two nearshore regions of the northern Great Barrier Reef	154
7.1	Introduction	155
7.2	Materials and methods	156
7.2.1	Study area and sampling design	156
7.2.2	Sclerochronology	156
7.2.3	Sea surface temperature	157
7.2.4	Statistical analyses	158
7.3	Results	159
7.4	Discussion	163
Chapter 8.0	General discussion, conclusions and future research	167
8.1	Selecting candidate coral indicators	168
8.1.1	Symbiont photo-physiology	173
8.1.2	Colony brightness of massive <i>Porites</i>	173
8.1.3	Skeletal and tissue growth of massive <i>Porites</i>	174
8.1.4	Density of macro-bioeroders in living <i>Porites</i>	175
8.1.5	Maximum depth of coral reef development	176
8.2	Conclusions	176
8.3	Future research	180
References		182

LIST OF TABLES

Table 1.1. Summary of criteria for selection of indicators to assess effects of stressors on corals and coral communities. Modified from Jones and Kaly (1996), Erdmann and Caldwell (1997) and Jameson et al. (1998).	8
Table 1.2. Examples of studies examining colony, population and/or community variables on coral reefs and reported responses to various stressors.	23
Table 2.1. Summary of mean water column, sediment and irradiance parameters (\pm standard error) at each of the 12 study locations in the Whitsunday Islands. Data for each location are averaged over sampling events from August 2004 to February 2006.	36
Table 2.2. Summary of analyses comparing water column, sediment and irradiance parameters with distance from the coast and among times of sampling. Data are \log_2 transformed, * denotes terms that were eliminated at $P > 0.25$.	38
Table 2.3. Total daily irradiance ($\text{mol photons m}^{-2}$) calculated from Odyssey PAR loggers deployed at 3 m and 6 m depth at three locations (Lindeman, Long and Deloraine Islands) on two occasions in the Whitsunday Islands. Data for Hardy Reef are for surface irradiance, supplied from the AIMS weather station (http://www.aims.gov.au/pages/facilities/weather-stations/weather-index.html). Numbers in parentheses are % of surface irradiance at Hardy Reef. Mean \pm standard error.	44
Table 2.4. Pearson correlations between maximal depth coral reef development and environmental variables averaged for each time of sampling in the Whitsunday Islands. Abbreviations: Max depth = maximum depth of reef development; Chl <i>a</i> = chlorophyll <i>a</i> , PN = particulate nitrogen, PP = particulate phosphorus, POC = particulate organic carbon, TSS = total suspended solids, DIN = dissolved inorganic nitrogen, DIP = dissolved inorganic phosphorus, DON = dissolved organic nitrogen, DOP = dissolved organic phosphorus, OD = optical depth, Sed value = Munsell colour value, Sed org C = sediment organic carbon, Sed pha = sediment phaeophytin, Sed inorg C = sediment inorganic carbon, Fine grains = %grains $< 63 \mu\text{m}$. Bold: $P < 0.05$.	45
Table 2.5. Estimates of light attenuation coefficients and percent of surface irradiance resulting in light limitation of zooxanthellate corals on reefs in the Whitsunday Islands. K_d (PAR) averaged over three times of sampling. Data are presented as means \pm standard error (SE). Maximal depth of coral reef development is presented as depth below lowest astronomical tide. E_z derived from Equation 1.	47
Table 3.1. Summary of mean photo-physiological variables (\pm standard error, $n=6$) of <i>Pocillopora damicornis</i> at each of the 7 study locations in the Whitsunday Islands, January 2007.	67
Table 3.2. Summary of two factor ANOVAs comparing photo-physiological variables of <i>Pocillopora damicornis</i> among reefs and between depths in the Whitsunday Islands. For <i>post hoc</i> tests, results are presented in ascending order. Abbreviations: R = Repulse Island; L = Lindeman Island; Lo = Long Island; D = Dent Island; Hs = Haslewood Island; H = Hook Island; DI = Deloraine Island.	68
Table 3.3. Summary of linear models testing relationships between photo-physiological variables of <i>Pocillopora damicornis</i> and the water quality index.	69
Table 4.1. Summary of linear models testing relationships between (a) coral reflectance % ($R_{675 \text{ nm}}$) and (b) concentrations of chlorophyll <i>a</i> (\log_2 transformed, $\mu\text{g cm}^{-2}$), with the colour chart for all species.	82
Table 4.2. Summary of analyses comparing the influence of shadows due to coral morphology produced by differing illumination angles on coral reflectance.	84

Table 4.3. Summary of linear models testing relationships between coral reflectance % ($R_{675\text{ nm}}$) and concentrations of chlorophyll a ($\mu\text{g cm}^{-2}$) among different coral species.	84
Table 4.4. Summary of analyses comparing (a) homogeneity of slopes and (b) differences among intercepts of the relationship between coral reflectance % ($R_{675\text{ nm}}$) and concentrations of chlorophyll a (\log_2 transformed, $\mu\text{g cm}^{-2}$) among different coral species.	85
Table 5.1. Summary of experimental treatments used to test hypotheses about the effects of water quality on colony brightness.	94
Table 5.2. Summary of linear models comparing indicators in (a–d) <i>Pocillopora damicornis</i> and (e–i) massive <i>Porites</i> with the Water Quality Index between two depths (shallow and deep) in the Whitsunday Islands.	98
Table 5.3. Summary of ANOVAs comparing colony parameters in <i>Porites lobata</i> nubbins after 56 d exposure to different treatments of nutrients and irradiance (Tank Experiment 1). * denotes term eliminated at $P > 0.25$. For <i>post hoc</i> tests, means (\pm SE) are untransformed and in ascending order. Underlined terms were not significantly different from each other. Abbreviations: FSW = filtered seawater, SPM = suspended particulate matter.	104
Table 5.4. Summary of ANOVAs comparing concentrations of chlorophyll a and spectral reflectance among experimental treatments for coral nubbins transplanted along an environmental gradient in the Whitsunday Islands. Inner nubbins refers to nubbins sourced from the nearshore islands (Long and Lindeman Islands); outer nubbins refers to nubbins sourced from the outer islands (Deloraine and Edward Islands) of the Whitsunday Islands.	109
Table 6.1. Summary of four factor ANOVAs comparing water quality variables between years and seasons, and among locations on the GBR. * denotes terms that were eliminated at $P > 0.25$. For <i>post hoc</i> tests, means (\pm SE) are untransformed and in ascending order. Underlined means were not significantly different from each other. Abbreviations: HB = Horseshoe Bay; DR = Davies Reef; BR = Broadhurst Reef.	132
Table 6.2. Summary of four factor ANOVAs comparing physiological variables of (a – e) <i>Pocillopora damicornis</i> and (f – g) massive <i>Porites</i> between years and seasons, and among locations on the GBR. * denotes terms that were eliminated at $P > 0.25$.	139
Table 6.3. Summary of <i>post hoc</i> tests of physiological variables of <i>Pocillopora damicornis</i> and massive <i>Porites</i> between years and seasons and among locations on the GBR. Means (\pm SE) are untransformed and in ascending order. Underlined terms were not significantly different from each other. Abbreviations: HB = Horseshoe Bay, DR = Davies Reef, BR = Broadhurst Reef.	141
Table 6.4. Summary of analyses for model selection to examine the relationship between physiological measures of <i>P. damicornis</i> (a – e) and massive <i>Porites</i> (f – g) with physical variables (predictors). Predictors selected by dropping terms from the full model based on calculation of Akaike Information Criterion (AIC). Data for sea surface temperature (SST), benthic irradiance and turbidity averaged over the 14 d period preceding the site visit.	145
Table 6.5. Summary of ANOVAs comparing physiological measures of <i>P. damicornis</i> (a – e) and massive <i>Porites</i> (f – g) among locations and with environmental variables.	146
Table 7.1. The numbers of colonies observed by (a) year and (b) reef shows the imbalance in the data due to fewer colonies having bands in earlier years.	159
Table 7.2. Cross-validated estimates of smoothness (degrees of freedom) of trends in years and sea surface temperature for skeletal density, annual extension and calcification. Estimates were based on linear mixed effects models.	159
Table 8.1. Assessment framework for identifying indicators of the effects of changes in water quality on coastal corals of the GBR. Indicators are assessed against the criteria defined in Chapter 1.2.2. Rank denotes the sum of positive scores when assessed against each criterion and determines the level of recommendation. Abbreviations: Med. = Medium; Rec. = Recommendation.	169

LIST OF FIGURES

- Fig. 1.1. Response of a hypothetical indicator to a disturbance (dark grey areas represent the disturbance in question; light grey areas represent other disturbances). A suitable indicator must detect differences between a disturbed state (solid line) and reference states (dashed lines). The situations described in a), b) c) and d) would be appropriate for inclusion into a monitoring program. 10
- Fig. 2.1. (a) Satellite image (Landsat 5 TM) of the Whitsunday Islands showing a flood plume emerging from the Proserpine and O'Connell Rivers, 28th January 2005. Areas of elevated suspended solids are visible near the mouths of the rivers, with areas of increased phytoplankton abundance indicative of nutrient enrichment that extend through the islands. Red circles indicate some of the sampling locations; (b) Map of study locations in the Whitsunday Islands of the Great Barrier Reef, Australia. Dashed area represents area shown in Fig. 1a. Image courtesy K. Rohde (Department of Natural Resources and Water, Queensland Government). 34
- Fig. 2.2. Summary of the relationships between each of the water column, sediment and irradiance variables and nearest distance from the coast. Samples collected from five sampling events between August 2004 and August 2006. Response variables are \log_2 transformed, except for the Water Quality Index. Abbreviations: TSS = total suspended solids, PN = particulate nitrogen, PP = particulate phosphorus, POC = particulate organic carbon, DIN = dissolved inorganic nitrogen, DIP = dissolved inorganic phosphorus, DON = dissolved organic nitrogen, DOP = dissolved organic phosphorus, Pha = phaeophytin. Water Quality Index (WQI) refers to the sum of z-scores calculated from z transformation of each of the water column and irradiance variables. Symbols represent each time of sampling: \square August 2004; \circ August 2005; $+$ January 2006; \times February 2006; \bullet August 2006. 39
- Fig. 2.3. Principal components analysis of water column and irradiance variables sampled at the Whitsunday Islands for all sampling events. *Chl a*=chlorophyll *a*, *Pha* = Phaeophytin, *TSS* = total suspended solids, *PN* = particulate nitrogen, *PP* = particulate phosphorus, *POC* = particulate organic carbon, *DIN* = dissolved inorganic nitrogen, *DIP* = dissolved inorganic phosphorus, *DON* = dissolved organic nitrogen, *DOP* = dissolved organic phosphorus, *Si* = silicate, *Secchi* = Secchi depth, *OD* = optical depth. WQ Index refers to the index calculated for the water quality variables. Distance to coast is determined as nearest distance to the Australian mainland. The latter two parameters, indicated by dashed lines, are superimposed on the biplot. 40
- Fig. 2.4. Principal components analysis of sediment variables at the Whitsunday Islands. *Chl a* = chlorophyll *a*, *Pha* = phaeophytin, *N* = nitrogen, *IC* = inorganic carbon, *OC* = organic carbon, *Sed value* = Munsell colour value, *Grain* = average grain size, *fine grains* = sediments < 63 μm . WQ Index refers to the index calculated for the water quality variables. Distance from coast is determined as nearest distance from the Australian mainland. The latter two parameters are indicated by dashed lines. 42
- Fig. 2.5. Relationship between maximal depth of coral reef development and the water quality index for the Whitsunday Islands. Dashed lines are ± 1 standard error (SE). 46
- Fig. 3.1. Map of study locations in the Whitsunday Islands, Great Barrier Reef. 60
- Fig. 3.2. Relationship between relative PAR-absorptivity of *Pocillopora damicornis* and the water quality index (WQI), where \square = shallow depth (3 m) and \bullet = deep depth (6 m). The WQI is determined by the sum of z-scores calculated from thirteen irradiance and water column nutrient variables collected between August 2004 and January 2007. A low WQI indicates high irradiance, low nutrient conditions whereas a high WQI indicates low irradiance, nutrient-enriched conditions. Arrow indicates direction of change along the environmental gradient from turbid nearshore to clear-water outer locations. Linear regression ± 1 standard error (dashed lines). 62

Fig. 3.3. Relationship between (a) minimum fluorescence (F_0) and (b) maximum quantum yield (F_v/F_m), respectively, of *Pocillopora damicornis* and the water quality index (WQI) derived for the Whitsunday Islands. \square = shallow depth (3 m), \bullet = deep depth (6 m). Linear regression \pm 1 standard error (dashed lines). 63

Fig. 3.4. Relationship between (a) maximum apparent photosynthetic rate (PS_{max}), (b) light utilisation coefficient (α) and (c) minimum saturating irradiance (E_k), respectively, of *Pocillopora damicornis* and the water quality index (WQI) derived for the Whitsunday Islands. \square = shallow depth (3 m), \bullet = deep depth (6 m). Linear regression \pm 1 standard error (dashed lines). 65

Fig. 3.5. Relationship between (a) relative non-photochemical quenching ($rNPQ_{241}$) and relative excitation pressure over PSII (rQ_{241}), respectively, of *Pocillopora damicornis* and the water quality index (WQI) derived for the Whitsunday Islands. \square = shallow depth (3 m), \bullet = deep depth (6 m). Linear regression \pm 1 standard error (dashed lines). 66

Fig. 3.6. Relative PAR-absorptivity images of *Pocillopora damicornis* collected at shallow (3 m) and deep (6 m) at seven locations along the environmental gradient. Arrow indicates direction of change along the environmental gradient from turbid nearshore (high WQI) to clear-water outer locations (low WQI). 71

Fig. 4.1. Diagrammatic representation of the coral reflectance measuring chamber. A piece of coral is placed on an adjustable platform and positioned near the detector. A fibre optic cable connects to an Ocean Optics USB 2000 spectrometer, which is connected to a computer. 79

Fig. 4.2. Relationship between (a) coral reflectance % ($R_{675\text{ nm}}$) and (b) the concentration of chlorophyll *a* (\log_2 transformed, $\mu\text{g cm}^{-2}$), and the colour chart for *Acropora millepora* (black Δ), *Pocillopora damicornis* (red +), *Stylophora pistillata* (blue \circ), *Turbinaria reniformis* (grey \square) and *Porites lobata* (brown ∇). 83

Fig. 4.3. Relationship between coral reflectance % ($R_{675\text{ nm}}$) and concentrations of chlorophyll *a* (\log_2 transformed, $\mu\text{g cm}^{-2}$). Symbols: *Acropora millepora* (black Δ), *Pocillopora damicornis* (red +), *Stylophora pistillata* (blue \circ), *Turbinaria reniformis* (grey \square) and *Porites lobata* (brown ∇). 85

Fig. 5.1. Map of study locations to examine spatial variation of colony indicators of *Pocillopora damicornis* and massive *Porites* in the Whitsunday Islands. Manipulative experiment involved transplanting small nubbins of *Porites* among Long and Lindeman Islands (inner), and Deloraine and Edward Islands (outer). 95

Fig. 5.2. Relationships between indicators in (a–d) *Pocillopora damicornis*, (e–i) massive *Porites* spp. between shallow (\square) and deep (\bullet) with a water quality index (WQI) for the Whitsunday Islands. Dashed lines \pm standard error (SE). WQI derived from five surveys between August 2004 and August 2006; large positive numbers correspond to elevated water column nutrients and low irradiance on nearshore reefs, negative numbers correspond to low water column nutrients and high irradiance on outer islands and mid-shelf reefs. 99

Fig. 5.3. Mean concentration (\pm SE) of water column parameters in Experiment 1 to examine response of *Porites lobata* nubbins exposed to suspended particulate matter (values averaged over 56 d). (a – d) dissolved nutrients ($n=20$) and (e – f) particulate nutrients and suspended solids ($n=40$). Treatments: FSW = filtered seawater (white bars) and SPM = suspended particulate matter (grey bars). * denotes statistical significance at $P < 0.05$. Abbreviations: DIN, dissolved inorganic nitrogen; DIP, dissolved inorganic phosphorus; DON, dissolved organic nitrogen; DOP, dissolved organic phosphorus; PN, particulate nitrogen; PP, particulate phosphorus; POC, particulate organic carbon; TSS, total suspended solids. 101

Fig. 5.4. Time series of mean concentration (\pm SE, $n=8$) of water column parameters in Experiment 2 to examine response of *Porites lobata* nubbins exposed to suspended particulate matter. Treatments: FSW = filtered seawater (grey lines) and SPM = suspended particulate matter (black lines). Abbreviations: DIN, dissolved inorganic nitrogen; DIP, dissolved inorganic

- phosphorus; PN, particulate nitrogen; PP, particulate phosphorus; POC, particulate organic carbon, TSS, total suspended solids. 103
- Fig. 5.5. (a) Tank Experiment 1: Response of mean coral brightness (\pm SE, $n=12$) of *Porites lobata* nubbins exposed to different treatments of SPM and irradiance. (b) Tank Experiment 2: Recovery of colony brightness (\pm SE, $n=12$) of *Porites lobata* nubbins following exposure to different treatments of nutrient and SPM. Symbols: circles = filtered seawater; squares = SPM; open symbols = unshaded; dark symbols = shaded. 105
- Fig. 5.6. Mean values (\pm SE, $n=12$) of (a) tissue thickness, (b) concentration of chlorophyll *a* and (c) density of symbionts in *Porites lobata* nubbins exposed to different treatments of SPM and irradiance (Tank Experiment 1). FSW = filtered seawater; SPM = suspended particulate matter. Symbols: black bars = shaded; white bars = unshaded; grey bars = unshaded + SPM. * denotes statistical significance at $P < 0.05$. 106
- Fig. 5.7. Mean brightness of colour (\pm SE) of coral nubbins sourced from (a) inner zone, and (b) outer zone, and transplanted along an environmental gradient in the Whitsunday Islands. Colour brightness measured with a Coral Health Monitoring Chart (Siebeck et al. 2006). Symbols: ● undisturbed; ○ cored; ▲ moved; □ translocated deep to shallow; ■ translocated shallow to deep; △ translocated reef; ✕ transplant inner to outer/outer to inner; ◆ transplant inner shallow to outer deep/outer shallow to inner deep; ◇ transplant inner deep to outer shallow/outer deep to inner shallow. 108
- Fig. 5.8. Mean concentration of chlorophyll *a* ($\mu\text{g cm}^{-2}$, \pm SE) for coral nubbins sourced from (a) inner zone, and (b) outer zone, and transplanted along an environmental gradient in the Whitsunday Islands. Abbreviations: DS = deep to shallow; SD = shallow to deep; IO = inner to outer; OI = outer to inner; transplant treatments are combinations of these. * denotes statistical significance at $P < 0.05$. 110
- Fig. 5.9. Mean reflectance (\pm SE) of coral nubbins sourced from (a) inner zone, and (b) outer zone, and transplanted along an environmental gradient in the Whitsunday Islands. Abbreviations: DS = deep to shallow; SD = shallow to deep; IO = inner to outer; OI = outer to inner; transplant treatments are combinations of these. * denotes statistical significance at $P < 0.05$. 111
- Fig. 6.1. Map of study locations at Horseshoe Bay on Magnetic Island (coastal) and Davies and Broadhurst Reefs (mid-shelf). ✕ AIMS weather station in Cleveland Bay. 120
- Fig. 6.2. MODIS-aqua satellite image of a flood event on the Great Barrier Reef taken 10th February 2007. Red line shows study area in Fig. 1, red dots indicate study locations. Image downloaded from Ocean Colour Web (Feldman and McClain 2007) and processed by SeaDAS (Baith et al. 2001). Image courtesy M Slivkoff. 125
- Fig. 6.3. Sea surface temperature ($^{\circ}\text{C}$, solid line) and monthly mean ($28 \text{ d} \pm$ SE) total daily irradiance ($\text{mol photons m}^{-2} \text{ d}^{-1}$) at the surface (○) recorded by an automated weather station, and benthic irradiance (●), recorded at (a) Horseshoe Bay and (b) Davies Reef. Gaps in the time-series are missing data due to instrument malfunction. 126
- Fig. 6.4. (a) Turbidity (NTU), (b) benthic irradiance ($\mu\text{mol photons m}^{-2} \text{ s}^{-1}$), (c) wind speed (m s^{-1}) and (d) total monthly rainfall during study. (a) and (b) recorded by a logger at a shallow depth (2 m below LAT) on the fringing reef at Horseshoe Bay, (c) recorded at by Cleveland Bay AWS. Gaps in the time-series during Dry Season of Year 1 for (a) and (b), and Wet Season of Year 1 for (c), are missing data due to instrument malfunction. Dashed line denotes time series shown in Fig. 6.5. 127
- Fig. 6.5. (a) Turbidity (NTU), (b) benthic irradiance ($\mu\text{mol photons m}^{-2} \text{ s}^{-1}$) and (c) wind speed (m s^{-1}) recorded during the flood event in February 2007. Arrow indicates the commencement of major flooding in the Houghton River. A peak level of 3.8 m was recorded above the Burdekin Falls Dam spillway on 4th February 2007 (Bureau of Meteorology 2007). 129

Fig. 6.6. Relationship between (a) benthic irradiance at noon and turbidity, and (b) the attenuation coefficient for noon downward irradiance (K_d), corrected for tide and solar zenith angle, and turbidity recorded by a logger deployed at 2 m depth at Horseshoe Bay between May 2005 and May 2007. Dashed lines are 95% confidence intervals. 131

Fig. 6.7. Mean concentrations of water column (a) chlorophyll *a* ($\mu\text{g L}^{-1}$), (b) particulate nitrogen ($\mu\text{mol L}^{-1}$), (c) particulate phosphorus ($\mu\text{mol L}^{-1}$), (d) particulate organic carbon ($\mu\text{mol L}^{-1}$), (e) dissolved inorganic nitrogen ($\mu\text{mol L}^{-1}$), (f) dissolved inorganic phosphorus ($\mu\text{mol L}^{-1}$), (g) dissolved organic nitrogen ($\mu\text{mol L}^{-1}$), (h) dissolved organic phosphorus ($\mu\text{mol L}^{-1}$) sampled at Horseshoe Bay (\bullet), and Davies (\square) and Broadhurst Reefs (\triangle). 136

Fig. 6.8. Principal components biplot of physiological variables of *P. damicornis* grouped by (a) locations: Horseshoe Bay (dark grey) and mid-shelf reefs (light grey); and (b) seasons: Dry Season of Year 1 (light grey), and Wet Season of Year 1 and both Dry and Wet Season of Year 2 (dark grey). Environmental variables are over-laid on the plot. Abbreviations: *WQI* = water quality index, *SST* = sea surface temperature. Data for benthic irradiance, turbidity and *SST* are 14 d averages for time preceding each sampling event. 138

Fig. 6.9. Summary of mean (\pm SE) (a) symbiont density (cells cm^{-2}), (b) chlorophyll *a* ($\mu\text{g cm}^{-2}$), (c) chlorophyll *a* symbiont cell $^{-1}$ (pg cell $^{-1}$), (d) skeletal density (g cm^{-3}), (e) colony brightness of *P. damicornis*, and (f) colony brightness, (g) density of macro-bioeroders of *Porites* sampled at each of Horseshoe Bay (\bullet), and Davies (\square) and Broadhurst Reefs (\triangle). 143

Fig. 6.10. Partial residual plots showing the estimated dependencies (\pm 1 standard error) of symbiont density, concentration of chlorophyll *a*, chlorophyll per symbiont, skeletal density and colony brightness of *P. damicornis* on (a) location, (b) sea surface temperature, (c) turbidity, (d) benthic irradiance and (e) water quality index. Each partial effects plot is adjusted for the effects of the other five explanatory variables. 147

Fig. 6.11. Partial residual plots showing the estimated dependencies (\pm 1 standard error) of the density of macro-bioeroders and colony brightness of massive *Porites* on (a) location, (b) sea surface temperature, (c) turbidity, (d) benthic irradiance and (e) water quality index. Each partial effects plot is adjusted for the effects of the other five explanatory variables. 149

Fig. 7.1. Study sites for sampling of colonies of massive *Porites* on the Great Barrier Reef. Hay and Hannah Islands in the Far Northern Region, High and Kent Islands in the Northern Region of the GBR. 157

Fig. 7.2. Temporal profiles for skeletal density, annual extension and calcification rate over years. The red lines indicate individual corals and the black lines indicate the mean profiles. The variation of annual extension and calcification are large (coefficient of variation, CV = 30.5% and 30.3% respectively) compared with skeletal density (CV = 9.1%). 160

Fig. 7.3. Partial effects plots showing the estimated dependencies (with 95% confidence intervals) of skeletal density, annual extension and calcification on (a) year, (b) sea surface temperature and (c) reef. Hannah and Hay Island are in the Far Northern Region, High and Kent Island in the Northern Region of the Great Barrier Reef. Each partial effects plot is adjusted for the effects of the other two explanatory variables. 161

Fig. 7.4. (a) X-ray of a coral slice showing a 33-year growth record for a massive *Porites* from Kent Island in the Northern Region of the Great Barrier Reef, (b) mean annual sea surface temperature for the Northern Region over the same period and (c) calcification rate of the colony. Dashed lines are 95% confidence intervals. 162

Fig. 8.1. Conceptual model of coral measures to indicate increasing exposure to the key components of water quality. Grey boxes indicate differences in response of the indicator depending on the type of stressor. 178

ABSTRACT

Reversing the decline in water quality is a key priority for the protection of the Great Barrier Reef (GBR). Strategies to improve the water quality of the GBR include conservation of riparian zones and the adoption of ecologically sustainable practices in the catchments. The implementation of these strategies requires feedback to resource managers and the community through monitoring programmes aimed at detecting biological responses to changes in water quality. This thesis investigates a range of coral indicators at different spatial and temporal scales and identifies those most suitable for inclusion into a toolbox for monitoring the condition of coastal coral reefs on the GBR. The approach combines *in situ* studies of coral indicators in different regions and environmental gradients on the GBR with controlled manipulative experiments exposing corals to differing water quality to examine causality of correlations observed in the field.

An environmental gradient was identified in the Whitsunday Islands where water column variables (especially chlorophyll *a*, total suspended solids, particulate organic carbon and particulate nutrients) and irradiance variables (Secchi and optical depth) differed significantly from nearshore to the outer islands. For example, mean concentrations of chlorophyll *a* were up to 1.9 times greater at nearshore (Repulse Island; RI: $0.59 \pm 0.12 \mu\text{g L}^{-1}$ mean \pm SE) compared with outer islands (Edward Island; EI: $0.31 \pm 0.06 \mu\text{g L}^{-1}$) averaged over five sampling events from 2004 to 2006, whereas mean Secchi depth was approximately 3 times lower at nearshore (RI: 4.0 ± 0.8 m) than outer locations (EI: 15.3 ± 3.3 m). Some of the coral indicators showed significant relationships with a water quality index (WQI) derived for the Whitsunday Islands. Responses of photo-physiological measures of *Symbiodinium* associated with *Pocillopora damicornis* along the gradient were consistent with patterns of light acclimatisation and suggested deep corals (i.e. below 5 – 6 m depth) on nearshore reefs in the Whitsunday Islands are light-limited. Both colony brightness and tissue thickness of massive *Porites* spp., and the maximum depth of reef building corals, increased from nearshore to outer locations along the gradient. Similarly, a 50-fold decrease in the density of macro-bioeroders in massive *Porites* from nearshore to outer locations was indicative of increased particle loads on the nearshore reefs. The data of the maximum depth limit for coral reef development at locations where suitable settlement substrata were available suggest that the absolute minimum of light required for a coral reef to persist is in the range of 6 – 8 % of surface irradiance in the Whitsunday Islands.

The model that color brightness of corals responded to changes in water quality was validated with manipulative experiments in the laboratory and by transplantation of small nubbins along the environmental gradient. The experiments showed nubbins of massive *Porites* became darker, i.e. concentrations of pigments increased, within 20 – 40 days of exposure to elevated nutrients and

reduced irradiances compared with corals kept in filtered sea water and unshaded conditions. The response in colony brightness was consistent with other studies of photo-acclimatisation to enhanced nutrients and light limitation. However, a 2.5-fold decrease in symbiont density of *P. damicornis* during the wet compared with the dry season, which in turn influenced colony brightness, was related strongly to seasonal changes in sea surface temperature (SST). Thus, effects of seasonal variation of a range of environmental parameters need to be considered if physiological measures such as colony brightness are used in water quality monitoring programmes.

The simultaneous *in situ* measurement of benthic irradiance and turbidity at a shallow depth (~3.5 m) on a coastal coral reef for 2 years allowed the quantification of potential thresholds of concern for turbidity. The linear relationship between the attenuation coefficient for downward irradiance K_d (PAR) and turbidity showed that a change from 0 to 3 nephelometric turbidity units (NTU) at 3.5 m results in a decrease of 88% of benthic irradiance to levels around 200 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$. The minimum saturating irradiance (E_k) of *Symbiodinium* associated with *P. damicornis* was approximately $206 \pm 8 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ at shallow depths on nearshore reefs of the Whitsunday Islands. Thus, levels of turbidity greater than 3 NTU can result in environmental conditions that are light limiting, and hence sublethal photo-physiological stress, for *P. damicornis*. Levels of turbidity of 4.5 NTU corresponded to 6 – 8% of surface irradiance, which was a critical level of irradiance required for coral reef development in the Whitsunday Islands. Thus, long-term turbidity >3 NTU could be used as a threshold of turbidity for sublethal photo-physiological stress, while long-term turbidity >5 NTU for severe stress effects on *P. damicornis* at shallow depths (~3.5 m) on coastal reefs.

Temporal variation in the growth parameters of massive *Porites* from two nearshore regions of the GBR were not consistent with regional differences in water quality. Mean annual SST increased by $\sim 0.38^\circ\text{C}$ over a 16 year study period that correlated with a decline of $\sim 21\%$ in coral calcification rates. A decline in calcification of this magnitude with increasing SST contrasts with results of previous studies and is unprecedented in recent centuries. Changes in the growth parameters were linear over time, while SST had no effect on skeletal density, but a modal effect on annual extension and calcification with maxima at $\sim 26.7^\circ\text{C}$. The findings were consistent with other experimental studies of the synergistic effect of elevated seawater temperatures and CO_2 partial pressure ($p\text{CO}_2$) on coral calcification and suggest that monitoring of seawater chemistry should be undertaken on the GBR.

Defining a set of key selection criteria and assessing the characteristics of candidate indicators in a matrix against changes in water quality, allowed the identification of coral indicators for a monitoring toolbox. The most suitable bioindicators were: symbiont photo-physiology, colony

brightness, skeletal and tissue growth, and bioeroder density in massive *Porites*, coral recruitment, community structure of corals, indicator organisms other than corals and the maximum depth of coral reef development. As each of these measures has a different sensitivity and response time to changes in environmental conditions, a combination of measures, i.e. a composite indicator system, is recommended for use in assessments of the condition of coastal reefs on the GBR.