A dynamic understanding of coral reef health informs resilience-based management of the Great Barrier Reef

Thesis submitted by

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ABSTRACT

Coral reefs are among the most sensitive ecosystems to climate change. Managing coral reefs at a time when changing sea temperatures, levels and chemistry are already negatively affecting the capacity of hard corals to settle, grow, calcify and persist, presents a unique set of challenges. In many reef areas, increasingly frequent environmental disturbances combined with anthropogenic stressors are challenging the natural resilience of reef systems. Adaptively managing coral reefs to support their resilience requires a dynamic understanding of their health and condition. The journey towards the goal of ensuring managers of the Great Barrier Reef (GBR) have a dynamic understanding of reef health and condition forms the focus of this thesis.

Dynamic information on reef health will only become available to managers at the scale of the GBR by building capacity among regular reef visitors to assess and monitor reef condition and impacts. A key issue is that many impacts on coral reef health are cryptic, ephemeral and readily confused with other impacts. Chapter 2 describes the development and production of a field guide that enables observers to recognise characteristic signs of compromised coral health on Indo-Pacific Reefs. The guide's structure is based on a colour-coded decision tree that serves as a visual index to help users navigate the content. The decision tree aids the differential diagnosis of diseases and other reef health impacts using characteristic macroscopic signs. The layout of the content was developed in consultation with coral health experts, managers, rangers and tourism operators. The final guide, published in 2008, takes the form of a spiral bound book of underwater cards made to fit the pockets found in dive equipment.

In the year following publication of the guide, it was used to enable managers, rangers and tourism staff working within the GBR Marine Park (GBRMP) to distinguish among coral diseases and other reef health impacts. Since 2009, this enhanced capacity among non-specialist observers has provided an early warning system for disease outbreaks. The value of this early warning system is described in the strategic framework for responding to disease presented in Chapter 3. The strategic framework enables managers to use remote sensing and field observations to produce a near real-time

estimate of outbreak likelihood and impact severity. Automated coral disease outbreak alerts are now created at the Great Barrier Reef Marine Park Authority (GBRMPA) based upon outbreak thresholds developed while writing the response framework.

The development and implementation of the framework helped to focus the views of my GBRMPA colleagues on the increasing need for holistic evaluation of coral reef health. Until 2009, GBRMP managers had limited access to detailed information on reef condition and impacts, primarily from only 48 sites surveyed once every two years by the AIMS Long Term Monitoring Program. In Chapter 4, I describe how from 2009-2014, I led the process of developing the revised 'Eye on the Reef' program, which integrates previous participatory monitoring programs and includes: a Reef Health and Impact Survey (RHIS) method tailored to the time constraints of rangers and tourism operators, an online and field-based training system, a web-enabled database and data entry interface, and automated reporting through Google Earth™. The integrated Eye on the Reef program has now become the primary mechanism by which the GBRMPA gathers up-to-date information on coral reef health and impacts in the Marine Park. Previously, the GBRMPA had access to less than 10% of the information on reef condition and impacts that is available now. Importantly, the scene is now set to use the information extensively to inform adaptive resilience-based management.

A severe tropical cyclone in 2011 provided an opportunity to test the RHIS protocol and evaluate the effectiveness of a management action. TC Yasi was a category 5 cyclone when it crossed the Park and was unique among the storms that have crossed the Park since 1985, in that it was both severe and had a large circulation size. In the weeks that followed TC Yasi crossing the Reef, dozens of managers, rangers and research scientists conducted 882 RHIS at 76 reef locations. In Chapter 5, I present the results of this study, which revealed cross-shelf variation in the severity of mechanical damage caused by the storm, as well as patterns in impact severity with respect to direction (north and south) and distance from the cyclone eye. A key conclusion from this work is that more coral was lost in the 24-hour period in which TC Yasi crossed the Park than in any other 24-hour period in at least the last 30 years.

Understanding spatial patterns in the severity of impacts following TC Yasi helped the GBRMPA to communicate key information about the event and to target local-scale actions to support recovery. After such actions are implemented, the integrated Eye on the Reef network can help managers evaluate the effectiveness of the actions. Chapter 6 reviews a recent example of such an evaluation from the southern Great Barrier Reef, where the RHIS protocol was used to assess the effectiveness of no-anchoring areas (NAAs) established in 2008. I led teams of managers from GBRMPA and rangers from Queensland Parks and Wildlife that completed RHIS protocols within the NAAs and at control sites from 2008-2012. Declines in anchor damage were immediately apparent in 2010 and virtually no anchor damage was seen within the NAAs by 2012. The Keppel Bay case study is an example of how the effectiveness of a management action can be evaluated by having non-specialist observers undertake RHIS. A significant outcome of the Keppel Bay study is a precedent for using the observer network and survey protocol to assess management effectiveness and that can guide the use of the network/protocol in this way in future years.

The ability to target local-scale, short-term actions to support recovery of the GBR has been greatly enhanced as a result of the work presented in this thesis. The Keppel Bay study within Chapter 6 highlights that there are multiple benefits for managers (and management of the Reef) as a result of involving community members in monitoring coral reef condition and impacts. The Keppel Bay study encapsulates the primary message of my thesis and the story of how adaptive management is meant to work. Actions to support reef resilience and recovery (Chapter 6), can now be targeted, evaluated and refined as a consequence of building capacity among non-specialists to monitor reef condition and impacts (Chapters 2-5). The network of observers participating in Eye on the Reef monitoring is now providing information on reef condition and impacts from hundreds of reefs every year. The consequence is that we are starting to dynamically understand reef health, condition and environmental exposure. Importantly, this enables the GBR to be managed adaptively by responding to impacts and by increasingly targeting and trialling actions to support reef resilience.

DECLARATION

This is to certify that:

1. The thesis comprises only my original work towards the PhD except where indicated in the Preface.
2. Due acknowledgment has been made in the text to all other material used.
3. Every reasonable effort has been made to gain permission and acknowledge the owners of copyright material. I would be pleased to hear from any copyright owner who has been omitted or incorrectly acknowledged.
4. The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council (NHMRC) National Statement on Ethical Conduct in Human Research, 2007. The proposed research study received human research ethics approval from the JCU Human Research Ethics Committee Approval Number # H4927
5. The thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

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Roger J. Beeden

SOURCE REFERENCES

The content within Chapters 2-6 of this thesis have been published (Chapers 2-4 and 6), or are in review (Chapter 5) and include content from published peer-reviewed technical reports. All publications were developed, submitted, reviewed and edited during my PhD candidature at James Cook University. See the Statement of the Contribution of Others section (next and Appendix 3) for descriptions of contributions made by co-authors to my thesis content.

Books

[Chapter 2] Beeden, RJ, Willis, BL, Raymundo, LJ, Page, CA & Weil, E 2008, *Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs.* Coral Reef Targeted Research & Capacity Building for Management Program, St Lucia, QLD. http://www.gefcoral.org/Portals/53/downloads/disease_products/0807%20Indo%20Pacific%20Underwater%20ID%20Cards.pdf

Journal Publications

[Chapter 3] Beeden, RJ, Maynard, JA, Marshall, P, Heron, S & Willis, B 2012, 'A framework for responding to coral disease outbreaks that facilitates adaptive management', *Environmental Management*, vol. 49, no. 1, pp. 1-13, doi: 10.1007/s00267-011-9770-9

[Chapter 4] Beeden, RJ, Turner, MA, Dryden, J, Merida, F, Goudkamp, K, Malone, C, Marshall, PA, Birtles, A & Maynard, JA 2014a, 'Rapid survey protocol that provides dynamic reef health condition information to managers of the Great Barrier Reef', *Environmental Monitoring and Assessment*, vol. 186, no. 12, pp. 8527-8540. doi: 10.1007/s10661-014-4022-0

[Chapter 5] Beeden, RJ, Puotinen, M, Marshall, P, Goldberg, J, Dryden, J, Williams, G & Maynard, J (in review) 'Impacts of severe tropical cyclone Yasi on the Great Barrier Reef', submitted to *PLoS One*

[Chapter 6] Beeden, RJ, Maynard, J, Johnson J, Dryden, J, Kininmonth, S & Marshall, P 2014b, 'No-anchoring areas reduce coral damage in an effort to build resilience in Keppel Bay, southern Great Barrier Reef', *Australasian Journal of Environmental Management*, vol. 21, no. 3, pp. 311-319, doi: 10.1080/14486563.2014.881307

Technical Reports

Authority, GBRMP 2013a, *Coral Bleaching Risk and Impact Assessment Plan*, eds **RJ, Beeden**, JA, Maynard, J, Dryden & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2810>

Authority, GBRMP 2013b, *Coral Disease Risk and Impact Assessment Plan*, eds **RJ, Beeden**, JA, Maynard, J, Dryden & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2809>

Authority, GBRMP 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2808>

Authority, GBRMP 2013d, *Tropical Cyclone Risk and Impact Assessment Plan*, eds **RJ, Beeden**, JA, Maynard, J, Goldberg, J. Dryden & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2813>

Authority, GBRMP, 2011, *Impacts of tropical cyclone Yasi on the Great Barrier Reef: a report on the findings of a rapid ecological impact assessment*, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/447>

Relevant Co-Authored Publications (not forming part of this thesis)

Anthony, KRN, Marshall, PA, Abdulla, A, **Beeden, R,** Bergh, C, Black, R, Eakin, CM, Game, ET, Gooch, M, Graham, NAJ, Green, A, Heron, SF, van Hooidonk, R, Knowland, C, Mangubhai, S, Marshall, N, Maynard, JA, McGinnity, P, McLeod, E, Mumby, PJ, Nyström, M, Obura, D, Oliver, J, Possingham, HP, Pressey, RL, Rowlands, GP, Tamelander, J, Wachenfeld, D & Wear, S 2014, 'Operationalizing resilience for adaptive coral reef management under global environmental change'. *Global Change Biology*, doi: 10.1111/gcb.12700.

Authority, GBRMP, 2012, *Climate Change Adaptation: Outcomes from the Great Barrier Reef Climate Change Action Plan 2007–2012*, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/1139>

Garde, L, Spillman, C, Heron, S, **Beeden, RJ,** 2014, 'ReefTemp Next Generation: A New Operational System for Monitoring Reef Thermal Stress', *Journal of Operational Oceanography*, vol. 7, no. 1, pp. 21-33.

Maynard JA, Anthony KRN, Harvell CD, Burgman MA, **Beeden R,** Lamb JB, Heron SF, Willis BL 2011, 'Predicting outbreaks of a climate-driven coral disease on the Great Barrier Reef', *Coral Reefs*, vol. 30, pp. 485-495, doi: 10.1007/s00338-010-0708-0.

Mcleod, E., Anthony, KRN, Andersson, A, **Beeden, R,** Golbuu, Y, Kleypas, J, Kroeker, K, Manzello, D, Salm, R, Schuttenberg, H, Smith, JE 2012, 'Preparing to manage coral reefs for ocean acidification: Lessons from coral bleaching', *Frontiers in Ecology and the Environment*, vol. 11, pp. 20–27, doi: 10.1890/110240.

STATEMENT OF THE CONTRIBUTIONS OF OTHERS

All of the work presented in this thesis was completed during my PhD candidature at James Cook University. Chapters two through six are based upon published, or in review books, journal publications and peer-reviewed technical reports. I have led the development of all of the content in these publications as well as the drafting and revision processes. All of the work presented within the thesis has benefited in various ways from contributions from colleagues and collaborators, some of whom have co-authored the publications. The work presented in each thesis chapter is my own. Co-author contributions to the published versions of chapter content are described below for each chapter, following a list of source references. A signed statement of contribution of others from each co-author is included in the thesis Appendix 3.

Chapter 2

Beeden, RJ, Willis, BL, Raymundo, LJ, Page, CA & Weil, E 2008, *Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs.* Coral Reef Targeted Research & Capacity Building for Management Program, St Lucia. http://www.gefcoral.org/Portals/53/downloads/disease_products/0807%20Indo%20Pacific%20Underwater%20ID%20Cards.pdf

The work presented in Chapter 2 describes the development of a published underwater field guide (see source reference) for identifying coral diseases in the Indo-Pacific. Willis and Raymundo developed the field-based morphological descriptions of coral diseases and other indicators of compromised health and advised on key disease identification signs described in the guide. I designed, developed and tested the field version of the decision tree and optimised the final product to make it ensure it met the needs of reef managers, reef tourism operators and ‘citizen scientists’. All co-authors contributed photographs and reviewed and commented on drafts of the text and layout of the field guide.

Chapter 3

Beeden, RJ, Maynard, JA, Marshall, P, Heron, S & Willis, B 2012, 'A framework for responding to coral disease outbreaks that facilitates adaptive management', *Environmental Management*, vol. 49, no. 1, pp. 1-13, doi: 10.1007/s00267-011-9770-9

Authority, GBRMP 2013a, *Coral Bleaching Risk and Impact Assessment Plan*, eds **RJ, Beeden**, JA, Maynard, J, Dryden & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2810

Authority, GBRMP 2013b, *Coral Disease Risk and Impact Assessment Plan*, eds **RJ, Beeden**, JA, Maynard, J, Dryden & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2809>

Authority, GBRMP 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2808>

Maynard, Willis, Marshall and Heron all reviewed and provided editorial comments to the manuscript published in *Environmental Management.* Willis, Maynard and Marshall also provided comments on the draft Coral Disease Response Plan (later Coral Disease Risk and Impact Assessment Plan) technical report. The approach to responding to incidents contained in the technical report is based upon work by Marshall and Maynard to respond to coral bleaching events presented within Maynard et al. (2009). Heron and Maynard developed the remote sensing tools and white syndromes forecasting models described in the Framework and the Risk and Impact Assessment Plan (Heron et al. 2010; Maynard et al. 2010).

Chapter 4

Beeden, RJ, Turner, MA, Dryden, J, Merida, F, Goudkamp, K, Malone, C, Marshall, PA, Birtles, A & Maynard, JA 2014a, 'Rapid survey protocol that provides dynamic reef health condition information to managers of the Great Barrier Reef', *Environmental Monitoring and Assessment,* vol. 186, no. 12, pp. 8527-8540. doi: 10.1007/s10661-014-4022-0

Authority, GBRMP 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville.

I developed the 'circular belt transect' method in close collaboration with Turner and Marshall. All co-authors of the manuscript published in *Environmental Monitoring and Assesssment* provided input into the selection of site, benthos and reef health indicators included in the Reef Health and Impact Survey form and supporting database. Merida commented on the utility of the survey method and datasheet. All co-authors and other GBRMPA, QPWS and tourism operator staff contributed to the 2 years of RHIS form and survey methodology evolution. Turner, Goudkamp, Malone, Merida and Dryden contributed to the development and implementation of the integrated Eye on the Reef information system (those authors and I formed a technical working group). Turner, Goudkamp and I co-managed the work program to deliver the operational supporting database. Goudkamp led the testing of the database. Malone helped with the development of visualisation algorithms and the Google Earth^{TM} Keyhole Markup Language (KML) layer design. Dryden helped project manage the development, testing and deployment of the e-learning system. The RHIS visual aid (Chapter 4, Figure 4.4) and educational support materials (Chapter 4, Figure 4.3 and Appendix 2) were developed in collaboration with R. Kelley, D. Tracey and D. Schultz based upon training content developed in collaboration with Turner, Merida, Marshall and Maynard.

Data collection described in this chapter and the submitted manuscript included some staff from the Great Barrier Reef Marine Park Authority (referred to throughout as

'GBRMPA'), QPWS and Great Barrier Reef tourism staff. Maynard and Marshall assisted with parts of the data analysis related to visualising impact extent and severity.

<u>Chapter 5</u>

Beeden, RJ, Puotinen, M, Marshall, P, Goldberg, J, Dryden, J, Williams, G & Maynard, J (in review) 'Impacts of severe tropical cyclone Yasi on the Great Barrier Reef', submitted to *PLoS One*

Authority, GBRMP 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2808>

Authority, GBRMP 2013d, *Tropical Cyclone Risk and Impact Assessment Plan*, eds **RJ, Beeden**, JA, Maynard, J, Goldberg, J. Dryden & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2813>

All co-authors contributed to the development and editing of the manuscript submitted to *PLoS ONE*. Marshall, Goldberg, Maynard and Dryden helped collect data on impact severity following TC Yasi after our working group implemented an impact assessment plan that I developed in collaboration with Marshall and Maynard. Many staff from the GBRMPA and QPWS helped assist with data collection following TC Yasi. Dryden, Goldberg and Goudkamp and Merida assisted with data entry and quality control following the surveys. Williams completed the PERMANOVA statistical analyses relating damage to distance and direction (north and south of the storm eye) in collaboration with Beeden, Puotinen and Maynard. Puotinen developed the analysis and graphic shown in Figure 5.5 comparing TC Yasi to all other cyclones that produced gale force winds in the GBR Marine Park since 1985 in collaboration with Beeden and Maynard. Final figures were designed in collaboration with D. Tracey, some of which include maps produced by C. Malone and R. Banks.

Chapter 6

Beeden, RJ, Maynard, J, Johnson J, Dryden, J, Kininmonth, S & Marshall, P 2014b, ‘No-anchoring areas reduce coral damage in an effort to build resilience in Keppel Bay, southern Great Barrier Reef’, *Australasian Journal of Environmental Management*, vol. 21, no. 3, pp. 311-319, doi: 10.1080/14486563.2014.881307

Authority, GBRMP 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2808>

All co-authors contributed to the development and editing of the manuscript published in the *Australasian Journal of Environmental Management*. I designed and led the no-anchoring area management action evaluation surveys using the RHIS protocol. The surveys in 2010, 2011 and 2012 were conducted in collaboration with Dryden. Kininmonth and other GBRMPA and QPWS staff also collected survey data. Kininmonth and Maynard assisted with the data analysis and figures were developed in collaboration with Maynard and Tracey. Maynard, Johnson and Marshall conducted the baseline Keppel Bay resilience assessment and established the no anchoring areas in 2008 in partnership with the local community.

ACKNOWLEDGEMENTS

My PhD candidature started in July 2007, whilst working with a not-for-profit reef monitoring organisation – Reef Check Australia. The original objectives of my PhD research were to: 1) train tourism industry staff and community volunteers to accurately identify coral diseases by their characteristic signs, and 2) to use the data collected by this network of observers to provide rapid assessments of coral disease outbreaks on the Great Barrier Reef. Since 2008, I have been employed by the Great Barrier Reef Marine Park Authority as the Manager of Climate Change and Ecosystems. The duties of my new role at GBRMPA were closely aligned with my PhD research. As a result, I was able to expand upon my original PhD objectives to examine coral disease in the context of coral health and resilience dynamics across the entire Great Barrier Reef ecosystem. The scope expansion resulted in a number of unexpected challenges but created even more opportunities. I was able to directly examine my research questions and deploy what I learned from each study in a real life management setting. Directly applying my research findings to management decisions has been invaluable to my thesis journey and aided the GBRMPA's efforts to enable resilience-based management of the Great Barrier Reef under a changing climate.

I am indebted to the Great Barrier Reef Marine Park Authority for the support of my PhD candidature in the form of study leave and professional development assistance. I would also like to acknowledge the important role that many of my colleagues have played (both directly and indirectly) in helping me address my research questions. Of particular note I would like to thank Paul Marshall for his expert mentorship, writing prowess and salient points, Malcolm Turner for his fountain of natural history knowledge and practical experience, Fiona Merida for her passion, drive and enthusiasm for the Great Barrier Reef and our tourism industry partners, Katrina Goudkamp for her good humour and persistence in the face of rapidly shifting goal posts, Jen Dryden for her dive buddy excellence, tenacious critical attention to detail and formidable project management capabilities, Cherie Malone for her GIS magic, Peter McGinnity for 30 years of GBRMP wisdom and the rest of the Climate Change and Science Group present and past (Johanna Johnson, Chloe Schauble, Rachel Pears, Anna Lyons, Catherine Moltzen, Fergus Molloy, Julia Chandler, Diane Koustenis, Jill

Brown, Antasia Azure, Dieter Tracey, Tyrone Ridgway, Paul Groves, Stuart Kininmonth, Jeremy Goldberg and James Moore) for their enduring support. Many other colleagues within GBRMPA have also been sources of inspiration throughout this journey. I would like to especially acknowledge the thought-provoking commentary and wise words of Mark Read, David Wachenfeld and Russell Reichelt. I would also like to thank and acknowledge all of my QPWS colleagues and in particular Richard Quincey (now at GBRMPA), Damien Head and Sascha Taylor who have supported and implemented the Reef Health and Impact Survey program 'vision' that has resulted in the collection of more than 10,000 surveys that underpin the case studies presented in this thesis. My thanks to all of my survey dive buddies during the course of my thesis. In particular Lauren Bird, Alison Paley, Megan Sperring and Tom Hatley who are pictured in the chapter photographs.

Beyond the immediate 'GBRMPA family' I would also like to thank and acknowledge the valuable insights, commentary and willingness to share of many of the researchers I have had the honour to work with during my candidature, including: my fellow students, (and in most cases now graduates) supervised by Bette Willis and Alastair Birtles, and the Australian Institute of Marine Science Long-Term Monitoring Program and Marine Monitoring Program teams with a special note of thanks to Hugh Sweatman. I would also like to acknowledge and thank Ken Anthony for being a colleague, mentor and sounding board on the path to resilience-based management.

I owe a great debt of thanks to my friends Jeremy Goldberg, Bryan Murphy, Jos Hill, Brett and Jane Hoggard, Sandie and Dean McCathie and Robert and Greet Teunisse for their belief and support as I climbed the PhD mountain. Jos's Reef Check work was a catalyst to start this PhD, and all of you have provided critical anchors, ropes and bridges along the way.

To all of my co-authors of the publications that form the backbone of this thesis a great many thanks for your collective wisdom. These collaborations have made this work greater than the sum of the parts, generating tools, strategies and actions that help us tackle the challenges facing the Great Barrier Reef under a changing climate.

The work presented within the thesis was made possible through the funding and in-kind support provided by: the Great Barrier Reef Marine Park Authority, the Queensland Parks and Wildlife Service, the Association of Marine Park Tourism Operators, James Cook University schools of Business, Earth and Environmental Science, Marine and Tropical Biology, the Australian Research Council Centre of Excellence for Coral Reef Studies, Commonwealth and Scientific Industrial Research Organisation (CSIRO) Marine and Atmospheric Research, the Bureau of Meteorology, the Coral Reef Watch program at NOAA, the Marine and Tropical Sciences Research Facility, The Nature Conservancy and Reef Check Australia.

I would like to thank my colleagues and the review teams at the *Australian Journal of Environmental Management, Environmental Management, Environmental Monitoring and Assessment* and the *Coral Reef Targeted Research Program* for their insightful critique that enabled the publication of several key findings of this research. The final versions of many of the figures produced for the thesis were created in collaboration with Dieter Tracey, Russell Kelley, Marji Puotinen and Daniel and Ruth Schultz.

To my supervisors: Dr Alastair Birtles, Professor Bette Willis, Professor Peter Valentine (2007 – 2012) and Dr Jeffrey Maynard (2013-2014). Your collective belief in the merit of a cross disciplinary PhD was the key to my being able to pursue these research questions in a way that immediately benefited the management of the Great Barrier Reef. At several points along the journey it must have seemed like I was on a different path and I am extremely grateful for the calm, wise and timely delivery of sign posts to show me the way. Alastair's depth of expertise and enthusiasm for adaptive-management research has been a constant source of inspiration, and I hope the foundation for fruitful collaborations beyond this thesis. I have been inspired by Bette ever since my MAppSc course; your Professorial homage to the humble coral polyp is a vision that I share and for ever after I shall be a proud and loyal "coralphile". Peter Valentine's knowledge and passion for protected area management has inspired many JCU students over the years and laid the foundations for the courses that provided me with the skills that enabled my transition from a career in the pharmaceutical industry to natural resource management. A special note of thanks to Jeffrey Maynard who selflessly volunteered to co-supervise when Peter Valentine retired. Without Jeffrey

Maynard I am not sure that I would have ever known where the summit of the PhD mountain was or how to reach it. To all of my supervisors it has been an honour working with you.

Of course without the nature and nurture of my parents this thesis could not exist. It is my parents' constant love and passion for the natural world that set me on my way and serves as a constant source of inspiration and passion to do my best to support coral reef ecosystems in the face of ever mounting pressures. Their support for my desire to work on the Great Barrier Reef, even though that means we live on opposite sides of the planet, demonstrates parental love in a way that is truly humbling. The journey from my junior school project on animal 'biodiversity' to my role at the GBRMPA and the work contained in this thesis is a direct consequence of your love, values and unwavering support through good times and bad. To my brothers Mike and Tom and the rest of the Garden of Beeden, a hearty thank you.

Without Ally my 'jive, dive and life buddy' this thesis would still be a figment of my imagination. As I said at our wedding my greatest accomplishment in life was convincing you to marry me. Thank you for your love, compassion, kindness, insights and unwavering support for leaps into the unknown.

"*We do not inherit the earth from our ancestors, we borrow it from our children*"

Native American Proverb

To my beautiful children, Max and Anya, this is for you, and your generation. May it be a small source of inspiration to you to follow your dreams and do your best to make a difference.

Acknowledgments sections presented within publications or manuscripts in review:

Beeden et al. (20012) [Chapter 3] - This work was made possible by funding and logistical support provided by the Great Barrier Reef Marine Park Authority. Part (b) of Figure 2 was provided by Claire Spillman, who provided critical comments on the early warning system section of the manuscript. Some of the content and presentation format resulted from insightful discussions and/or other collaborative efforts with L. Raymundo, D. Harvell, G. Aeby, J. Johnson, M. Turner, D. Abrego, H. Schuttenberg, E. Weil, K. Ritchie, M. Eakin, and C. Woodley. Figures and tables were developed in collaboration with D. Tracey. This is a contribution by the ARC Centre of Excellence for Coral Reef Studies. The manuscript contents are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of NOAA or GBRMPA or the U.S. or Australian Governments.

Beeden et al. (2014a) [Chapter 4] - Funding for the development of the RHIS protocol and integrated Eye on the Reef program database and training tools was provided under the Great Barrier Reef Marine Park Authority's Climate Change Action Plan in partnership with the Queensland Department of National Parks Sport and Racing and Great Barrier Reef Field Management Program. The authors would like to acknowledge that this work has its foundations in the timed swim based joint GBRMPA / QPWS Rapid Assessment Monitoring Protocol (RAMP, the joint GBRMPA and Tourism Industry weekly Eye on the Reef survey and the GBRMPA led BleachWatch program. Beyond the team of authors we would like to specifically thank Richard Quincey from the Great Barrier Reef Field Management Program, Sascha Taylor, Chris Maple and John Olds from the Queensland Department of National Parks Sport and Racing, Chris Briggs and Chris Jones from the Great Barrier Reef Marine Park Authority's Tourism Section, former GBRMPA staff members Peter McGinnity, Andrew Chin, Jo Johnson, Dean Miller and Robin Aeillo. We also would like to thank all of the participating Queensland Department of National Parks Sport and Racing rangers, GBRMPA and tourism industry staff who have completed RHIS.

Beeden et al. (in review) [Chapter 5] - Fieldwork, data analysis and manuscript preparation were all supported by the Great Barrier Reef Marine Park Authority and

Queensland Parks and Wildlife Service. All co-authors contributed to the development and editing of the manuscript. Roger Beeden designed and led the initial impact assessment surveys supported by Paul Marshall, Jeff Maynard, Jeremy Goldberg and Jen Dryden. Beeden also led the recovery surveys in partnership with Jen Dryden. Marji Puotinen led the development of figure 5.5 in collaboration with Roger Beeden and Jeff Maynard. Gareth Williams completed the PERMANOVA statistical analysis in collaboration with Roger Beeden, Marji Puotinen and Jeff Maynard. Final figures were designed in collaboration with Dieter Tracey, some of which include maps produced by Cherie Malone and Rhonda Banks.

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

CHAPTER 1
Introduction

Coral reefs are hugely biodiverse and critically important to hundreds of millions of people as both a source of protein and the basis for a diversity of livelihoods (reviewed in Hoegh-Guldberg et al. 2007; Hughes et al. 2003). Reefs also provide other services like shoreline protection, which buffers island and coastal communities throughout the world's tropics from the effects of severe storms (reviewed in Wells, Ravilious & Corcoran 2006). These vital ecosystems are now critically threatened by climate change (reviewed in Hoegh-Guldberg et al. 2007; Hughes et al. 2003; Hughes et al. 2010; Pandolfi et al. 2003; Pandolfi et al. 2011). Corals grow within a narrow range of environmental conditions that constrain them to the warm shallow (<40 m mostly) coastal waters of the world's tropics (Jokiel 2004; Wilkinson 2000). The climate change and coral reef crisis has been widely communicated because climate change greatly increases the frequency and severity of stress coral reef communities must endure (Bellwood et al. 2004; Veron et al. 2009) and the impacts of some of these stressors are already apparent (De'ath et al. 2012). As an example, coral bleaching caused by higher-than-normal sea temperatures devastated 16% of the world's reefs in 1998 (reviewed in Wilkinson 2000 and 2008). Bleaching events are expected to increase greatly in both frequency and severity in the coming decades as the climate changes (Hoegh-Guldberg et al. 2007; Van Hooidonk, Maynard & Planes 2013). Importantly, acute mortality impacts only tell part of the story of coral health dynamics. Recovery following coral bleaching is energetically expensive for corals, reducing growth rates (Albright 2011; Anthony, Connolly & Willis 2002) and gamete production (Albright 2011; Doropoulos et al. 2012) and increasing susceptibility to disease (Burge et al. 2013; Harvell et al. 2007; Raymundo et al. 2008). In addition, bleaching events often do not occur in isolation from other pressures on reefs; storm damage, predation and competition can all occur during the recovery period (De'ath et al. 2012; Graham, Nash & Kool 2011; Osborne et al. 2011; Raymundo et al. 2008; Sweatman, Delean & Syms 2011).

Higher frequencies of severe storms are expected as a result of climate change (Stocker et al. 2013), as are changes to the ocean circulation patterns that drive regional-scale reef connectivity (Stocker et al. 2013). Changes in rainfall patterns are also expected, (BoM / CSIRO report card 2013, Stocker et al. 2013), which will cause flooding events that result in freshwater inundation of some near-shore reefs as well as greater sediment and the transport of nutrients and other pollutants into reef lagoons (McCulloch et al. 2003; Stocker et al. 2013). All of these acute episodic disturbances are expected to increase in frequency and/or severity in the coming decades and are compounded by chronic stressors (Hughes et al. 2010). As an example of a chronic stressor, sea levels are and will continue to rise, meaning corals need to grow at rates sufficient for reefs to accrete rapidly enough to stay within optimal light habitats (Lough & Hobday 2011; Stocker et al. 2013). Also, the root cause of climate change – an increase in greenhouse gas emissions – is acidifying the world's oceans. Ocean warming is already weakening coral skeletons and slowing growth rates, and both trends are projected to be exacerbated by ocean acidification (reviewed in Anthony et al. 2011). Recent research indicates that crustose coralline algae are highly sensitive to ocean acidification. Reductions in the abundance of crustose coralline algae over the coming decades threaten both reef accretion and coral recruitment (reviewed in Anthony & Maynard 2011; Doropoulos et al. 2012). More rapid acidification at high latitudes in the oceans is also likely to limit the capacity of coral communities to adapt via larval migration pole-wards as the climate warms. The combined effects of warming and ocean acidification on reefs by mid-century are unprecedented in recent history, and are forecast to tip the balance from net accretion to erosion (Pandolfi et al. 2011; Van Hooidonk, Maynard & Planes 2013; Veron 2008), limiting the capacity of coral reefs to keep pace with expected sea level rises (Stocker et al. 2013).

Projected climate change impacts on reefs have been widely popularised, however, most reefs are under greater immediate threat from stress and pressure created by local anthropogenic activities than from climate change (Hoegh-Guldberg et al. 2007; Hughes et al. 2003; Wooldridge & Done 2009). In many parts of the world, fishing pressure depletes the stocks of herbivores that consume the algae that compete directly with corals for space, which slows recovery following disturbances. The act of fishing can also badly damage corals and reef substrate via anchoring or when destructive fishing practices like bombing and trawling are used. Coastal development, land clearing and use, waste management and shipping can all work to deteriorate water quality on reefs. Increased sedimentation and nutrient input typifies declining water quality on reefs (Brodie et al. 2012; reviewed in Fabricius 2005). Furthermore, in the Great Barrier Reef (GBR) region, poor water quality has been implicated in the development of outbreaks of crown-of-thorns starfish (Fabricius, Okaji & De'ath 2010), a major predator of corals, and hypothesised to increase the sensitivity of corals to coral bleaching (Wooldridge 2009a, 2009b; Wooldridge & Done 2009). Thus high sediment and nutrient levels, high fishing pressure and all of the impacts expected from and associated with climate change, compromise the health of scleractinian corals, the primary framework builders on coral reefs (Authority 2009, 2014).

Coral reefs have always been dynamic systems; stable periods of growth and maintenance are punctuated by disturbances that 'set the coral growth clock back' (reviewed in Graham, Nash & Kool 2011). Following partial or whole colony mortality of corals and other sessile modular invertebrates, any resulting empty space is re-colonised and the system recovers (Diaz-Pulido et al. 2009; Hughes & Connell 1999). This natural capacity of reefs and other ecosystems to withstand and tolerate disturbances and to recover following disturbances is now commonly referred to as resilience (Holling 1973; Hughes et al. 2003; Levin & Lubchenco 2008; Nyström, Folke & Moberg 2000; reviewed in Plummer & Armitage 2007; Walker et al. 2002). Considered from an adaptive management perspective:

"Anderies et al. (2004 and 2006) make the key point that resilience is a framework for systematically thinking through system dynamics (rather than a coherent body of theory) and that the concept helps in our understanding of complex systems behaviour." (Plummer & Armitage 2007, p. 65).

Viewing resilience in this way has implications for managers (like me) who are tasked with operationalising resilience theory. In essence, resilience provides a way of thinking about the challenges that complex systems face now and in the future, offering an approach to adaptively prioritise management actions. The immediate and urgent challenge for coral reefs and coral reef managers is that the compromised health caused by multiple, cumulative (or interactive) anthropogenic activities, combined with increases in disturbance frequency and severity, reduce reef resilience (Anthony & Maynard 2011; Anthony et al. 2014; Nyström, Folke & Moberg 2000). Less resilient reefs are more susceptible to all of the common stressors on reefs, and consequently recover more slowly (Hoegh-Guldberg 2011; Hughes et al. 2010; Nyström et al. 2008). Managing reefs to maintain and support their natural resilience will give reefs the best chance of persisting as the coral-dominated systems that provide the ecosystem goods and services on which so many have come to depend (Anthony et al. 2014; Hughes et al. 2010; Nyström, Folke & Moberg 2000; Nyström et al. 2008; Plummer & Armitage 2007). As a practicing coral reef manager I am currently responsible for implementing my research findings, in partnership with my colleagues, to enhance the recovery of the Great Barrier Reef and hence its long-term outlook (Anthony et al. 2014; Authority, GBRMP 2014).

Resilience-based management (Anderies, Walker & Kinzig 2006; Brock 1998; Folke 2006) of reefs in an era of climate change requires a two-pronged approach. Firstly, members of the coral reef community must continue to contribute to national and global policy debates, communicating the dire need to reduce greenhouse gas emissions and anthropogenic impacts on reefs. Efforts in this area by the coral reef scientific and management community resulted in the Inter-governmental Panel on Climate Change (IPCC) dedicating an entire chapter in the 2007 technical report to the coral reef crisis (Pachauri & Reisinger 2007). However, total outputs of greenhouse gas emissions and the growth rate of emissions continue to increase. Thus managers must focus on their second and more tractable option – reducing stress on reefs and supporting recovery processes directly and indirectly and at multiple spatial scales by limiting and shaping resource use, extraction and land practices (Authority, GBRMP 2009, 2014).

Management approaches based on reducing anthropogenic stress on reefs are nothing new, however managing for resilience adds a prognostic dimension to these efforts (Anthony et al. 2014; Nyström, Folke & Moberg 2000; Nyström et al. 2008; Walker et al. 2002). The added imperative to manage for resilience increases the impetus for, and defines the reasoning and justification behind, actions that shape and limit use to reduce current and future risk. As in the past, in an era of climate change, broad-scale actions (e.g., watershed-scale changes to land use to improve water quality, Brodie et al. 2012, ReefPlan 2013) need be complemented by local-scale actions that reduce specific impacts (e.g., anchoring, Beeden, R et al. 2014b; Dinsdale & Harriott 2004; Malcolm 1998; Maynard et al. 2010). To adaptively manage coral reefs to support their natural resilience, managers need a dynamic understanding of reef health and condition, and of the critical thresholds that determine the future state of the reef areas that they manage (Mumby et al. 2011). Many reef systems are large and include remote sites impossible for a small group to regularly monitor, particularly in the Great Barrier Reef Marine Park (GBRMP), the world's largest coral reef ecosystem, which includes thousands of reefs more than 50 km offshore and/or hundreds of km from main population centres. However, thousands visit reefs in the GBRMP daily and Marine Park rangers visit hundreds of reefs every year creating the potential for visitors, reef users and rangers to provide information to reef managers. This potential has been utilised to assess individual impacts for a number of decades (see review by Kenchington 1978; and coral bleaching example in Marshall & Schuttenberg 2006). Full realisation of this potential is vital to gaining access to holistic information on condition and impacts with sufficient spatial and temporal resolution to inform actions and strategy. The focus of this thesis is the journey towards the goal of ensuring GBRMP managers have a dynamic understanding of reef condition.

Informing resilience-based management of the Great Barrier Reef forms the unifying theme of this thesis. My overarching goal has been to build capacity among a range of different types of observers to assess and monitor coral reef condition and impacts in the Marine Park; a goal that has been achieved through a collaborative process that I co-led during my candidature that was enabled by my role at GBRMPA. The parts of the process I directly led involved all of the following: (1) ensuring cryptic impacts like coral disease could be correctly identified (Chapter 2), (2) developing a strategic framework for responding to coral disease when disease prevalence is found at outbreak levels (Chapter 3), and (3) developing a survey methodology that meets management needs but fits within the time and knowledge/skill constraints of non-specialists (Chapter 4). I then (4) tested the utility of the survey methodology and participatory monitoring network by assessing spatial variation in the impacts of a severe cyclone (Chapter 5) and (5) assessed the effectiveness of a management action (Chapter 6). The published descriptions of these five parts of the progression of my work as a GBRMPA manager form the data chapters within this thesis.

The specific objectives addressed by the thesis chapters build on one another and are inter-related; all are work programs that relate to building a dynamic understanding of reef health to manage the GBR adaptively (Figure 1.1). At the commencement of my PhD research, I identified the following management needs, and formulated the accompanying specific objectives that were designed to address these needs.

1. Building capacity - Create a guide that builds capacity to identify coral disease and assess reef health impacts (Chapter 2).

2. Strategic response planning - Develop a response framework for managers for coral disease that links information on status to management actions (Chapter 3).

3. Participatory monitoring - Iteratively develop and refine a monitoring protocol that enables rapid assessments of reef health by a range of observer types complemented by a data storage and reporting system that meets the adaptive management information needs (Chapter 4).

4. Impact assessment - Demonstrate the capacity of non-specialist observers to quantify impacts following a major reef health disturbance (Chapter 5).

5. Evaluating actions - Use the protocol developed and the participatory monitoring network to test the effectiveness of a management action (Chapter 6).

Figure 1.1. Conceptual diagram relating thesis chapters (C2-C6) to an adaptive management cycle. The expressions used to describe the chapter content represent capabilities that coral reef managers need to invest in so that dynamic reef health information can inform adaptive resilience-based management. The graphic is shown again at the start of each chapter with a caption that describes how that chapter's content builds on that of the preceding chapter. The graphic is also reviewed in the conclusion to describe the implications of this body of thesis work for the future of GBR management.

Each chapter begins with an abstract, and where applicable, the chapters end with a section on management applications that details how managers in Queensland and the Indo-Pacific are already using outputs of the work presented here. The concluding chapter, Chapter 7, contains an overview of key findings and outcomes, and focuses on how the objectives described above were met and how they are linked. The document concludes with my personal vision for the most logical progression from here to build on areas of research and work contained within this thesis.

CHAPTER 2

Development of a decision tree and field guide for assessing coral health impacts on Indo-Pacific reefs

Marine biologist from Reef Check Australia using the *Underwater Cards* developed to help observers distinguish among coral diseases and other reef health impacts in the Indo-Pacific.

This chapter describes the process through which capacity to identify coral diseases and other reef health impacts was built throughout the Indo-Pacific through the development and distribution of an underwater field guide.

Source Reference:

Beeden, RJ, Willis, BL, Raymundo, LJ, Page, CA & Weil, E 2008, *Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs.* Coral Reef Targeted Research & Capacity Building for Management Program, St Lucia. http://www.gefcoral.org/Portals/53/downloads/disease_products/0807%20Indo%20Pacific%20Underwater%20ID%20Cards.pdf

2.1 Abstract

Outbreaks of disease can cause extensive coral mortality and are expected to occur with greater frequency and severity on Indo-Pacific reefs as the climate changes. Disease also affects coral resistance to and recovery from other disturbances, like cyclones and predation; therefore, an understanding of disease dynamics is a valuable indicator of reef resilience. Because the signs of coral diseases are cryptic, challenging to identify and difficult to distinguish from other reef health impacts, there is a critical need to build capacity to accurately identify diseases and infer potential causes. Increased capacity to identify coral diseases will: 1) alert management and research communities to the occurrence of disease outbreaks, 2) increase current understanding of disease dynamics and their influence on reef resilience, and 3) enable targeted management responses to address this emerging threat to Indo-Pacific reefs. To meet this need, an underwater field guide was designed, published and made publicly accessible via the World Bank-funded Global Environment Facility's Coral Reef Targeted Research website. The guide's structure is based on a decision tree that classifies diseases affecting stony corals and other reef organisms based on their visible signs. The presence of three types of signs helps to classify coral diseases: tissue loss causing partial colony mortality, tissue discolouration, and anomalous growth. Within these broad classifications, other signs can be used to help identify both the specific disease and the potential cause. The guide has 8 main sections: (1) Tissue loss – Predation, (2) Tissue Loss – Non-Predation (coloured bands), (3) Tissue loss – Non-Predation (no coloured bands), (4) Tissue discolouration (white), (5) Tissue discolouration (non-white), (6) Growth anomalies, (7) Other indicators of compromised health, and (8) Diseases in other reef organisms. Within each section, the following information is provided: a description of each reef health impact, causative agents when known, key identification characteristics, and a list of other diseases or impacts that can commonly be confused with the disease. Images of diseases and other common signs are shown throughout the guide at the polyp and whole-of-colony scale. The guide was published in 2008, and is now widely used throughout the Indo-Pacific by researchers, tourism operators, conservation staff, and park rangers.

2.2 Introduction

Corals, like all animals, can be affected by a range of diseases (Burge et al. 2014; Harvell et al. 2007). More than twenty different coral diseases have been described based upon macroscopic signs (Bourne et al. 2009; Harvell et al. 2007), although infectious agents have been identified for only a small subset of these (reviewed in Raymundo et al. 2008). Current understanding of the microbial associations that underpin coral health is also generally poor. Reef-building corals live in close association with endosymbiotic algae called zooxanthellae (*Symbiodinium* sp.) and with diverse microbial communities that live on and within coral tissues (Ainsworth & Hoegh-Guldberg 2009; Harvell et al. 2007; Ritchie 2006). The combined coral-microbial complex is referred to as the coral holobiont (Margulis & Fester 1991; Rosenberg et al. 2007; Rowan 1998). As a relatively simple invertebrate, the coral animal has an innate immune system (Mydlarz et al. 2009; Willis, Page & Dinsdale 2004); however the combined coral 'holobiont' also displays characteristics akin to the adaptive immune systems found in vertebrates (Bourne et al. 2009; Reshef et al. 2006). Recent research indicates that changes in microbial communities associated with corals may provide immune functions similar to that of acquired immune systems (Mydlarz et al. 2009; Palmer, Bythell & Willis 2010; Palmer, Mydlarz & Willis 2008; Palmer et al. 2011; Ritchie 2006), and that the coral holobiont should be considered as the evolutionary unit of adaption (Rosenberg et al. 2007). It is likely that the complex associations that comprise the coral holobiont have contributed to the persistence of corals over millennia (Bourne et al. 2009; Burge et al. 2014; Harvell et al. 2007; Rosenberg et al. 2007; Willis et al. 2006). However, the future persistence of corals is increasingly threatened by a changing climate and other anthropogenic disturbances (Veron et al. 2009). Holobiont health (coral health) can be compromised in a number of ways, highlighting the need for greater understanding of coral diseases, their causes and enhanced capacity to detect coral disease outbreaks by their characteristic signs.

Health in corals and other animals is a dynamic balance between host susceptibility to infection and pathogen load and virulence. Changes in environmental conditions can shift the fulcrum to favour either the diseased or healthy state (Altizer et al. 2013; Burge et al. 2013; Burge et al. 2014; Harvell et al. 2009; Harvell et al. 2007). For example, environmental conditions can: 1) increase the virulence or abundance of coral pathogens (Bourne et al. 2009; Harvell et al. 2007; Mydlarz et al. 2009; Raina et al. 2010), 2) increase the susceptibility of the coral host to infection (Rosenberg et al. 2007), and/or 3) result in changes in the typical microbial community associated with the healthy coral holobiont (Ainsworth & Hoegh-Guldberg 2009; Bourne et al. 2009; Littman, Willis & Bourne 2011; Mieog et al. 2009; Mydlarz et al. 2009; Raina et al. 2013; Sato, Willis & Bourne 2009). All three changes in host-pathogen dynamics can be caused by changes in environmental conditions that are either gradual and chronic (Burge et al. 2014; Harvell et al. 2007; Rosenberg & Ben-Haim 2002) or abrupt and acute (Haapkylä et al. 2013; Haapkylä et al. 2011; Osborne et al. 2011; Raymundo et al. 2008). Examples of rapid acute impacts to coral health include mechanical damage caused by tropical cyclones (Haapkylä et al. 2013; Osborne et al. 2011), low salinity stress caused by exposure to freshwater inundation (Haapkylä et al. 2011; Thompson et al. 2011), and thermal stress caused by anomalously warm sea temperatures (Bruno et al. 2007; Harvell et al. 2009; Ruiz-Morenol et al. 2012; Selig et al. 2006; Thompson & Dolman 2010). Variation in disease susceptibility among coral species and in virulence among the causative agents of coral diseases (Mydlarz et al. 2009; Palmer, Bythell & Willis 2010; Zilber-Rosenberg & Rosenberg 2008) suggests that reef resilience (the capacity to resist and or recover from diseases) is dependent on the structure of coral communities, coupled with their exposure to pathogens and unfavourable environmental conditions.

Over four decades of research on the impacts of thermally-induced bleaching on coral communities (reviewed in Hoegh-Guldberg 1999; and Marshall & Schuttenberg 2006) has led to the practise of considering bleaching to be a process distinct from disease, and has even led to controversy over what constitutes coral disease (e.g. Lesser et al. 2007; but see Work et al. 2008) . Coral health and disease dynamics are still poorly understood though knowledge is improving (reviewed in Raymundo et al. 2008; and Ruiz-Morenol et al. 2012). Although diseases caused by environmental (abiotic) conditions can be considered to have different disease causation mechanisms than infectious (biotic) diseases (Bourne & Webster 2013; Burge et al. 2014), long-established biomedical definitions clearly identify any interruption, cessation or disorder of body functions, systems or organs as a disease (Cutler & Hensyl 1976;

Wobeser 2006; Work et al. 2008). Moreover, the classic epidemiological triangle highlights that the host, causative agent and the environment are all involved in disease causation; thus from the perspective of the holobiont, it can be difficult to distinguish the proximate (pathogen) and ultimate (changed environment) cause of many diseases (Aeby et al. 2011; Ainsworth et al. 2007; Bourne et al. 2009; Burge et al. 2014; Pollock et al. 2014). Coral bleaching occurs as a consequence of a breakdown in the coral-zooxanthellae symbiosis that is integral to coral health, and thus clearly falls within the abiotic class of coral diseases (Burge et al. 2014; Glynn 1993; Harvell et al. 2007; Hoegh-Guldberg 1999; Mydlarz et al. 2009). Under normal conditions, zooxanthellae perform photosynthesis and provide corals with food in the form of glucose in exchange for being provided a home. Under stressful conditions, such as anomalously warm temperatures combined with high light (the usual cause), zooxanthellae produce reactive oxygen species (ROS), which are toxic to the coral (Baker, Glynn & Riegl 2008; Glynn 1993; Hoegh-Guldberg 1999; Wooldridge 2010). In response, the symbiosis breaks down and the zooxanthellae are lost from the inner tissue layer (the gastroderm) of the host coral. Zooxanthellae give corals their healthy brown colouration, so once absent or in low densities, the white skeleton can be seen through the transparent coral tissue. Aside from elevated temperatures, bleaching can be caused by lowered salinity, altered ocean chemistry or infection by pathogens such as *Vibrio shiloi* (Glynn 1993; Hoegh-Guldberg 1999; Kushmaro et al. 1997). Bleached corals are still alive and zooxanthellae densities can return to typical levels, but if stress persists, coral mortality can be extensive (e.g., global bleaching event in 1998 (described in Wilkinson 2000); GBR-wide bleaching events in 1998 and 2002 (Elvidge et al. 2004)). The widespread practice of considering coral bleaching separately from other diseases has confounded a holistic understanding of coral health, warranting the development of a clear concise operational field guide to identify signs of coral health on the Indo-Pacific reefs.

Corals have a limited repertoire of macroscopic signs that signify stress or disease, with bleaching and tissue loss being the two most common signs. Visibility of white skeleton through transparent tissue during bleaching is visually striking, but the resulting white appearance of corals can be confused with macroscopic signs associated with other impacts. Predation and a range of diseases remove coral tissues to expose underlying white calcium carbonate coral skeleton. At first glance, tissue loss exposing white skeleton can look very similar to localised tissue bleaching, the difference being that predation and diseases cause partial mortality so the tissue is no longer present. Typically, white signs associated with tissue loss are ephemeral because turfing and other algae quickly colonise the skeleton. Consequently, mortality, both partial and whole-of-colony, can only be attributed to causative agents, like bleaching, predation or diseases that leave a white skeleton, if observations occur within days to a few weeks of the disturbance. Similarly, bleaching that does not kill corals may only be visible temporarily, limiting a manager's capacity to ascribe a causative factor. Coral diseases pose other challenges to observers aside from the transient nature of their impacts. For example, signs of many coral diseases (e.g. the presence of ciliates; see Figure 2.2) are more cryptic than the appearance of bare white skeleton. In summary, diagnostic signs of many coral diseases can be cryptic, ephemeral, challenging to identify, and difficult to distinguish, all of which poses challenges for non-specialist observers. In the Indo-Pacific, at least seven distinct infectious diseases have been described (Anthony et al. 2008; Bourne et al. 2008; Boyett, Bourne & Willis 2007; Page & Willis 2006; Page & Willis 2008; Sato, Bourne & Willis 2009; Sussman et al. 2008; Willis, Page & Dinsdale 2004). Most of these share signs that can be confused with each other and with a range of other signs of compromised health that are typically seen on reefs in the Indo-Pacific. Accurately identifying diseases requires that observers know colony level signs of common diseases, know the potential causes of those signs, and can deduce which disease is the most likely cause of the signs (Raymundo et al. 2008).

Coral disease prevalence has been increasing on reefs around the world over the past few decades (Burge et al. 2014; Harvell et al. 2007; Raymundo et al. 2008; Rosenberg & Loya 2004; reviewed in Ruiz-Morenol et al. 2012; Willis, Page & Dinsdale 2004). This trend is expected to continue and disease outbreaks will likely occur more frequently as the climate changes and the frequency of disturbances on coral reefs increases (reviewed in Burge et al. 2014; Raymundo et al. 2008). The presence of coral disease can provide critical insights into reef health and resilience (McClanahan et al. 2012). However, the spatial and temporal constraints of most reef monitoring programs and similarities among the visible signs of disease mean it is easy to misidentify coral diseases and to miss (due to survey timing) disease progression and impacts. Clearly, building capacity to accurately identify diseases and infer potential causes is critically needed so that: 1) management and research communities know when outbreaks are occurring, 2) understanding of disease dynamics and their influence on reef resilience can be increased, and 3) management responses can be targeted to address this emerging threat to Indo-Pacific reefs.

To meet the urgent need for greater understanding of the impact of coral disease on coral reef communities, the Global Environment Facility's (GEF) Coral Reef Targeted Research program established an expert working group on coral disease, co-chaired by Professors Drew Harvell from Cornell University and Bette Willis from James Cook University (http://www.gefcoral.org/en-us/targetedresearch/disease.aspx). The group was tasked with summarising the current state of knowledge on coral disease processes globally and with developing tools to aid with identifying both diseases and potential management actions (e.g. Cohen et al. 2013; Harvell et al. 2007; Page et al. 2009; Raymundo et al. 2008; Ruiz-Morenol et al. 2012). I was included in the annual meeting of the expert working group in 2007 and suggested an underwater decision support tool as a partial solution to helping non-specialist observers identify Indo-Pacific coral diseases. My objective for research described in this chapter was to develop a decision support tool, in the form of an underwater field guide for Indo-Pacific coral diseases, to enable reef users and managers to detect the early signs of coral disease outbreaks and inform the implementation of response actions (see Chapter 3). The following sections describe the process by which the content for the decision support tool was structured and how the final product was designed, constructed and then distributed and used.

2.3 Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs

2.3.1 Guide Content structure and layout

Through discussions with members of the GEF Coral Disease Working Group (CDWG), key criteria for the underwater field guide were identified. As the first step, a decision tree was developed in the form of a polytomous key to enable users to distinguish among visible signs of disease (Figure 2.1). The decision tree also fulfilled the dual purpose of providing an index for the field guide. At the highest level of the decision tree hierarchy, coral health impacts are classified into groups that share characteristic visible signs: (A) tissue loss leading to partial colony mortality (colour coded red/orange in the tree; Figure 2.1), (B) tissue discolouration (colour coded blue), and (C) anomalous growth (colour coded green). Subdivisions within each of these three primary groups correspond to sections numbered 1-6 in the Tree. The Tissue Loss group (A) includes sections: (1) Tissue loss – Predation, (2) Tissue Loss – Non-Predation (coloured bands), (3) Tissue loss – Non-Predation (no coloured bands). The Tissue Discolouration group (B) includes sections: (4) Tissue discolouration (white) and (5) Tissue discolouration (non-white). The Growth Anomalies group (C) comprises section (6) Growth anomalies. Sections 1 – 6 are distinct from the final two sections in the guide sections 7 (Other Indicators of Compromised health) and 8 (Diseases in other reef organisms). Other indicators of compromised health could be considered to be signs of disease, however, they have not yet been classified as such. Hence, these last two sections are maintained as separate sections to help observers to distinguish them from the specific diseases that have been described in the Indo-Pacific. Section 8 on ‘Diseases affecting other reef organisms’ was included to assist untrained observers in distinguishing diseases affecting organisms from those that affect stony corals. Overall, the hierarchical nature of the decision tree (Figure 2.1) is arranged as a tool that enables differential diagnosis, with the most likely cause of each observable sign listed first followed by other impacts encountered less frequently.

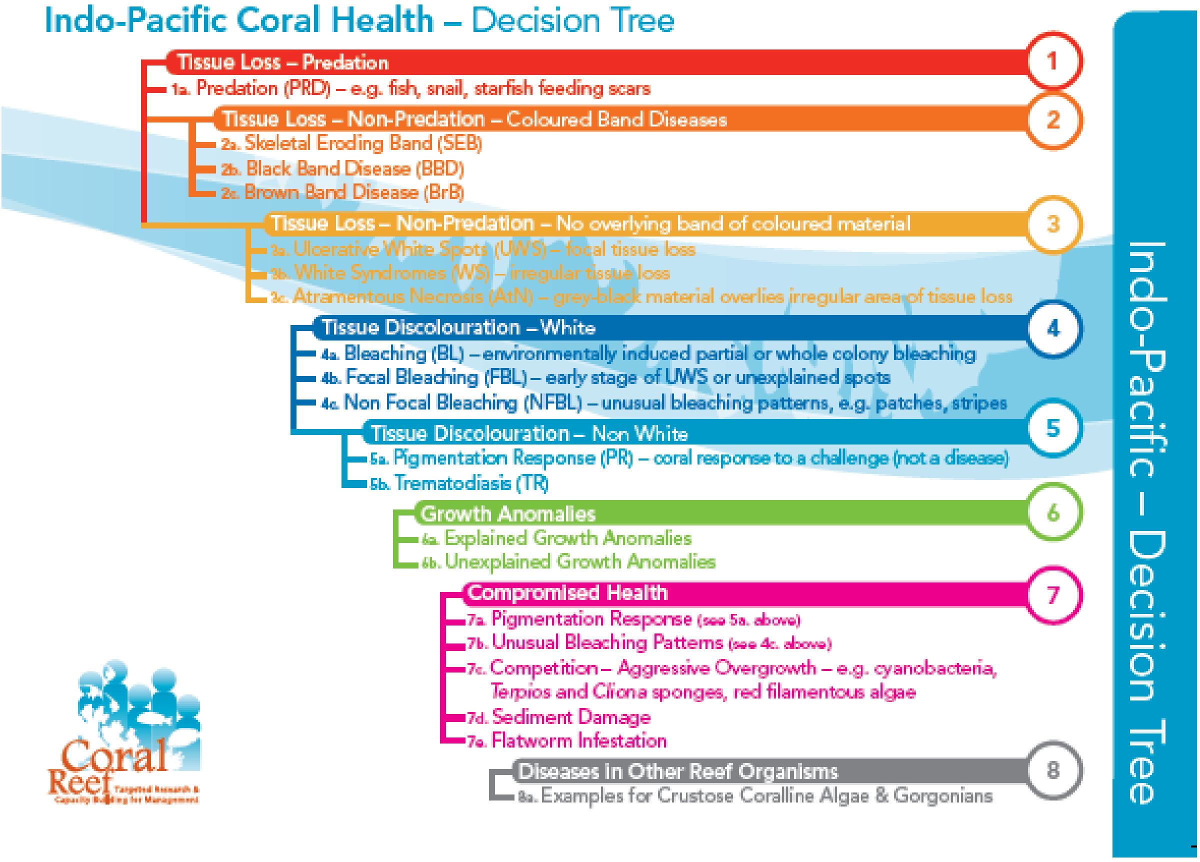

Figure 2.1: Decision Tree for Indo-Pacific Underwater Cards. The decision tree serves as a dichotomous key – users can determine the likely classification and cause of impacts to coral health based on characteristic visible signs. The tree also serves as a visual index as the colours used match the colour-coded titled index bars in the right-hand margin of each content page.

A number of choices were made with respect to the content, design and layout of the Guide to ensure the final product facilitated its use underwater. For example, the main groups and sections in the decision tree are colour coded so that the tree serves as a readily accessible, visual index. Users can easily pair pages within the guide with the relevant visible signs described in appropriate section of the decision tree, as all guide pages include a colour-coded titled index bar along the right-hand margin (Figure 2.2). Furthermore, in keeping with the concept and target audience for the Guide, content within the various pages was set out to help users identify a disease and to distinguish diseases from other reef health impacts that have similar signs. The standardised layout places text on the left hand side of each page at a font size that is easily read through a mask (noting the 33% page magnification underwater). Following the colour-coded title, information is provided in succinct bullet points, with text divided under three subheadings: ‘Description’, ‘Key ID characteristic’, and ‘Commonly confused with’ (Figure 2.2). These subsections provide details of the cause (where known), features and scale of each impact, the key visible differentiating characteristics, and the other impacts with which the signs may be easily confused. Page text was written to be as concise and simple as possible, with clear headings that serve as memory prompts for the user to differentiate between similar signs. Where relevant, circled numbers (corresponding to numbered circles on images) are appended after specific bullet points to highlight specific parts of the images provided within the page (Figure 2.3).

On each page, photographs of various diseases and impacts were sourced from CDW members and other disease experts to clearly illustrate the visual signs that can aid with differential diagnosis (Figure 2.3). Images for all diseases and impacts are shown at several scales, including the colony, branch, polyp (and microscopic level when available). Comparative images from different scales prompts users to examine affected coral colonies at the appropriate scale before reaching a conclusion (Figure 2.4). Photographs illustrating characteristic signs for each disease and other indicators or compromised health are placed to the right of the text. The right hand margin of each page is reserved for the visual index tab and number that corresponds to the decision tree. Section numbers are included on the bottom right corner of facing pages and the top right corner of reverse side pages. The dual page-numbering feature ensures users can rapidly flick through the guide and find the relevant pages when they are in the water, irrespective of the direction in which they flip through the pages (Figure 2.2).

Figure 2.2: Colour-based visual index facilitating use of the Guide underwater. Examples of the first page of four of the eight colour-coded sections of the field guide. The coloured, right-hand margin of each content page and the section numbering match that in the decision tree (see Fig. 2.1).

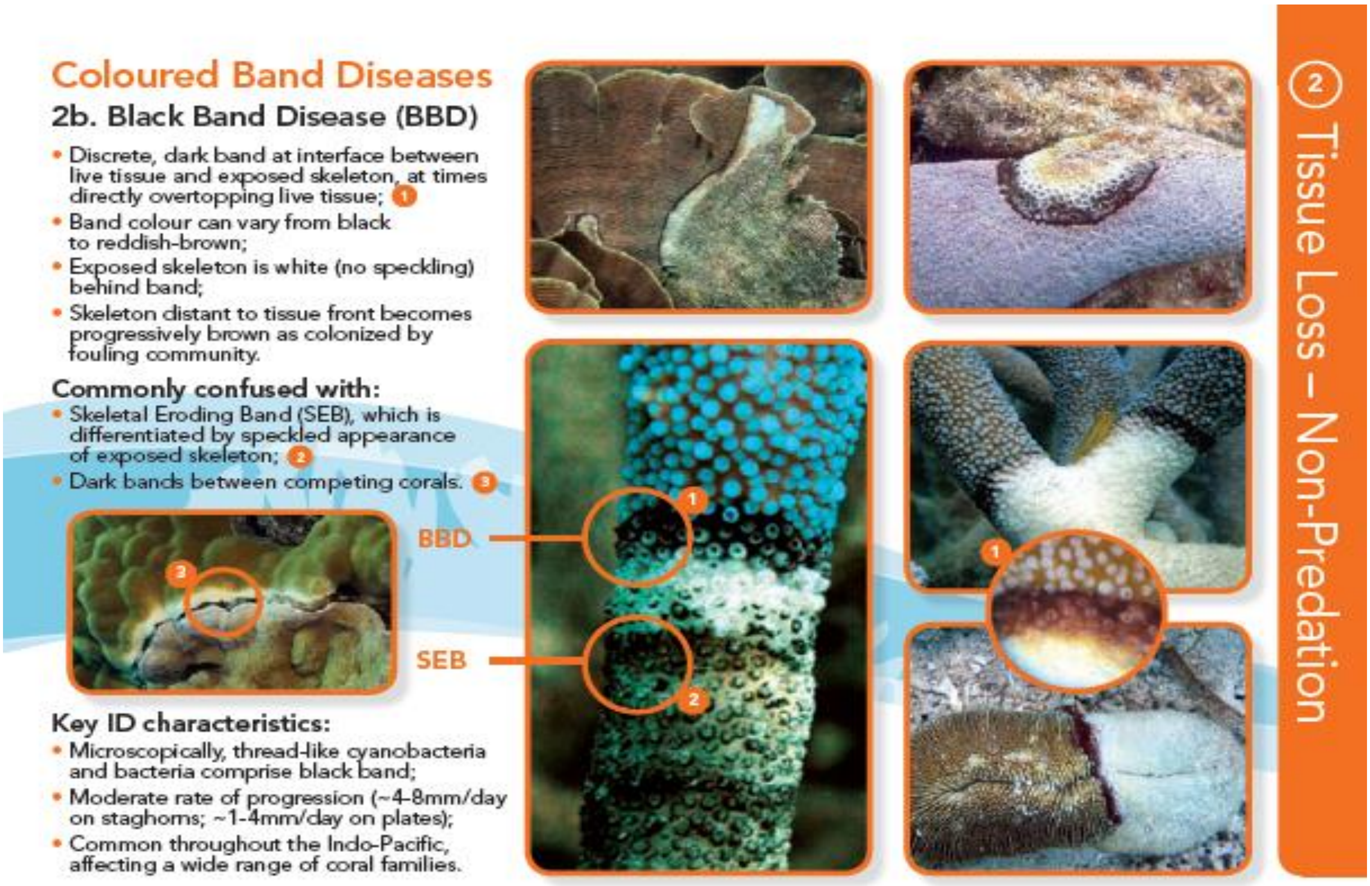

Figure 2.3: Standard page layout for *Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs* (Beeden et al. 2008). Left-hand side of page: a description of the impact is provided, key identification characteristics are described and references to commonly confused sign of reef health impacts are listed. Centre and right-hand side: images of the disease or other impact illustrate key signs at a range of scales. Highlighted numbers: these pair text with images illustrating key features/signs. Right-hand margin: titles and colour bars match the decision tree (see Figure 2.1).

To provide an overview of the common coloured band diseases in the Indo-Pacific and facilitate comparisons among their respective signs, the one exception to the standard layout is the first page of section 2: Tissue Loss - Non-Predation – Coloured Band Diseases. This page, entitled ‘Coloured Band Diseases’, contains images without text, and the images are arranged in a matrix, where the rows correspond to images of skeletal eroding band (SEB), black band disease (BBD) and brown band (BrB). Each column contains representative photographs taken at the same scale: whole of colony first, and then branch, individual polyps and microscopic images (Figure 2.4).

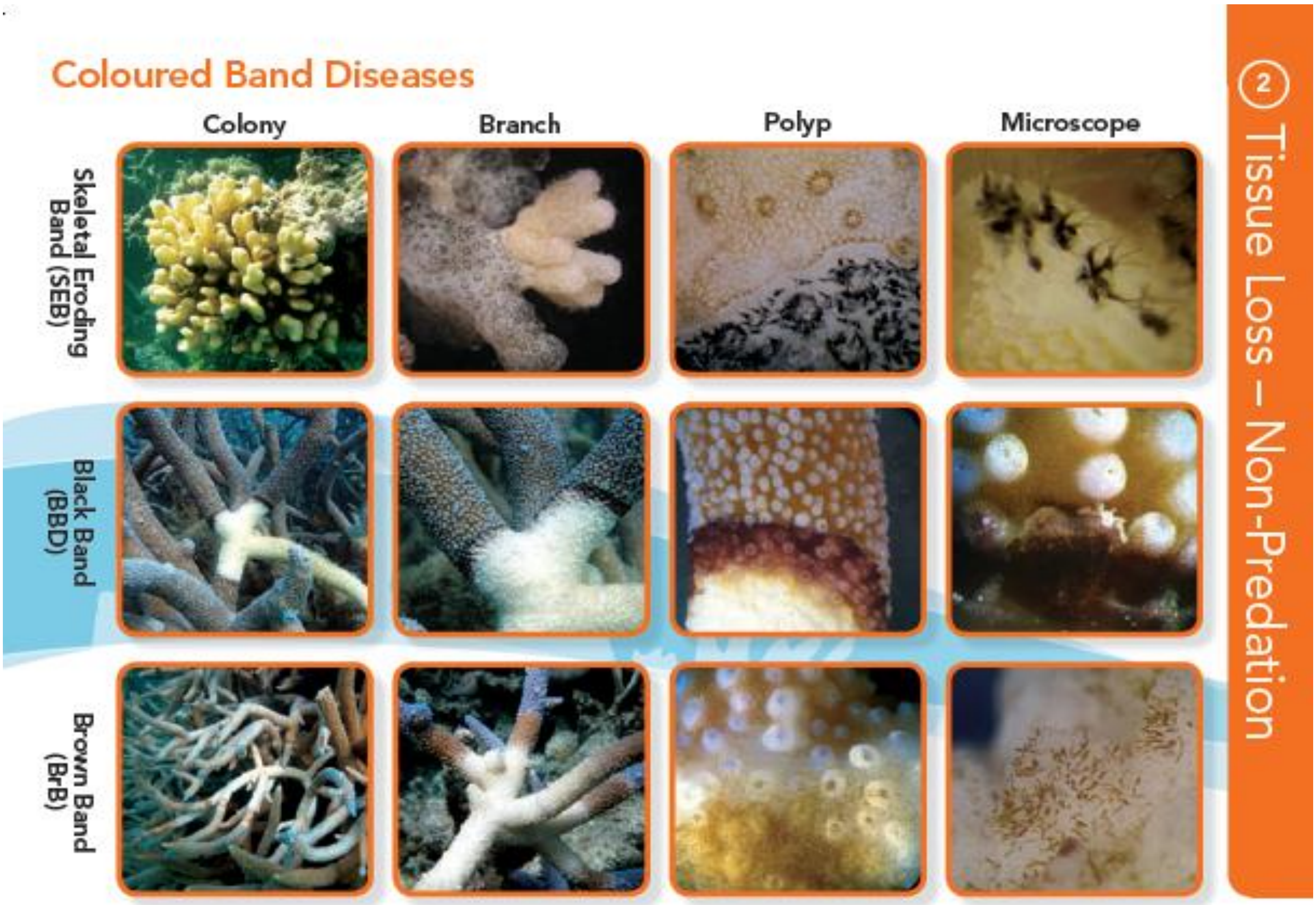

Figure 2.4: Overview of coloured band diseases to facilitate comparison of signs at different scales. Section 2, page 1 of Underwater Cards (Beeden et al. 2008). Reference images are shown here at a range of scales to assist users in distinguishing between the similar signs of these diseases, and to illustrate the pathogens that cause each of these diseases.

The Guide also contains three additional pages that further increase its usefulness as an Underwater Decision Support Tool. The first page describes the Guide's intended purpose and instructions for appropriate use (Figure 2.5). The penultimate page describes the most commonly used methods for surveying disease abundance, prevalence, incidence and / or progression (Figure 2.6). Lastly, a double-sided matte datasheet is included as the final page and is an adaptation of field datasheets used by members of the coral disease working group.

Recording & Reporting

Underwater Cards -
Options for Recording & Reporting Observations of Coral Disease

Qualitative observations of coral disease

At the simplest level, it is useful to photograph and / or record details of corals that are diseased or show signs of compromised health. The following data could be recorded:

Date & Recorder: __________

Site/Habitat/Depth: __________

Disease/compromised health sign: __________

Growth form/Genus/species of coral: __________

Photo name(s) & number(s): __________

Additional observations (e.g. #corals/species affected): __________

Quantifying observations of coral disease

Disease abundance: Recording the number of cases of disease per unit area without recording all healthy corals gives a measure of disease abundance. *To quantify disease abundance:*

1. Select an appropriate area (e.g. 20m x 2m belt transect);
2. Select appropriate replication (e.g. 3 belt transects per site);
3. Record all corals showing signs of disease or compromised health on the data sheet at the end of this guide;
4. Calculate mean (± SE) number of disease cases per 40m².

Disease prevalence: Recording the number of cases of disease and the total number of healthy corals per unit area gives a measure of disease prevalence. This is a better, but more time consuming way of quantifying disease.

1. Select an appropriate area (e.g. 20m x 2m belt transect);
2. Select appropriate replication (e.g. 3 belt transects per site);
3. Record all corals showing signs of disease or compromised health and all healthy corals on the following data sheets;
4. Calculate mean (± SE) percent of corals that are diseased per 40m².

Disease incidence: Tagging and monitoring the number of diseased corals in a given area through time identifies the number of new cases of disease per unit time and gives a measure of disease incidence or spread throughout the population.

1. Select an appropriate area (e.g. 10m x 10m quadrat) ;
2. Select appropriate replication (e.g. 3 quadrats per site);
3. Tag all diseased colonies within quadrats;
4. Monitor quadrats regularly (e.g. monthly), tagging all new cases of disease;
5. Calculate mean (± SE) # of new disease cases per unit time.

Disease progression: Tagging and photographing corals through time enables rates of disease progression across corals to be calculated.

1. Tag replicate diseased corals at study site;
2. Photograph each diseased coral with a scale bar and at a standard angle;
3. Re-photograph tagged corals at regular intervals (e.g. weekly or monthly) ;
4. Measure linear spread of disease front or progressive area of tissue loss from images;
5. Calculate mean (± SE) rate of disease progression.

We are grateful to the following people for images reproduced in these Cards: David Abrego, Greta Aeby, Shelley Anthony, Roger Beeden, Doug Fenner, Mike Flavel, Great Barrier Marine Park Authority, Mohammed Mohammed, Cathie Page, Laurie Raymundo, Marta Rodrigues, Kathryn Rosell, Emily Smart (Fantasea Cruises), Yui Sato, David Stewart, Meir Sussman and Bette Willis. We thank Greta Aeby, Andy Bruckner, Drew Harvell and Thierry Work for invaluable discussions during the genesis of these Cards. We thank the CRTR Program for its support and for funding this publication, and the ARC Centre of Excellence for Coral Reef Studies for funding the majority of research underpinning these cards.

Product code: CRTR 002/2008

Figure 2.5. Introduction and instruction page for the Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs (Beeden et al. 2008). Background on coral disease and the CRTR Disease Working Group is provided, and a description of what can be achieved using the cards and how to use them.

Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs

Roger Beeden[1,2], Bette L. Willis[1], Laurie J. Raymundo[3], Cathie A. Page[1], Ernesto Weil[4].

How to use these cards

Coral Disease

Coral reefs are under increasing stress globally from a number of causes, including climate warming, poor water quality and over-fishing. Disease outbreaks not only result in coral loss, but they also cause significant changes in community structure, species diversity and reef-associated organisms.

Coral diseases potentially impact both well-managed and unmanaged reefs. However, strategies for dealing with disease outbreaks are currently non-existent. The increasing frequency with which diseases influence and alter reef communities means they must be considered and incorporated into management plans.

The CRTR Disease Working Group

The CRTR *Disease Working Group* has been funded by the Coral Reef Targeted Research & Capacity Building for Management Program (CRTR) to advance understanding of coral disease in a number of key areas.

In particular, the CRTR *Disease Working Group's* research is providing a greater understanding of the ways in which coral diseases can alter reef function and the conditions under which outbreaks may occur. Documenting abundance and prevalence of disease and monitoring changes in disease through time are key steps in understanding how factors like ocean warming and deteriorating water quality may affect disease dynamics.

To assist with our objectives, the CRTR *Disease Working Group* has produced these Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs so that recreational, professional and scientific divers can all assist with gathering information on the occurrence of coral diseases.

By using these cards, you can:

- Learn to identify Indo-Pacific coral diseases and survey techniques for measuring coral disease prevalence;
- Gather information on the distribution and abundance of coral diseases on local reefs;
- Monitor the health of local coral reefs and identify potential drivers of disease abundance;
- Contribute to a world-wide data base on coral disease;
- Help to conserve the world's coral reefs.

How to use these cards

These cards start with a decision tree for assessing the health status of Indo-Pacific corals. The decision tree is colour coded to assist with navigation through the cards. After reviewing all disease descriptions and images to gain an overview of the range of signs of disease and compromised health, the following steps will enable you to assess the health status of a coral. Note that a variety of factors other than disease (e.g. predation, grazing) cause lesions.

1. Decide if a coral shows signs of tissue loss (red section), tissue discolouration (blue section), anomalous growth (green section) or some other sign of compromised health (yellow section).
2. At each level in the key for the coloured section selected, decide which category best describes the signs observed.
3. Go to the appropriate coloured section in this card set to check disease images and descriptions.
4. Record your observations on the data sheet provided at the end of this card set.

The CRTR Program is a partnership between the Global Environment Facility, the World Bank, The University of Queensland (Australia), the United States National Oceanic and Atmospheric Administration (NOAA) and approximately 50 research institutes and other third-parties around the world.

GEF

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Figure 2.6. Survey methods overview in the Underwater Cards. Text-based descriptions are offered on this page of the guide to aid observers in quantifying disease abundance, incidence and progression.

2.3.2 Construction and distribution of the guide

In addition to extensive consideration and testing of the contents and layout of the Guide (as described above), the utility and functionality of the field guide was maximised by careful consideration of the materials used in its construction. Each of the double-sided content pages is made from a flexible lightweight plastic, with a durable gloss lacquer finish over the pages to prevent scratching and the trapping of salt crystals. Following discussions with potential users, including dive tourism staff and community volunteers, dimensions of the Guide were constrained to enable it to be stored in pockets of SCUBA buoyancy compensation devices (BCD). The pages were designed to be slightly larger than the content so that a pencil could be attached and inserted through the spiral binding. The final page was printed with a matte finish so that observers could record their observations on the printed data sheet using the attached pencil. The printed version of the guide has a durable and flexible construction, including a clear cover to protect the guide pages from being scratched when stored with dive equipment.

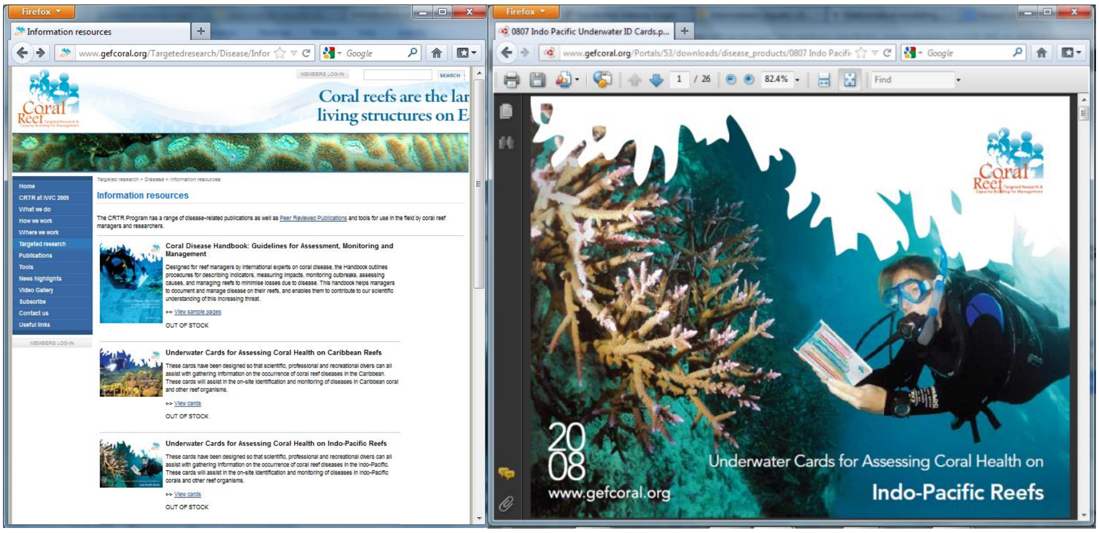


Figure 2.7: Final product: *Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs* CRTR distribution webpage (left), and Cover of Underwater Cards illustrating use during a training session on the Great Barrier Reef (right).

The field guide was completed in early 2008 and the full guide is included as Appendix 1 of this thesis. The guide was launched at the International Coral Reef Symposium in Florida in July of that year. The guide was made available at cost price ($24.20 AUD) to the general public immediately following its launch via the CRTR website (Figure 2.7). The original print run of 1000 guides sold out in 2010.

2.4 Use of the Guide and Future Plans

The decision tree and field guide have been used extensively since they were first published. To date, field guide users have primarily been tourism operator staff, marine park rangers, researchers and recreational divers. In the Great Barrier Reef Marine Park (GBRMP) the field guide has become a core capacity building tool to provide early warning system information for the Reef Health Incident Response System that I developed for the GBRMPA (Authority, GBRMP 2013a). Specifically, coral disease identification capacity developed through the use of the field guide is vital to the effective implementation of "the framework for responding to coral disease outbreaks that facilitates adaptive management" (see Chapter 3). Currently, the guide is a primary reference resource when training managers, rangers, tourism staff and community volunteers to conduct the Reef Health and Impact Survey (RHIS) protocol described in Chapter 4. The field guide has fulfilled its intended purpose in that a decision tree-based tool was developed and distributed and is now helping a wide range of observers to recognise the characteristic signs of coral diseases and compromised health in the Indo-Pacific.

Future revisions to the decision tree and field guide will include the addition of a section detailing signs of coral damage based upon the findings of the impact assessment conducted after Tropical Cyclone Yasi (see Chapter 5). It is also proposed that the slate included at the back of the field guide will be replaced with the datasheet I developed for RHIS. The inclusion of the RHIS protocol datasheet at the back of the revised guide will also require that the survey method, benthic categories and coral and macro algae life-forms used in RHIS are illustrated. All of this information is shown in the visual aid I developed to support RHIS (see Figure 4.4, and Appendix 2). A revised guide will be produced in the coming year and will contain updated photographs to improve clarity about reef health signs that have proven to be especially difficult to identify.

CHAPTER 3

A framework for responding to coral disease outbreaks that facilitates adaptive management

Diver from James Cook University examines white syndromes lesions while undertaking reef health surveys in the Far Northern Great Barrier Reef.

This chapter describes a strategic framework for responding to coral disease outbreaks that enables adaptive management and involves people trained to distinguish coral diseases using the *Underwater Cards* described in Chapter 2.

Source References:

Beeden, RJ, Maynard, JA, Marshall, P, Heron, S & Willis, B 2012, 'A framework for responding to coral disease outbreaks that facilitates adaptive management', *Environmental Management*, vol. 49, no. 1, pp. 1-13, doi: 10.1007/s00267-011-9770-9

Authority, GBRMP 2013a, *Coral Bleaching Risk and Impact Assessment Plan*, eds **RJ, Beeden**, JA, Maynard, J, Dryden & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville.
http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2810

Authority, GBRMP 2013b, *Coral Disease Risk and Impact Assessment Plan*, eds **RJ, Beeden**, JA, Maynard, J, Dryden & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville.
<http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2809>

Authority, GBRMP 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville.
<http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2808>

3.1 Abstract

Predicted increases in coral disease outbreaks associated with climate change have implications for coral reef ecosystems and the people and industries that depend on them. It is critical that coral reef managers understand these implications and have the ability to assess and reduce risk, detect and contain outbreaks, and monitor and minimise impacts. Here, I describe a coral disease response framework that I developed with strategic input from collaborators, which has four core components: 1) an early warning system, 2) a tiered impact assessment program, 3) scaled management actions and 4) a communication plan. The early warning system combines predictive tools that monitor the risk of outbreaks of temperature-dependent coral diseases with in situ observations provided by a network of observers who regularly report on coral health and reef state. Verified reports of an increase in disease prevalence trigger a tiered response of more detailed impact assessment, targeted research and/or management actions. The response is scaled to the risk posed by the outbreak, which is a function of the severity and spatial extent of the impacts. Potential management actions to mitigate coral disease impacts and facilitate recovery are reviewed, considering emerging strategies unique to coral disease and more established strategies to support

reef resilience. I also describe approaches to communicating about coral disease outbreaks that will address common misperceptions and raise awareness of the coral disease threat. By adopting this framework, managers and researchers can establish a community of practice and can develop response plans to manage coral disease outbreaks based on local needs. The collaborations between managers and researchers suggested will enable adaptive management of disease impacts based on cost-effectiveness evaluations of emerging response actions and will incrementally improve understanding of outbreak causation.

3.2 Introduction

Coral diseases can cause widespread coral mortality and have been a key factor in the degradation of important reef ecosystems, such as the Florida Keys (Porter et al. 2001) and the wider Caribbean (Pandolfi et al. 2005; Weil 2004). Because coral diseases can progress rapidly, there is often only a brief window of opportunity for observations that can confidently attribute mortality to agents of disease (Harvell et al. 2007). Some coral diseases are more prevalent in summer, like black band disease (BBD) (Sato, Bourne & Willis 2011; Sato, Bourne & Willis 2009) and white syndromes (WS) (Willis, Page & Dinsdale 2004). Summer provides a focal period for disease detection but even monitoring programs that visit sites repeatedly can underestimate disease-induced mortality if they are not undertaken when temperatures are at their peak. Therefore, the extent to which disease drives coral community structure – especially on Indo Pacific reefs – is largely unknown (Bruno et al. 2007; Sutherland, Porter & Torres 2004) and probably under-appreciated since it is likely that mortality caused by disease may be attributed to other disturbances (Osborne et al. 2011). The risk of more frequent coral disease outbreaks as the climate changes will be exacerbated by regional and local-scale anthropogenic stressors (Bruno et al. 2007; Marshall & Schuttenberg 2006). This makes it almost certain that coral disease will be an increasingly large contributor to coral reef decline as the climate changes this century (Harvell et al. 2007)

The ecological and social impacts of coral disease outbreaks can be severe, and a *Handbook* (Raymundo et al. 2008) has been produced that provides a review of management options and aids managers in the identification of diseases and the assessment of impacts when they occur. As yet though, there remains little guidance for coral reef managers faced with the need to operationally respond to coral disease outbreaks in a clearly defined, structured manner. From this point forward, 'managers' refers to anyone who has a responsibility to respond over any time scale to coral reef health impacts from the perspective of impact mitigation, communications, or policymaking. Response actions for managers include: determining where outbreaks are likely to occur, effectively targeting response capacity and prioritising management investment, mitigating impacts at severely affected sites, trialling various emerging strategies, and communicating with other managers and stakeholders about outbreaks and their impacts. Guidance in all of these areas is critical given the prospect of increasingly frequent coral disease outbreaks and increasing expectations of a meaningful management response (Raymundo et al. 2008). The framework for responding to coral disease outbreaks presented in this chapter helps meet these emerging challenges, enabling a structured adaptive response to this important emerging risk.

The framework has four core objectives:

1. To increase our understanding of coral disease outbreak causation and help elucidate the relative importance of climate-related and anthropogenic stressors as drivers of outbreaks.

2. To enable rigorous assessments of outbreak severity so that the investment of management responses can relate directly to the severity and spatial extent of the impacts.

3. To facilitate prioritisation (based on cost-effectiveness and successful trials) of emerging responsive management actions that mitigate disease impacts or enhance recovery.

4. To ensure timely and credible information on coral disease outbreaks is made available to inform management responses and raise awareness of the coral disease threat amongst stakeholders.

The coral disease response framework is based on the widely adopted response framework for coral bleaching (see Maynard et al. 2009), which also has 4 components (Authority 2013a): an early warning system, impact assessment and monitoring, management actions, and communication. Although the framework component names are shared, the nature of coral diseases and coral disease outbreaks requires that managers develop a response plan based on a framework that is distinct from bleaching because: a) diseases affect corals year-round rather than seasonally, b) diseases can be cryptic and can be difficult to identify rather than nearly always being visible at great distance, c) there is greater scope for management action at a range of spatial scales, and d) coral disease outbreaks pose unique challenges for communications given the potential for misperceptions and lack of understanding of what coral disease outbreaks mean for human communities.

Each component of the framework forms a section of the chapter and has been set up to be readily adapted by managers everywhere. Managers can prepare a tailored response plan based on the framework presented here by adapting the parts of the framework they find most applicable and relevant in their management area and given their organisation's structure and resources.

The early warning system section describes tools that predict the likelihood of outbreaks of temperature-dependent diseases (Heron et al. 2010; Maynard et al. 2011). These tools are combined with a monitoring network that can both ground-truth predictions and report to managers when anomalous levels of disease are observed. Managers can either use the guidance here to develop their own predictive tools and monitoring networks or can use or tailor those already established. In the impact assessment and monitoring section, reports of outbreaks trigger site inspections that are used to determine whether further management investment is warranted in more detailed impact assessments. Managers can either undertake impact assessments themselves or collaborate with those implementing other monitoring programs and/or with researchers. If outbreaks are documented during impact assessment, management actions and communications efforts are triggered that vary from targeted research to temporary closures, reef restoration, trials of emerging strategies to mitigate the impacts of coral disease, and communication. A range of management actions and communications approaches are proposed so that all managers have at least some options and to provide implementation guidance for the framework (Figure 3.1).

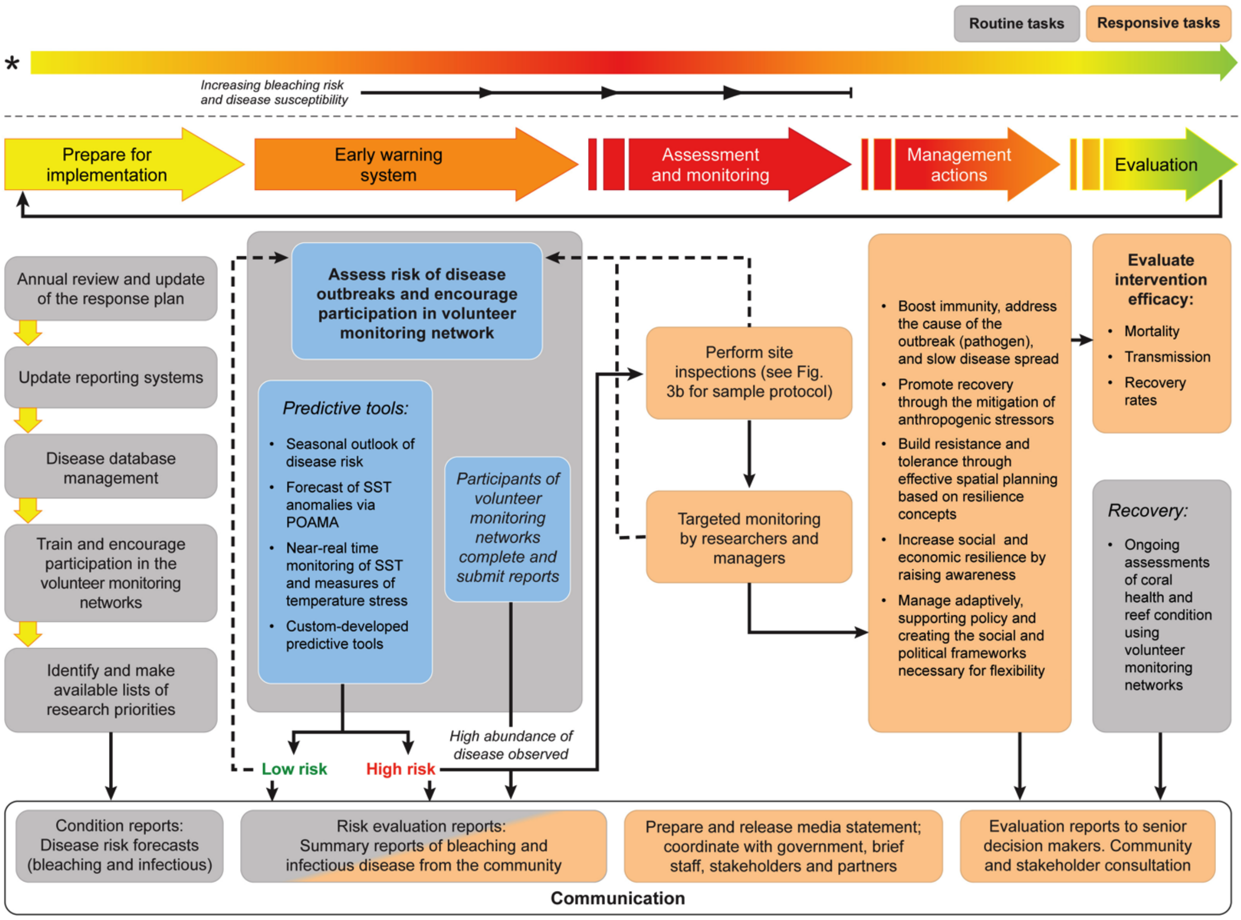


Figure 3.1. Flow chart describing routine and responsive tasks for the coral disease response plan framework. Famework implementation involves completion of routine and responsive tasks through the course of a year. The coloured bar running along the top highlights the elevated risk of outbreaks of some coral diseases during summer, though managers could be at any stage of the response framework during any part of the year (*), depending on when outbreaks are documented. The framework and its implementation are both necessarily adaptive; evaluation informs the preparations for implementation as the results of targeted monitoring and advances in research inform future management actions and iterative framework improvements.

3.3 Early Warning System

An effective response to coral disease outbreaks depends on knowledge of where they are likely to occur and/or timely receipt of in situ observations of an outbreak. Therefore, the early warning system has two parts: 1) predictive tools for assessing the risk of *temperature-dependent* disease outbreaks, and 2) a monitoring network (volunteer or otherwise) for in situ detection of *all* diseases that has the added benefit of strengthening relationships between managers, stakeholders and community members. More generic guidance on monitoring environmental conditions and assessing reef health can be found in the detailed publications available on these topics (e.g., Hill & Wilkinson 2004; Marshall & Schuttenberg 2006; Raymundo et al. 2008).

3.3.1 Predictive tools

Outbreaks of some coral diseases are caused by combinations of environmental and ecological conditions that can be used to assess outbreak likelihood. For example, researchers have shown that outbreaks of WS and BBD both appear to be seasonal, with the greatest prevalence detected at the end of hot summers (Bruno et al. 2007; Maynard et al. 2011; Selig et al. 2006). Tools that assess bleaching risk can also be useful for determining the likelihood that outbreaks of temperature-dependent diseases will occur because bleaching increases disease susceptibility (Mydlarz et al. 2009). For temperature-dependent diseases, there are four approaches to determining the likelihood that an outbreak will occur. Two are useful in the lead-up to summer: seasonal outlooks and forecasts of temperature anomalies. These help predict the likelihood of a spatially extensive bleaching event and are reviewed in (Maynard et al. 2009), so are not covered here. Two others are useful during the months when sea temperatures usually peak (summer or otherwise): near real-time monitoring of sea surface temperature (SST) and measures of temperature stress, and integrated risk prediction models. Tools that enable near real-time monitoring of SST and measures of temperature stress help to target surveys of bleaching impacts (Maynard et al. 2009), and managers can then survey these sites in the months that follow for disease. Here, I focus on new integrated risk prediction models developed specifically for a group of coral diseases called white syndromes (WS).

Seasonal outlooks for temperature-dependent diseases can be produced in the lead-up to the known risk period for outbreaks of temperature-dependent diseases (i.e., summer). Research in Australia suggests the likelihood of outbreaks of WS in summer is increased when preceded by mild winter temperatures (Heron et al. 2010, see Figure 3.2a). The experimental seasonal outlook product produced by NOAA Coral Reef

Watch is currently only available (at http://coralreefwatch.noaa.gov) for Australia's Great Barrier Reef and the Hawaiian archipelago but will become available for other reef regions as our understanding of the role of winter temperatures in causing coral disease outbreaks in other reef regions increases.

Forecasts of sea surface temperature (SST) anomalies are produced for the tropical oceans at lead times 0-5 months by the dynamical coupled ocean-atmosphere model POAMA (Predictive Ocean Atmosphere Model for Australia, available at: http://poama.bom.gov.au/experimental/poama15/sp_gbr.htm) (Spillman 2011; Spillman & Alves 2009; Spillman, Alves & Hudson 2011). In addition, NOAA Coral Reef Watch employs a statistical forecast model of SST to produce a 2-4 month outlook of global thermal stress (Liu et al. 2008; http://coralreefwatch.noaa.gov). In the months that precede the summer, these forecasts can be used in conjunction with the statistical seasonal outlook described above, providing managers with advance warning of the likelihood of anomalously warm temperatures, suggesting risk of a spatially extensive bleaching event, which would greatly increase susceptibility to disease at sites where bleaching occurs (Figure 3.2b). Current and past forecasts are presented in Google Earth™, so managers can readily compare forecasts for an upcoming summer to observations of past summers when bleaching events or disease outbreaks occurred.

The abundance of WS on the Great Barrier Reef has been related to temperature stress and coral host density (Bruno et al. 2007), leading to the recent development of two *near real-time* tools for monitoring likelihood of outbreaks of WS. Using a decision-tree approach, one tool (Heron et al. 2010) uses winter and summer sea temperature stress metrics at 50-km resolution to produce an outbreak risk assessment that has to be interpreted based on local knowledge of host density – i.e., risk is highest where coral cover is highest (http://coralreefwatch.noaa.gov). The complementary tool (Maynard et al. 2011) provides advanced capacity to inform management decision-making in two ways: (1) it is based on the high-resolution (~1.5 km) temperature data used for the *ReefTemp* product suite (Figure 3.2c, and see Garde et al. 2014; Maynard et al. 2008), thus the tool enables the monitoring of disease risk at the scale of an individual reef; and (2) an overlay of historical coral cover is included, so outbreak likelihood is only shown to be high for locations where long-term monitoring suggests host density exceeds an empirically derived threshold. The integrated risk prediction tool (Figure 3.2d) presented in (Maynard et al. 2011) is based on a multivariate regression model of disease abundance, temperature stress and coral cover calibrated against the values for each variable documented during an known outbreak of WS on the Great Barrier Reef (GBR).

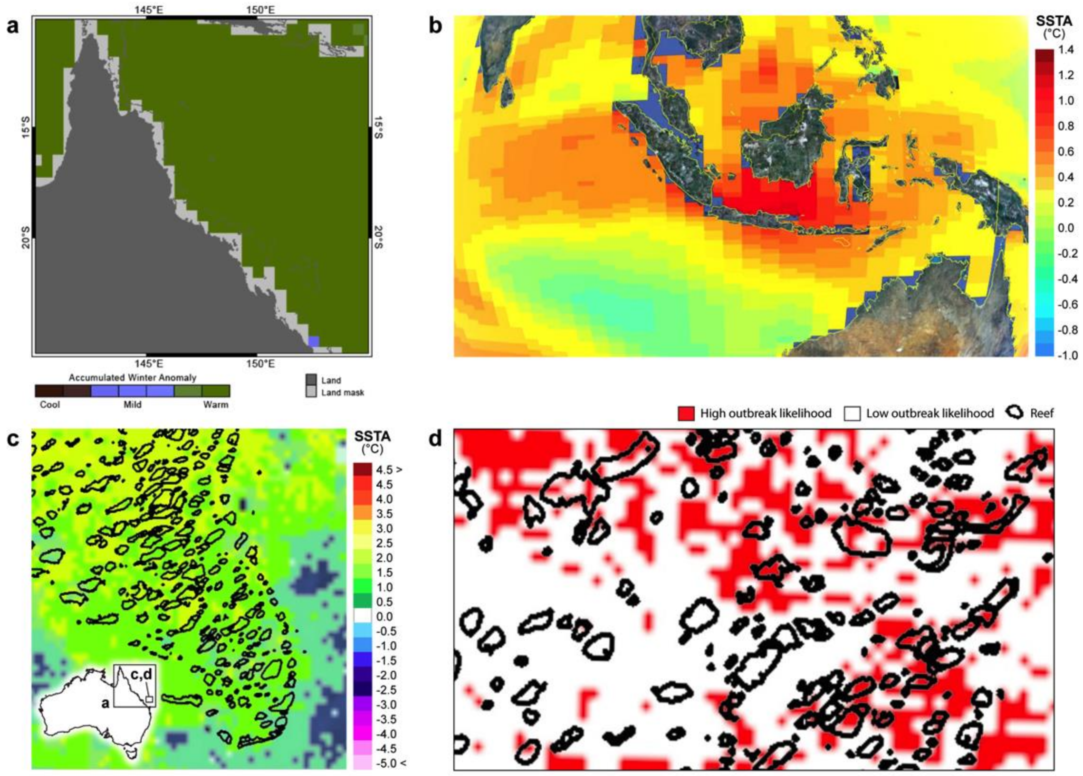


Figure 3.2. Predictive tools used in the coral disease outbreak early warning system. The experimental seasonal outlook of disease risk for the 2010/11 austral summer, issued October 2010, is shown in (a) and reflects that the 2010 winter was amongst the warmest on record for the area (Heron et al. 2010). The Bureau of Meteorology's POAMA forecasts of tropical sea surface temperature (SST) anomalies for SW Asia in February 2010, as of December 1st, 2009 are shown in (b). Tools from the ReefTemp product suite that enable remote monitoring of SST anomalies at the scale of individual reefs (c – from winter 2010), and the likelihood of outbreaks of white syndromes (d – from Swains reefs in the southern Great Barrier Reef in 2002). The images shown in (b, c and d) were produced in Google Earth™.

The value of the integrated risk prediction tool (Figure 3.2d) was demonstrated in the north-central GBR in 2009 when the tool correctly identified locations where abundance levels of WS were anomalous. Targeted expert prevalence surveys in these locations (Figure 3.3e) revealed more disease than was expected at sites with less than 50% coral cover (Maynard et al. 2011). This result suggested that the density of coral hosts required for WS outbreaks on the GBR is likely to be lower than earlier research had suggested (Bruno et al. 2007). The implication is that more reefs on the GBR are susceptible to WS outbreaks when temperature stress is severe than previously thought. This validation work has changed the way outbreak risk is calculated on the GBR enabling more targeted impact assessment and management responses.

Ground-truthing predictions made by predictive tools helps increase our understanding of the links between stressful temperatures and both the susceptibility of corals to diseases and the virulence of disease-causing pathogens. For now, these models are available for the Great Barrier Reef and Hawaii only and only for WS. However, the iterative approaches used to produce predictive models and tools can be applied to other diseases and/or reef regions. Models can be conditioned based on observations made at sites where disease outbreaks are known to have occurred in the past, then used to predict outbreaks, and validated and refined when stressful conditions suggest outbreaks will occur.

3.3.2 Monitoring Network

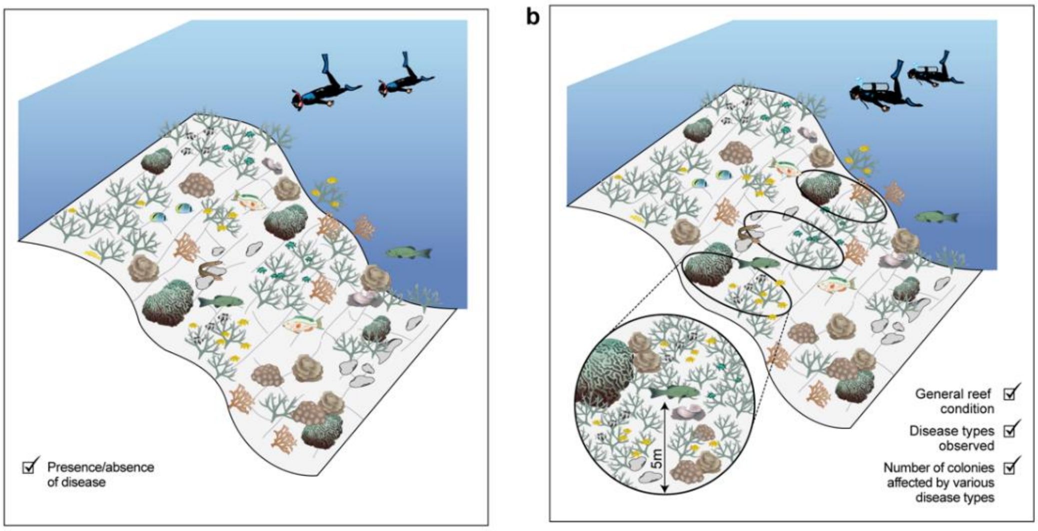
Detecting the early signs of a disease outbreak requires a network of observers because many reefs are visited by managers infrequently and because a disease outbreak can spread quickly (Francini-Filho et al. 2008). For temperature-dependent diseases, observer networks can ground-truth predictions made by tools that predict bleaching, as well as the models predicting disease described above and others like them when they become available. For all other coral diseases, networks can provide cost-effective reports on disease abundance from sites throughout a management area (see Mayfield, Joliat & Cowan 2001for a general review).

During the 2002 coral bleaching event GBRMPA established *BleachWatch*, a community based monitoring network designed to detect the early signs of coral bleaching (Marshall & Schuttenberg 2006). *BleachWatch* was subsequently adopted by NOAA, and the two networks have proven their merit by detecting the early signs of bleaching on the Great Barrier Reef and in Florida and helping to quantify the spatial extent and severity of bleaching events (Maynard et al. 2009). Establishing and maintaining volunteer monitoring networks requires: 1) identifying potential participants, 2) training and knowledge/skill testing, 3) data collection, and 4) facilitating communication between participants and managers (Musso & Inglis 1998). Several community-based monitoring programs have been established globally (e.g., ReefCheck, Global Coral Reef Monitoring Network (GCRMN)). Managers may find benefit in strengthening links with these networks to increase participation or improve alignment of the objectives of monitoring programs with the information needs of managers (as in Pattengill-Semmens & Semmens 2003). New networks can be set up, or existing networks can be aligned with the managers' information needs, irrespective of local resource availability. How each of the four steps recommended above are carried out, the technologies used, and the extent to which existing training materials and datasheets are tailored for local use can all be adapted to local resource levels.

The training required will vary with different observers (i.e., some participants will not need to be trained) and needs to focus on the data collection protocol (see Chapter 4) while also providing critical background and some insights as to how the information collected will be used. Ideally, the protocols used for monitoring networks will produce data that are comparable between reef regions (see Beeden et al. 2008 ; and Bruckner 2002). This suggests that protocols for regularly collecting coral disease data at the scale of the GBR should have the following characteristics: cover a defined area, produce estimates of the % of coral cover affected, list the number of colonies affected by the common types of coral diseases in a management area, describe the coral life-forms affected by each of the common diseases, and be able to be completed in a timeframe (10-20 minutes) that does not interfere with the reason the observer is visiting the reef (see Fig. 3.3b, c). The development, characteristics and use of the data collection protocol used by the volunteer monitoring networks in Australia is the subject of Chapter 4.

a

b



c

Coral disease			Present: Y / N			Photos taken: Y / N			
Proportion of coral cover affected	CORAL TYPE:		Soft coral	Branching	Bushy	Plate / table	Vase / foliose	Encrusting	Massive	Mushroom
%	Black band disease	Number of affected colonies								
%	Brown band disease									
%	White syndromes									
%	Other disease / tumours									

d

e

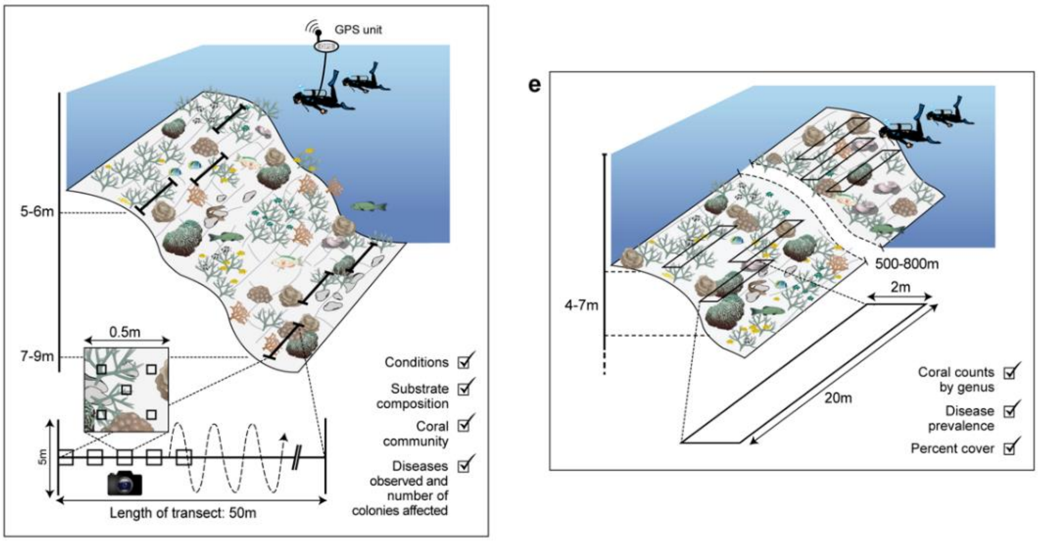


Figure 3.3. Suggested impact assessment (a-c) and monitoring protocols (d) for the response framework. The simplest surveys conducted by participants in a monitoring network might only record presence/absence of disease (a). The monitoring network of marine park rangers, tourism staff and volunteers on the Great Barrier Reef use the protocol shown in (b), as do managers when undertaking targeted impact assessments during site inspections, enabling completion of the table shown in (c) (See detailed description of development and use in Chapter 4). When outbreaks occur, surveying reefs using the protocol shown in (d) enables a rapid assessment of impacts and the creation of a longer-term record. Protocols forming a, b, and d are useful in determining 'status', measures of coral health and reef condition. Researchers can undertake (e) annually to determine trends in disease prevalence in an area.

In summary, a series (usually 3) of circular areas of reef with 5m radii are surveyed at the same depth and the number of colonies within eight life-form categories affected by common disease types are recorded, as is the coral cover, and percentage cover affected by disease (Figure 3.3c). Notes regarding the prevalence of other diseases can also be taken as can photos. More simply, managers can have participants collect data on presence/absence of diseases (Figure 3.3a). In this way, even when resources are limited managers increase the chance that they will detect disease and can get in contact with collaborating NGO's, universities, or other management agencies to determine whether more detailed assessment and monitoring can be undertaken.

Observations of diseases from a monitoring network can ensure broad coverage that may help make clear whether coral diseases are more or less prevalent in areas of higher relative anthropogenic stress. In this way, having an early warning system helps ensure that targeted impact assessment, monitoring and research efforts help to elucidate the relative importance of climate-related and anthropogenic stressors in disease outbreak causation (objective 1 of the framework). Monitoring networks can also promote stewardship (Savan, Morgan & Gore 2003; Stepath 2000) by encouraging members of reef-dependent industries (such as tourism and fishing), regular reef visitors, amateur naturalists and other enthusiasts to participate in monitoring while also tapping into the great wealth of their knowledge (see Chapter 4).

Monitoring seasonal outlooks of disease risk, sea temperature forecasts, measures of sea temperature stress in near real-time, custom-developed predictive tools (see Figure 3.2) and reports sent in by observers *all* form routine tasks carried out every year regardless of conditions (see Figure 3.1). 'Site inspections' will be conducted if conditions are highly conducive to disease outbreaks and/or reports of disease outbreaks are received from observers participating in a monitoring network. Site inspections form a responsive task and part of the impact assessment and monitoring component of the framework (Figure 3.1), discussed in the next section.

3.4 Impact Assessment

The overarching objective of the assessment and monitoring component (objective 2 of the framework) is to assess the spatial extent and severity of outbreaks as a foundation for: communicating the status of coral health and reef condition at impacted sites, making management decisions, and taking account of likely social and economic impacts. Both assessment and monitoring and management actions are responsive tasks in the framework (see Figure 3.1) and hence represent investment of management resources. A hierarchical approach whereby relatively small investments are made into site inspections first is valuable, since they can determine whether larger investments are justified. Under the framework site inspections are impact assessments at high risk sites. These surveys determine whether and where targeted research and monitoring should be undertaken, which, in turn, determines whether and where management actions should be taken, as well as what management actions are appropriate.

Locations may be classified as having a high risk of an outbreak due to conditions at the site being conducive to either bleaching or diseases. At these locations, site inspections will often be the first surveys conducted at the site since the onset of stressful conditions. Alternately, disease outbreak risk at a site may be classified as high due to the receipt of numerous reports of coral disease from participants in the monitoring network. In these cases, site inspections serve to validate observations made by observers participating in monitoring. In either case, the survey protocol could be that proposed for the monitoring networks (Figure 3.3d) and completed by either managers or collaborating researchers.

On the Great Barrier Reef (GBR), the severity of an outbreak is defined by a matrix of disease abundance (cases in a defined area) and the spatial extent of the outbreak – the number of reefs affected in the management area (see Figure 3.4). The matrix helps to scale management responses and could be adapted for any management area. Managers can work with researchers to determine what level of disease abundance or prevalence should correspond to the low, medium and high categories. Spatial extent may not be a useful component of a measure of the severity of threat posed by a disease outbreak in small management areas. For larger areas, managers can set the spatial areas (or number of reefs) that define local, regional and widespread. Managers may also want to simplify the matrix to low and high, and local and regional. In these cases, the severity of the disease threat either triggers a management response or does not, rather than the scaled responses produced by the 4x3 matrix shown in Figure 3.4. In the matrix used in the Great Barrier Reef, expert site inspections are triggered if disease abundance is high and/or medium disease abundance (see Figure 3.4) has been observed at reefs throughout the management area.

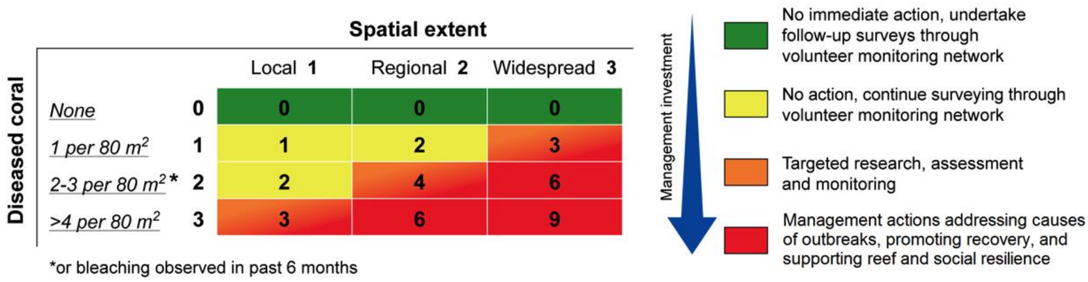


Figure 3.4. Extent and severity matrix for disease impacts. The matrix informs hierarchical investment of management resources. The criteria for each level of coral disease impacts and spatial extent can be adapted to local knowledge of diseases and the size and number of reefs contained within a management area. Values shown in brackets for the levels of coral disease impacts refer to those used in the Great Barrier Reef (based on Raymundo et al. 2008; and Willis, Page & Dinsdale 2004).

The approach to monitoring coral disease outbreaks on the GBR is similar to that used for bleaching for two reasons. Disease outbreaks require some of the same communication and engagement with the media and stakeholders (but see communications section below for more detail). Also, like bleaching events, disease outbreaks create opportunities for researchers and managers to collaborate to advance our understanding of outbreak causation and trial actions to mitigate impacts (see next section). Rapid assessments of outbreak severity are complemented with detailed surveys to meet communications and engagement requirements as well as take advantage of the research opportunities outbreaks present. The survey protocols used in the Great Barrier Reef for disease are shown in Figure 3.3 (b and e). The rapid assessments are conducted using the same protocol employed by the monitoring networks whereby disease cases are counted within 78.5 m^2 circles using a radial belt sampling method (Figure 3.3b, Chapter 4, Beeden, RJ et al. 2014). Detailed prevalence surveys involve counting all corals and disease cases on three 20 m x 2 m belt transects at two sites at each reef location (Figure 3.3e). The detailed surveys are undertaken in collaboration with researchers that identify infected and healthy corals to genus to help determine whether spatial patterns in disease prevalence are correlated with climate and/or anthropogenic stressors.

Given links between bleaching and disease, managers and their collaborators can look for disease when assessing the spatial extent and severity of bleaching impacts or when undertaking surveys to assess recovery from bleaching. Surveys of bleaching may work to target disease surveys to locations where bleaching was most severe (see * in Figure 3.4). This highlights that managers will want to train staff to identify a range of reef health impacts. Protocols used to monitor impacts are useful in determining the status of coral health and reef condition but managers may also want to work with researchers to develop a long-term monitoring program that can detect trends in disease abundance and prevalence (see Beeden et al. 2008; Page et al. 2009).

3.5 Levels of management responses in the GBR

GBRMPA uses the Australasian Inter-service Incident Management System (AFAC 2011) framework to coordinate the governance, planning, operations, logistics, financial and inter-agency liaison arrangements required to adequately respond to a reef health incident (see top of Figure 3.4). Information gathered from the early warning system and site inspections help managers understand the severity and spatial extent of impacts. Once the spatial extent and severity of the impact have been classified based on the standardised criteria for each incident, the matrix in Figure 3.4 is used to inform a detailed situation analysis.

The information presented within the situation analysis is assessed by the governance group to make a final decision on the required level of response. The situation analysis is assessed by the GBRMPA governance group (the executive management group, the incident coordinator and the scientific, communications and liaison, and stakeholder advisory groups), which makes a final decision on the required level of response (Figure 3.5). There are three potential response levels — 1, 2 and 3. Each increase in response level (from 1 to 3) correlates to a corresponding increase in the severity and spatial extent of the impacts as well as an increase in the management investment and resources required to effectively respond. The activation and conditional activation of the incident response framework varies according to each response level but the framework used for each of the three response levels is standardised for all reef health incidents.

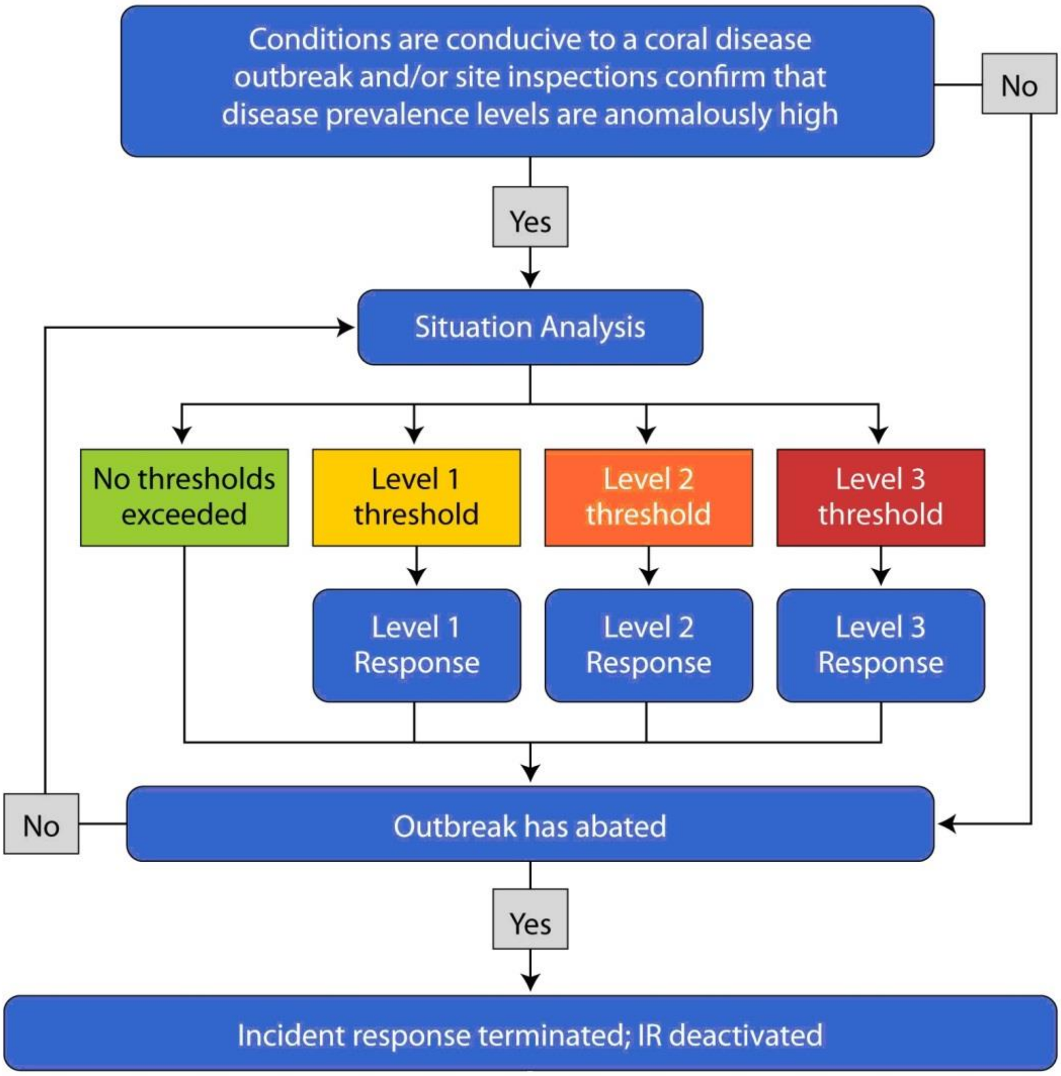


Figure 3.5. Incident response chain of events during a reef health event. The situation analysis is informed by the matrix seen in Figure 3.4 and is re-visited following responses if the high risk season has not passed. The flowchart is consistent with the recommendations of the U.S. Government's Field Manual for Investigating Coral Disease Outbreaks (Woodley et al. 2008, p. 14).

Once the appropriate response level has been determined, the corresponding planning and resource provisions of the incident response are activated. Communication, liaison, and reporting tasks are activated for all response levels. For response level 1, which may lead to response levels 2 or 3 if impacts become more severe or extensive through time, the logistics for extensive underwater surveys are only conditionally activated, and budgeting, contracting, staff procurement, and impact mitigation/recovery surveys are not activated (Figure 3.6). Conditional activation is based upon the type of incident and the outcome of the situation analysis. For response level 2, vessel support and underwater surveys are activated, as are budgeting and administration. Contracting, staff procurement, and impact mitigation/recovery surveys are all conditionally activated (Figure 3.7). For response level 3, the entire incident response framework is activated (Figure 3.8).

The degree of management investment in a response to a coral disease (or other reef health impact) is determined based upon the assessment of the risk of an outbreak and the reality of any outbreak observed in the field. The scaling of management responses to coral disease outbreaks in the Great Barrier Reef is dependent upon the disease impact matrix in Figure 3.4. Field observations that generate scores colour coded yellow (1-2) in figure 3.4 are assigned a response level of 1 (figure 3.5, 3.6). Scores colour coded orange (3-4) warrant a level 2 response (figure 3.5, 3.7) and regional or widespread outbreak scores colour coded red (>4) trigger a level 3 response (figure 3.5, 3.8).

The management resources that are mobilised for each level of response are depicted in Figures 3.6, 3.7, 3.8). Management resources are separated and organised based upon the Australian Interagency Incident Management System Australian Standard for incident response developed by the Australian Fire Service. Responses to coral disease outbreaks are organised and resourced in a consistent manner to that used for coral bleaching, and tropical cyclone impacts under the GBRMPA Reef Health Incident Response System (Authority, GBRMP 2013c).

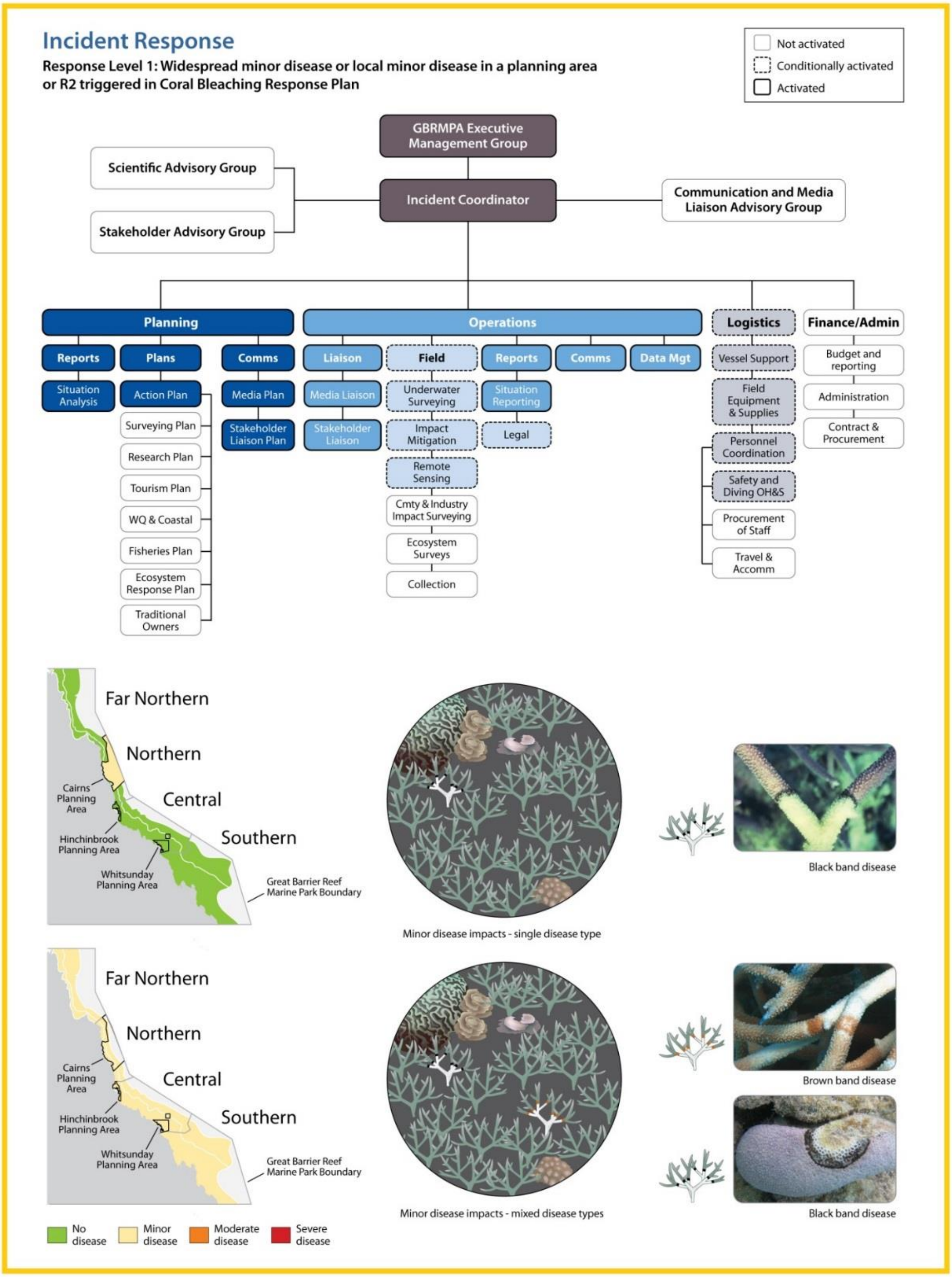


Figure 3.6: Response level 1 within the disease response plan framework. Activation and conditional activation of components are illustrated by the intensity of colour and border for each box within the diagram above. Scenarios shown in the maps are examples as are the disease types shown (i.e., local disease in a different planning area would result in the same management response, and so would different disease types). The response level 1 threshold can be reached due to the prevalence of a single disease type or numerous disease types.

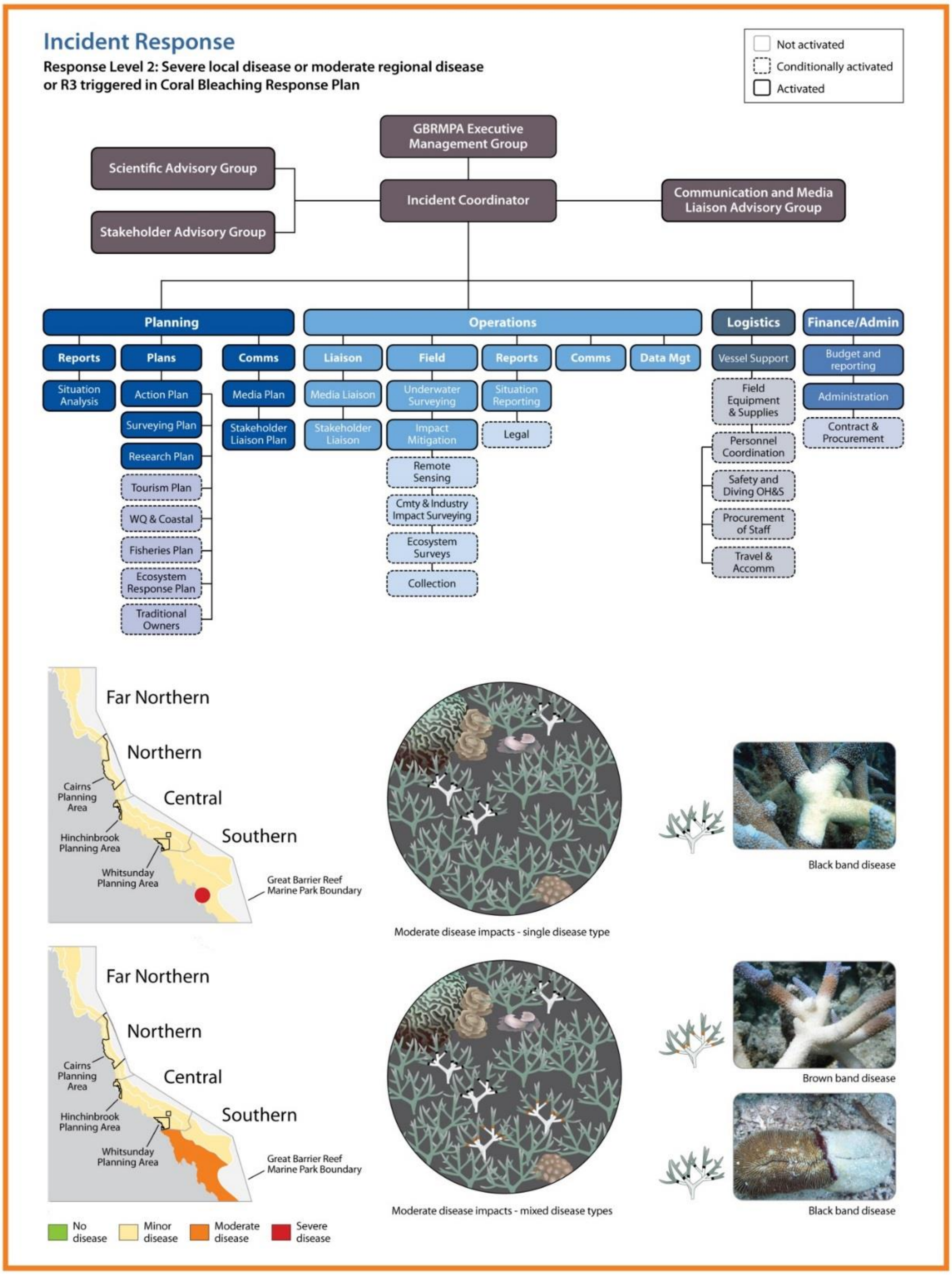


Figure 3.7. Response level 2 within the disease response plan framework. Activation and conditional activation of components are illustrated by the intensity of colour and border for each box within the diagram above. Scenarios shown in the maps are examples as are the disease types shown (i.e., local or moderate disease in a different region would result in the same management response, and so would different disease types). The response level 2 threshold can be reached due to the prevalence of a single disease type or numerous disease types.

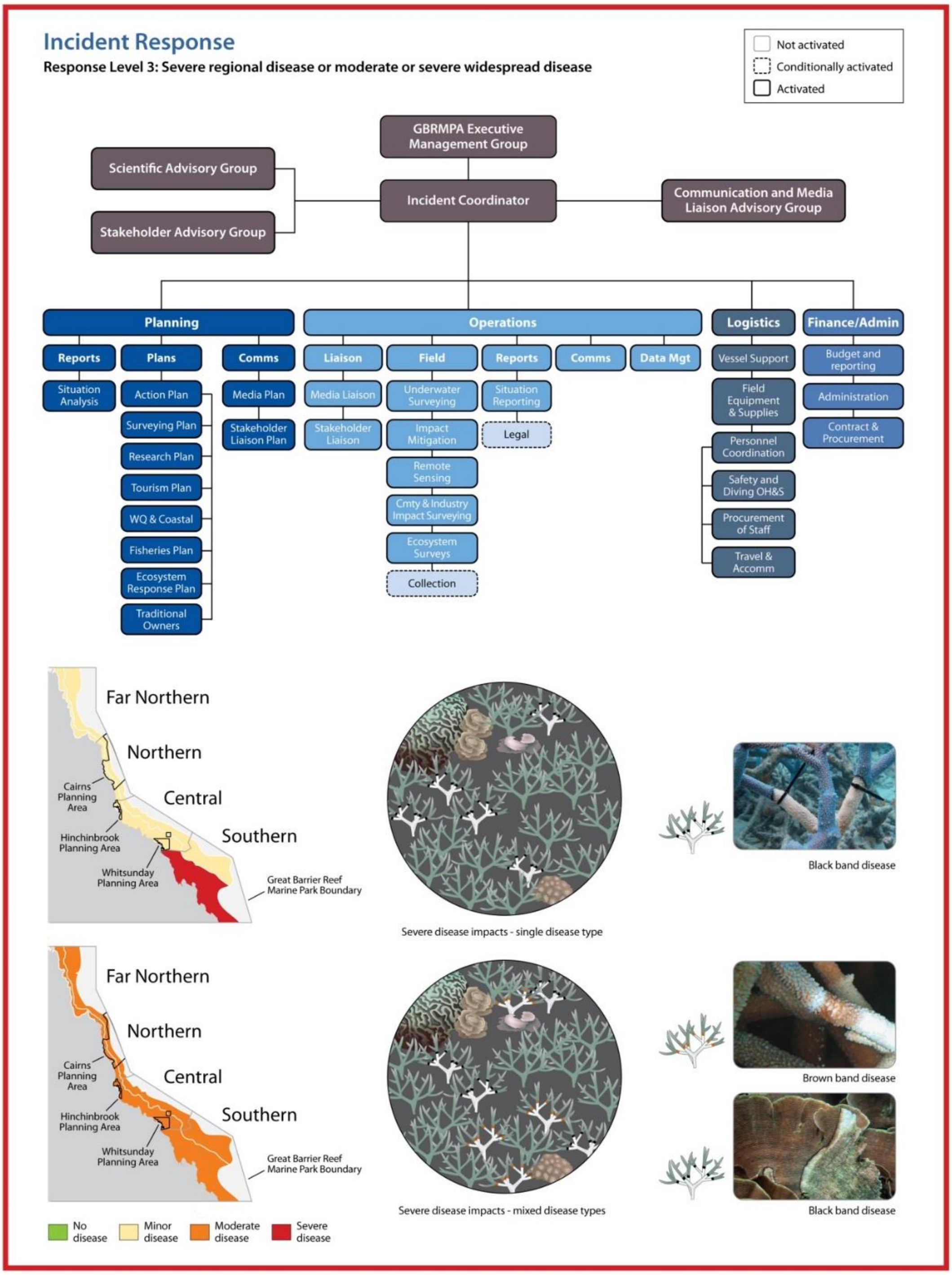


Figure 3.8: Response level 3 within the disease response plan framework. Activation and conditional activation of components are illustrated by the intensity of colour and border for each box within the diagram above. Scenarios shown in the maps are examples as are the disease types shown (i.e., severe disease in a different region would result in the same management response, and so would different disease types). The response level 3 threshold can be reached due to the prevalence of a single disease type or numerous disease types.

3.6 Management Actions

The response framework described here is designed to facilitate the implementation of established management strategies to support reef resilience while enabling testing and evaluation of the effectiveness of emerging actions specific to restoring reefs and mitigating coral disease impacts (objective 3 of the framework). Both types of actions are described below. For restoring reefs and actions that can mitigate disease impacts knowledge gaps are identified that when filled will enable managers to prioritise the action options based on their effectiveness.

3.6.1 Mitigating disease impacts and reef restoration

The growing awareness of disease risk has resulted in an exponential increase in research efforts to identify and test ways to mitigate disease impacts (Bruckner 2002; Raymundo et al. 2008). Preventing outbreaks or reducing their impact may be acheived by boosting immunity, or reducing pathogen abundance or rates of disease transmission (see overview in Raymundo et al. 2010). Strategies include: stimulating coral immune systems (as in Little & Kraaijeveld 2004), removal of disease by physical means (Hudson 2000), aspirating the disease bands on corals affected by black band and yellow band and covering the affected area with clay or putty (reviewed in Raymundo et al. 2010), phage therapy (Efrony, Atad & Rosenberg 2009; Efrony et al. 2007), using normal cell micro-biota as probiotics (Ritchie 2006), disruption of cell-cell communication in pathogenic bacterial communities (Teplitski & Ritchie 2009), and traditional strategies like quarantining, vaccination, and antibiotic treatment and culling (Wobeser 2006). Though these strategies have strong potential to be vital to managers in the future, currently they are all highly experimental and likely to be prohibitively expensive on all but the smallest of spatial scales (10's-100's of m^2, but not km^2). Just as importantly, there are critical gaps in our understanding of how to implement these strategies. A list of the critical knowledge gaps is provided in Table 3.1, which can serve to inform future research and trials of these actions both in labs and at outbreak sites. Managers communicating the need for this research and targeting trials of the approaches at sites severely affected by disease can help ensure the most effective of the strategies listed above become operational in the future.

Table 3.1. *Potential management response actions for coral disease outbreaks:* Critical knowledge gaps for management action options (1) specific to coral disease outbreaks and (2) for enhancing reef recovery once the outbreak abates or is controlled. This list is not intended to be an exhaustive list of the research that should or could be conducted in each of these areas but highlights the knowledge gaps that, if filled, would facilitate a re-assessment of the feasibility of implementing these strategies over any spatial scale.

Category	Strategy	Critical knowledge gaps
(1) Mitigating disease impacts by boosting immunity, and reducing pathogen abundance and rates of disease transmission	Removal of disease by physical means	• Extent to which known methods will be successful when suctioning disease agents from branching corals • Procedures for safely implementing known methods in areas with high coral cover have yet to be developed
	Traditional strategies including quarantine, vaccination, antibiotic treatment, and culling.	• Causative agents of many types of coral diseases • The threshold number of affected colonies that have to be treated in an area (of any given size) for the strategy to significantly decrease either disease transmission rates or total mortality rates
	Phage therapy	• Understanding the effects of phages on other closely related bacteria • Threshold numbers of affected colonies that have to be treated to significantly decrease disease transmission rates and/or total mortality rates
	Normal coral micro-biota as probiotics	• The precise roles of beneficial bacteria • The cellular mechanisms underlying the anti-microbial activity, and conditions driving microbial activity
	Disruption of cell-cell communication in pathogenic bacterial communities	• Whether cell-cell communication is an important virulence mechanism in coral diseases • Whether strategies to disrupt cell-cell signalling and reduce pathogenicity will disrupt the production of antibiotics that contribute to natural mechanisms of disease resistance
	Stimulation of coral immune systems	• Whether coral immune systems can be primed at all • If the immune systems of corals can be primed, whether a process can be developed that prevents undesirable decreases in physiological resources that affect susceptibility to diseases or other disturbance and reduce reproductive output
(2) Promoting recovery	Coral transplantation/assisted colonization and coral gardening	• The threshold number of colonies that need to be translocated to see significant increases in recovery rates • The extent to which threshold numbers vary between species
	Mitigating anthropogenic stressors	• Effectiveness when anthropogenic stress is low to moderate.

Sites severely impacted by disease can be restored through well documented approaches that are notoriously expensive and challenging to implement like transplantation, coral gardening and installing artificial reefs (Edwards & Gomez 2007; Edwards, AJ 2010). These actions are like those described above to mitigate impacts in that they are likely to be useful only on small spatial scales but may be warranted at high priority sites (e.g., sites with high resilience, or special conservation, social, cultural, historical and / or economic significance).

There are critical gaps in our understanding of approaches to restoring reefs given the extent and nature of all of the potential downsides to these approaches (see Table 3.1 and review for coral transplantation in Edwards & Gomez 2007). For that reason, continuing to fill those knowledge gaps should be complemented with other actions that managers can take to promote reef resilience.

3.6.2 Promoting reef resilience

Replacement of corals by macroalgae following disturbances or as a consequence of competition for space will reduce reef recovery rates, either through limiting the growth of resident corals or by reducing substrate available to new recruits for settlement (Hughes et al. 2007). Local stressors, like poor water quality (i.e., nutrient rich), the extraction of herbivorous fishes (Mumby et al. 2006), and physical damage due to anchoring and/or divers and snorkelers (McManus, Reyes & Nanola 1997) all have the potential to increase the competitive advantage of macroalgae and hence reduce recovery rates. Aside from reducing recovery rates, these anthropogenic stressors can increase pathogen virulence and coral susceptibility (Raymundo et al. 2008; Willis, Page & Dinsdale 2004). As an example, increased dissolved nutrients, bacterial loads, and dissolved pollutants (i.e., poor water quality) have all been linked to some coral diseases and can increase the susceptibility of corals to pathogens (Raymundo 2010). Management actions that minimize human stressors therefore promote both of the key components of reef resilience: resistance and recovery.

Improving local water quality and temporary closures could be the most successful management actions in response to disease. Improving water quality is an action some local managers will have control over and can result in a number of positive consequences for coastal ecosystems (Raymundo et al. 2009). Managers with no or limited direct control over the quality of water coming from adjacent catchments can add increasing coral bleaching (Wooldridge 2009a, 2009b, 2010; Wooldridge & Done 2009) and disease resistance to the list of coral health and resilience benefits to come from improving water quality when engaging with the agencies with jurisdictional responsibility. Local stressors can also be reactively mitigated by many coral reef managers following outbreaks through temporary closures (Day 2002), as was done following the severe bleaching in 2010 in Thailand. Some of the benefits of temporary closures will be realised immediately because preventing entry can reduce rates of disease spread directly (i.e., through disease transfer, though this requires more research) or indirectly (i.e., through injuring corals with fins or anchors Lamb et al. 2014; Lamb & Willis 2011; Raymundo et al. 2008; Raymundo et al. 2009). Other benefits could take years to manifest (i.e., increased larval survival see Lukoschek et al. 2013) and the capacity of temporary closures to enhance recovery rates will depend on the severity of anthropogenic stress in the area, and whether the site is severely disturbed again in the near-term. The latter is largely out of management control. The former, however, requires managers to decide whether it is worth investing resources – temporary closures will have the greatest impact on recovery timeframes in areas where anthropogenic stress is high (but will also be the most controversial here), while closures may have no impact on recovery if anthropogenic stress is low or moderate (review in McClanahan et al. 2009).

Identification of reefs (or reef sites) with greater relative resilience to climate change provides an opportunity to build the goal of minimizing coral disease risk into long-term spatial management plans. Approaches to assessing coral reef resilience are available (Maynard et al. 2009; Obura & Grimsditch 2009) that focus mostly on resilience to thermal stress and bleaching. These approaches are also likely to be of use in identifying sites resilient to disease given links between bleaching and disease and between thermal stress and temperature-dependent diseases (Raina et al. 2013; Selig et al. 2006). The published resilience assessment protocols identify sites: 1) that are likely to have lower relative exposure or greater resistance to exposure, and/or 2) have features (like high coral diversity) that reduce the likelihood a coral bleaching event or disease outbreak will kill high proportions of coral colonies at the sites.

Sites with lower relative exposure often have features (e.g., adjacent deep water or high mixing) that reduce exposure to stressful temperatures, which can be identified, measured or estimated (see Salm 2006). As for resistance, when exposed to stressful temperatures, recent evidence suggests having highly variable temperatures can confer resistance to bleaching (Howells et al. 2013; McClanahan et al. 2007; Oliver & Palumbi 2011). Managers can identify locations with features that reduce exposure, and efforts are underway to produce high-resolution maps of locations where past temperature regimes are characterised by high variability (Guest et al. 2012). Identifying and protecting sites with low exposure or greater relative resistance can and should be complemented with protecting sites with high biodiversity when possible. Protecting and promoting diversity could offer some protection from loss of reef services and resilience (as shown for bleaching in Baskett et al. 2010) given differences among coral taxa in their susceptibility to bleaching (Marshall & Baird 2000) and disease (Willis, Page & Dinsdale 2004).

Communication, discussed next, will be vital to the success of trials of emerging actions to mitigate disease impacts and to the implementation of the established actions discussed above to support reef resilience.

3.7 Communication

Communication is critical to an effective management response to coral disease outbreaks. Disease outbreaks can cause significant and rapid declines in reef condition, and therefore have the potential to attract interest from the public, media and fellow managers. Response plans produced by adapting this framework can ensure timely and credible information on coral disease outbreaks, enabling reef managers and reef users to be proactive in presenting information to the broader community (objective 3 of the framework). Some of the issues warranting strategic management of communications relating to coral disease include:

- Outbreaks of diseases can catch managers by surprise, highlighting the importance of raising awareness of the threat of coral disease amongst managers to facilitate allocation of resources to support outbreak responses.

- Injuries and other stressors have the potential to increase susceptibility of corals to diseases. Consequently, increased management of tourism activities at reef sites susceptible to disease outbreaks may be warranted. Appropriate communications can be used to minimise the frequency of touching, kicking and otherwise contacting corals by tourists visiting vulnerable sites.

- Managers need to train participants to identify coral diseases and motivate participants through a two-way exchange of information for monitoring networks to be effective as part of the early warning system.

- The term 'disease' may frighten the very stakeholders and community members that need to support actions managers take in response to coral disease. Managers can play an educational role and explain that: impacts from human activities can increase susceptibility of corals to diseases, but humans cannot contract the common types of coral diseases, and that caution will need to be exercised if outbreaks of an unknown disease occur as the disease may pose a human health risk.

- Awareness also needs to be raised amongst stakeholders and community members that some management responses to coral disease necessarily limit use. Heightened awareness is likely to raise support for and compliance with management actions when implemented. Through informing resource users, managers can raise their own awareness of stakeholder needs, ensuring future management strategies are as tailored to the needs of users as possible.

- Misinformation can affect reef-dependent industries like tourism operators, who depend on clients whose perception of reef condition in an area can be easily influenced by the media. Timely reporting of the severity and extent of coral disease outbreaks can dispel misinformation in the media about an outbreak.

- Managers need to select sites and determine timeframes for trials of emerging strategies to mitigate coral disease impacts. This decision-making process should be transparent and participatory to raise further support for the implementation of management actions in response to coral disease.

- Researchers and managers need to share results following trialling various management strategies through inter-institutional collaboration and email and report exchange.

3.8 Implementation of the response framework

Response plans produced based on this framework would be in effect year-round since coral disease outbreaks can occur during any time of the year (e.g. annually updated plan for the GBRMP Authority 2013b). However, research suggests corals become more susceptible to diseases following periods of anomalously warm summer and winter sea temperatures (e.g. Bruno et al. 2007; Heron et al. 2010; Maynard et al. 2011). Also, spatially extensive bleaching events, caused by anomalously warm temperatures, can greatly increase the susceptibility of corals to diseases, as can seasonal rainfall and runoff (Haapkylä et al. 2011; Miller et al. 2009; Mydlarz et al. 2009). For these reasons, the schedule of implementation (shown in detail in Figure 3.1) has been set up with ‘Preparation’ scheduled for pre-summer. This ensures that systems that monitor summer conditions as part of the early warning system are maintained, and also provides an opportunity to evaluate the response framework and revise/update it as necessary. Both preparation and evaluation are routine (shown in grey in Figure 3.1) and hence ongoing tasks. Assessing impacts when disease outbreaks are documented and the implementation and trial of management actions both form responsive tasks. Re-prioritising various management actions once tested may need to become a routine task given the severity of the climate change threat and the need for adaptive management (Tompkins & Adger 2004).

3.9 Conclusion

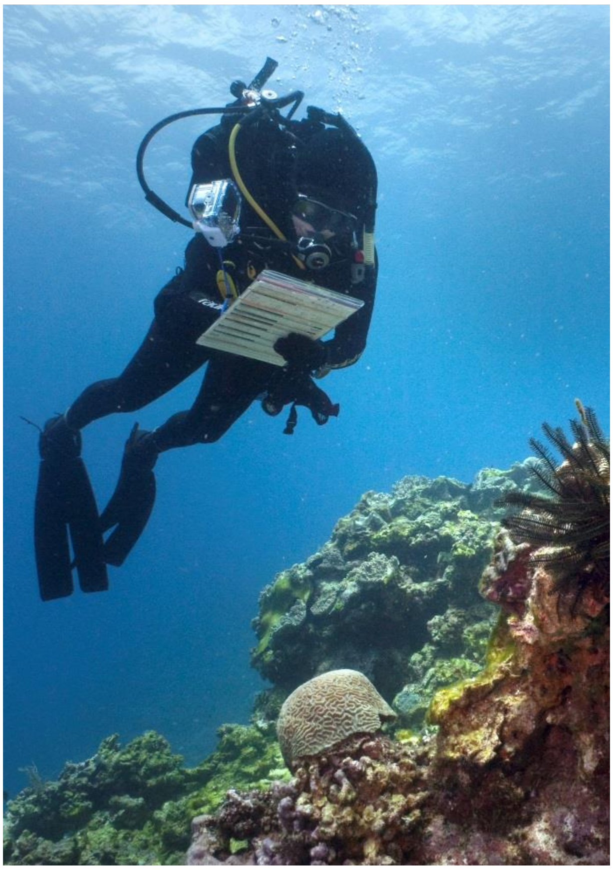
This framework was developed to meet a rapidly emerging need among coral reef managers. While initially developed for use on the Great Barrier Reef, it draws on studies and management experiences from coral reef regions around the world and makes operational the components of a structured adaptive disease response first reviewed by Raymundo et al. (2008). The framework can be tailored to different regions and scaled to suit different levels of management resources and operational capabilities.

Widespread adoption of the framework presented here would help establish a community of practice. A community like this already exists for bleaching, with more managers adopting the response framework presented in Marshall and Schuttenberg (2006), see also Maynard et al. (2009) each year and sharing their experiences. A similar community of those managing coral disease could lead to vital advances in our understanding of how to manage coral disease outbreaks. Knowledge transfer and experience sharing are critical to determining the cost-effectiveness of the emerging strategies to mitigate disease impacts reviewed in this chapter. For this reason, adding to the arsenal of strategies available to managers to respond to coral disease outbreaks requires management responses be implemented in collaboration with researchers. This framework is designed to encourage and facilitate such a collaborative approach, and thus can accelerate improvements in the management of coral disease impacts and risk globally.

The responsive tasks described within the coral disease response plan framework are triggered by managers learning that coral disease abundance has breached the outbreak threshold at one or many reef sites. In order to receive that information, people need to be taught to identify the signs of coral disease (focus of Chapter 2). However, in a system as large as the GBR, only a large network of non-specialist observers can provide information about coral and reef condition and impacts with sufficient spatial and temporal resolution to detect the early signs of outbreaks and inform some of the responses described within this chapter. The next chapter, Chapter 4, describes the iterative development of a survey methodology tailored to the non-specialist observers that regularly visit reefs within the GBR. Effective implementation of the coral disease response plan framework is dependent upon the large participatory monitoring network of observers that use the survey protocol to provide year-round surveillance of disease and other reef health impacts.

CHAPTER 4

Rapid survey protocol that provides dynamic reef health condition information to managers of the Great Barrier Reef



Diver conducting a Reef Health and Impact Survey as a part of the integrated Eye on the Reef Network on an outer-shelf reef in the Great Barrier Reef.

This chapter describes a rapid survey protocol developed for use by observers participating in the Eye on the Reef network, which now forms part of the early warning system for a range of reef health impacts, including coral disease, as described in Chapter 3.

Source References:

Beeden, RJ, Turner, MA, Dryden, J, Merida, F, Goudkamp, K, Malone, C, Marshall, PA, Birtles, A & Maynard, JA 2014a, 'Rapid survey protocol that provides dynamic reef health condition information to managers of the Great Barrier Reef', *Environmental Monitoring and Assessment,* vol. 186, no. 12, pp. 8527-8540, doi: 10.1007/s10661-014-4022-0

Authority, GBRMP 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville.
<http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2808>

4.1 Abstract

Managing to support coral reef resilience as the climate changes requires strategic and responsive actions that reduce anthropogenic stress. Managers can only target and tailor these actions if they regularly receive information on system condition and impact severity. In large coral reef areas like the Great Barrier Reef Marine Park (GBRMP), acquiring condition and impact data with good spatial and temporal coverage requires using a large network of observers. Here I describe the result of a nearly 10 year process of evolving and refining participatory monitoring programs that have rangers, tourism operators, and members of the public as observers of reef health on the Great Barrier Reef (GBR). Participants complete Reef Health and Impact Surveys (RHIS) using a protocol developed to meet coral reef managers' needs for up-to-date information on: benthic community composition, reef condition, and impacts, which include coral diseases, damage, predation and the presence of rubbish. Training programs ensure the information gathered is sufficiently precise to inform management decisions. Participants report regularly because the demands of the survey methodology have been matched to their time availability. Undertaking the RHIS protocol involves three ~20 minute surveys at each site. Participants enter data into an online data management system that can create reports for managers and participants within minutes of data being submitted. The two-way exchange of information between managers and participants increases the capacity to manage reefs adaptively, meets education and outreach objectives and can increase stewardship. The general approach used and the survey methodology are both sufficiently adaptable to be used globally in all reef regions.

4.2 Introduction

Using adaptive management to minimise vulnerability and support coral reef resilience will require complementary long term strategies that reduce exposure to anthropogenic stress at all spatial scales, combined with responsive actions targeted to minimise impacts and support recovery processes at local scales (Beeden et al. 2012; Done & Reichelt 1998; Done 1999; Maynard et al. 2009). Tailoring long-term strategies and targeting local-scale actions both require dynamic information on system condition and impacts (Beeden et al. 2012; Conrad & Hilchey 2011; Kenchington 1978; Maynard et al. 2009). Consequently, coral reef monitoring will become increasingly important to management decision-making as disturbance frequencies increase under the interaction of climate change and other anthropogenic impacts.

All approaches to monitoring represent trade-offs between precision and spatial and temporal coverage (Hobbs 2003). Traditional monitoring schemes use expert/researcher observers and are highly precise but usually resource intensive and thus always provide limited coverage (Danielsen, Burgess & Balmford 2005; Danielsen et al. 2010; Hill & Wilkinson 2004; Kenchington 1978). In the Great Barrier Reef, coral reef monitoring has been occurring for many decades (i.e. Kenchington 1978), including the Australian Institute of Marine Science's (AIMS) Long Term Monitoring Program (LTMP) has been surveying the health of reefs since 1993. The LTMP enables critical studies on trends in condition, and this information and the resultant research meet some management needs but not for all timeframes or spatial scales required. The capacity to rapidly and regularly gather information with good spatial coverage is critical in the GBRMP because the system is very large (344,000 km^2) and contains hundreds of reefs more than 100 km from a population centre (Authority 2004; McCook et al. 2010), so monitoring is especially resource-intensive. Temporal coverage is important too because some impacts on coral reefs are difficult or impossible to detect with infrequent monitoring because they are cryptic and ephemeral, like coral disease and crown-of-thorns starfish outbreaks (Harvell et al. 2007; Sweatman 2008; Willis, Page & Dinsdale 2004). Only a large network of non-expert trained observers can provide information regularly enough and with sufficiently broad coverage to manage a system like the GBR adaptively.

Using non-expert observers - 'citizen scientists' - in participatory monitoring programs has rapidly expanded in the terrestrial and marine environment since the early 1990's (Danielsen, Burgess & Balmford 2005; Hodgson 2001; Wilkinson et al. 1999). In the 1990's uncertainty about global coral reef condition and an unprecedented worldwide coral bleaching event (1998) established the critical need for spatially extensive information on reef condition and impacts. This resulted in a proliferation of participatory monitoring programs in reef regions (Hodgson 2001; Wilkinson et al. 1999). The Global Coral Reef Monitoring Network (GCRMN) was created to produce Status of the Coral Reefs of the World reports (Wilkinson 2000) and the Reef Check organisation began to train volunteer observers (Hodgson 2001).

The shift in the last 20 years towards participatory instead of, or to complement, 'professional' (paid expert based) monitoring schemes is bordering on paradigmatic (Danielsen et al. 2010). There are now thought to be more than a hundred participatory monitoring programs run by management agencies (Conrad & Hilchey 2011; Danielsen et al. 2010). Agencies first questioned the defensibility of actions implemented on the back of the seemingly imprecise information non-expert observers could provide (Danielsen, Burgess & Balmford 2005). This has and continues to be overcome by aligning monitoring objectives with observer capabilities (Savan, Morgan & Gore 2003) and investing in training so that data collected are sufficiently accurate and precise to inform decisions (Danielsen et al. 2009; Danielsen et al. 2010; Mayfield, Joliat & Cowan 2001; Savan, Morgan & Gore 2003; Uychiaoco et al. 2005). Recent research indicates that data from participatory monitoring programs is often more readily and rapidly translated into management actions than data from professional monitoring schemes that require expert observers (Danielsen et al. 2009; Danielsen et al. 2010; Uychiaoco et al. 2005).

This chapter describes the endpoint of a 10+ year evolution of the survey protocols and training components of the participatory coral reef monitoring program for the GBRMP, known as Eye on the Reef (EotR). The EotR program combines quantitative and qualitative monitoring tools that are used by rangers, tourism operators, and community participants. The primary quantitative reef health assessment tool regularly completed by participants is the *Reef Health and Impact Survey* (RHIS). There are four information needs common to coral reef managers that participatory monitoring programs can meet (Conrad & Hilchey 2011): reef condition, impact detection, impact assessment following disturbances, and assessments of the effectiveness of management actions. The last three describe the role of RHIS and the EotR network in GBRMPA's operational incident response plans (Figure 4.1 and Chapter 3). The response plan framework includes routine tasks of assessing conditions and communication that may trigger responsive tasks of assessing impacts, implementing executing actions and evaluating their effectiveness (Beeden et al. 2012; Maynard et al. 2009). In the framework, completing RHIS is both a routine and responsive task because: data from the surveys provide an early warning, surveys are targeted if impacts are observed or suspected, and follow-up surveys help assess management effectiveness. In essence, the EotR participatory monitoring network tightens the adaptive management cycle (Uychiaoco et al. 2005), enabling actions to be linked closely to system condition and an ongoing evaluation of their effectiveness.

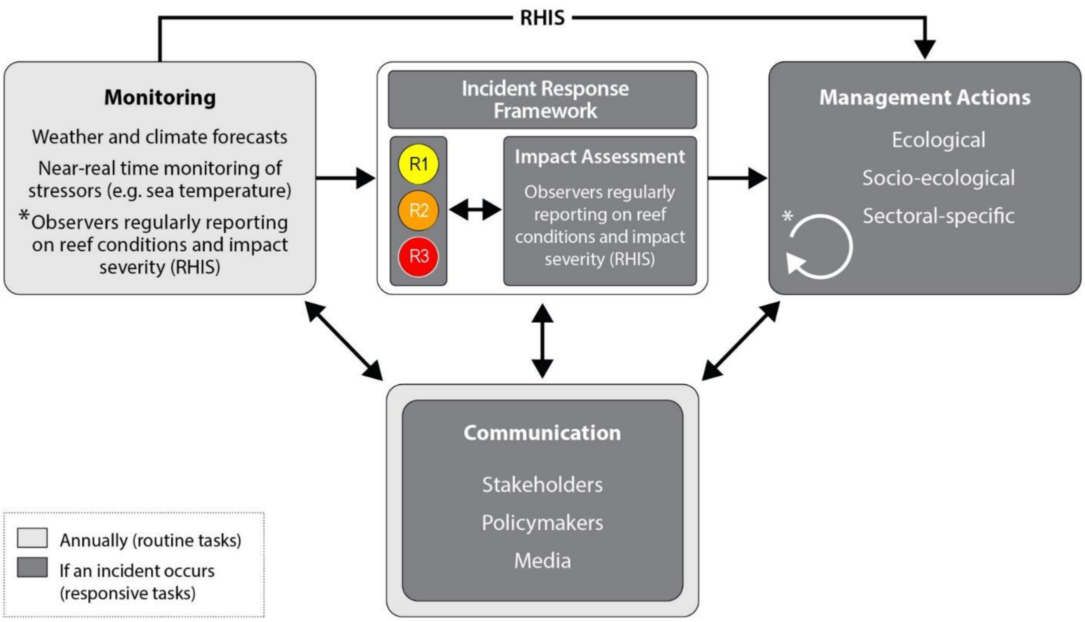


Figure 4.1. Schematic illustrating components of the GBRMPA's year-round operational incident response plan. Asterisks denote the three primary roles of the RHIS based survey network: Monitoring * denotes i) regular monitoring of reef health and impacts, ii) assessment of the extent and severity of impacts when they occur. Management Actions * denotes iii) monitoring and assessment of management action effectiveness (figure adapted from Beeden et al. 2012, also see Chapter 3).

In this chapter, my objective was to iteratively develop and refine a monitoring protocol that enables rapid assessments of reef health by a range of observer types, complemented by a data storage and reporting system that meets management information needs. Here I describe the resulting Reef Health and Impact Survey (RHIS) protocol, and capacity building program that is now used to train and educate participants. I also describe how the monitoring program makes adaptive management possible through a system that uses readily available technology that is, to my knowledge, unique in marine park management. The following Chapters (5 and 6) provide two detailed examples of how the RHIS observer network and information management system has met management information needs in the last 3 years.

4.3 Survey protocol

In collaboration with colleagues and GBRMPA staff, I led the development of the RHIS survey form, which was iteratively developed over three years (2009-2012) in response to user feedback about form layout and terminology. Changes were introduced to align the terminology used with other monitoring programs, and to ensure survey data gathered could be quantitatively assessed. The survey methodology is described below, followed by the specific types of information collected on the RHIS form and the ways the information is useful to managers.

4.3.1 Survey methodology

Stakeholder consultation led to the conclusion that participants could only undertake surveys regularly and at a large number of sites if a survey could be completed in ~20 minutes or less. Such a timeframe enables the rapid completion of a survey on snorkel by tourism operators who have no more than 20 minutes available during a day. Furthermore, a survey methodology taking ~20 minutes can be completed three times during a one hour dive time, which is common for ranger participants diving in shallow water.

To undertake a RHIS survey, observers first select a site (based upon their survey plan objectives) and then swim to find the habitat (lagoon, reef crest, slope, reef flat, see Figure 4.2) they intend to survey and then do several fin kicks with their eyes closed to randomly select a starting point. A memorable starting point on the substrate is found and the observer raises a hand so people on the boat can get a GPS fix on the centre of the survey. The survey area is a circle with a five metre radius, so observers learn the number of their fin kicks that equate to five metre. From the survey start point, a five metre swim is made to four points from the centre; like the N, S, E and W cardinal points of a compass. These points form the circle perimeter and, as with the centre point, something memorable on the substrate is noted at each point. Observers then swim the circumference while looking into the survey area to estimate the percent cover of the substrate made up by the various benthic groups (see section 4.3.2). Coral and macroalgae are then classified by life-form and type, respectively, and then observers focus on signs of impacts and infer their potential causes.

SCUBA divers swim around the survey area while completing the form. Snorkelers survey from the surface maintaining a synoptic view of the survey area, and then swim down to clarify anything difficult to see or to more carefully review any impacts. Photographs are recommended for impacts and to aid with post-survey identification of anything observers do not immediately recognise. Observers take three photographs of impacts to corals; the whole coral, the branch or part of the coral affected, and a close-up at the polyp-scale of the impact. Macro photographs enable observers to differentiate between similar impacts, such as coral disease and predation. The surveyors then check each section of the form for completion, checking that: the benthic group percent cover estimate adds up to 100; all impacts noted have been described, and comments have been written about the photos taken and any sightings of protected species. The survey protocol is completed three times in the same habitat, either on the same dive or day for divers, or during the same snorkel outing or day for snorkelers.

4.3.2 Survey form: information collected and its uses

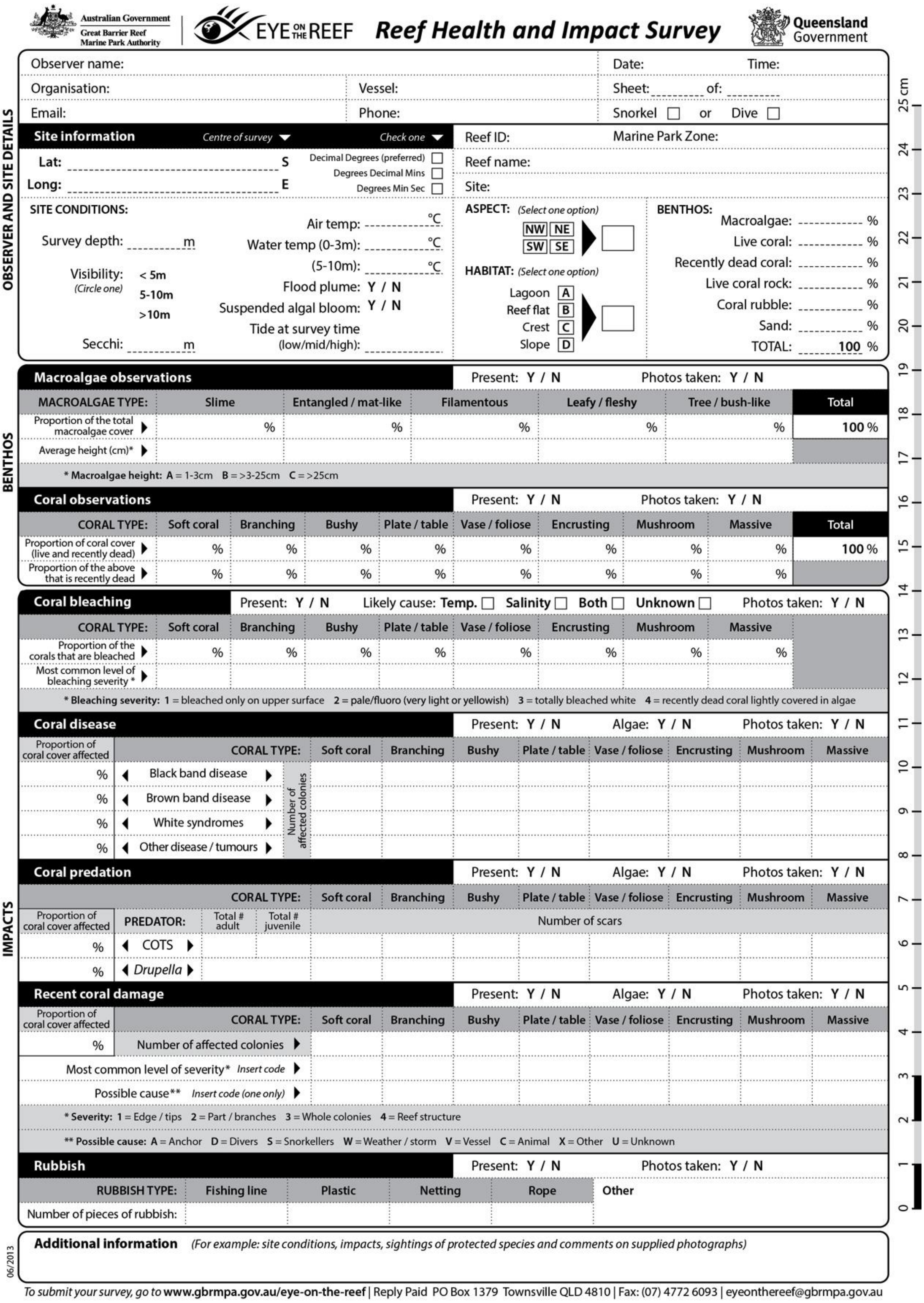
The RHIS survey form is divided into four sections: 1) observer and site details, 2) benthos, 3) impacts, and 4) additional information (Figure 4.2). Aside from basic contact information about the observer and the survey date and time, the observer and site details section captures the coordinates of the survey location, its classification as a habitat type, and its orientation. Site location information ensures the site can be re-located for follow-up surveys, enabling managers to track condition through time. By regularly surveying the same location, tourism operators participating in the program can track the progression of impacts like coral disease. Site environmental condition information is also captured, including: air and water temperature, prevailing winds, visibility, and the presence or absence of algal blooms. Information on environmental conditions enables ground-truthing of the remote sensing data used in systems like ReefTemp (Elvidge et al. 2004; Maynard et al. 2011; Maynard et al. 2008) to predict bleaching and disease conditions, and ongoing refinement of algorithms that interpret remotely sensed water quality data (Brodie et al. 2012; Fabricius, Okaji & De'ath 2010; Phinn et al. 2005; Weeks et al. 2012).

Observers record information on the benthic community structure in the benthos section. The percentage of the substrate made up by macroalgae, live coral, recently dead coral, live coral rock, coral rubble and sand is recorded (Figure 4.2). This is valuable information on current habitat condition that can be indicative of the presence of processes that support reef resilience (McClanahan et al. 2012). Macroalgae abundance can be indicative of the presence or absence of healthy herbivore populations and the levels of nutrients in the water column (Hay 1997). Coral cover and recently dead coral can be indicative of the conditions for coral growth in the area, and the time since the last severe disturbance. The ratios between live coral rock and rubble/sand are indicative of how optimal the substrate is for coral recruitment and thus help assess the recovery potential of the site (Lukoschek et al. 2013).

For macroalgae and corals, observers also note the percentage of various types and life-form classifications that make up each of these two groups (e.g., filamentous and leafy/fleshy for macroalgae, and branching and massive for corals). Recording macroalga type and the average height of specimens increases our understanding of the extent to which herbivory and nutrients at the site potentially control or fuel algal growth. The susceptibility of the coral community to bleaching, damage and predation can be derived from the life-form information (Diaz & Madin 2011; Madin 2005; Marshall & Baird 2000; Marshall 2000).

General information on benthic habitat captured in the benthos section of the RHIS form describes *current* reef condition. This is valuable information for all reefs globally, given the dynamic nature of reef condition, and for the GBR in particular, because little to nothing is known about a large percentage of the approximately 3000 individual reefs being managed. Habitat condition, however, is driven and influenced by both current and past disturbances and impacts. Typically, signs of current impacts are easily discernible and readily captured in the impacts section of the RHIS form (Figure 4.2), which is divided into five key reef health impacts: bleaching, disease, predation, physical damage, and rubbish. In contrast, signs of past disturbances and impacts are difficult to identify, although the benthic community structure itself provides some insights (Bruno & Selig 2007; Graham, Nash & Kool 2011; Hughes & Connell 1999).

For bleaching, the percentage of each life-form bleached and the severity of the bleaching is classified on a 1-4 scale (Figure 4.2). The coral disease section captures the proportion of coral cover affected and the life-forms affected by four disease classifications: black band disease, brown band disease, white syndromes, and 'other'. The predation section captures the proportion of coral cover affected by adult and juvenile corallivorous crown–of–thorns starfish (*Acanthaster planci*) and snails (*Drupella spp.)*. The recently incorporated coral damage section asks observers to assess the percent of coral cover damaged, the life-forms damaged and the suspected causes of the damage (e.g., storms, anchoring, vessel grounding, Figure 4.2). The rubbish section provides an indication of use in the area that may be illegal (i.e., fishing line found in a no-take protected area zone), and can trigger a management compliance and/or clean-up response. Plastic found in high abundance can be harmful to a range of animals, especially turtles and seabirds, and abandoned nets and other gear can 'ghost fish', so may need to be removed.



Australian Government
Great Barrier Reef Marine Park Authority

EYE ON THE REEF **Reef Health and Impact Survey** Queensland Government

Observer name:		Date:	Time:
Organisation:	Vessel:	Sheet:________ of: ________	
Email:	Phone:	Snorkel ☐ or Dive ☐	

OBSERVER AND SITE DETAILS

Site information *Centre of survey* *Check one*

Lat: ______________________ S	Decimal Degrees (preferred) ☐	Reef ID:	Marine Park Zone:
Long: ______________________ E	Degrees Decimal Mins ☐	Reef name:	
	Degrees Min Sec ☐	Site:	

SITE CONDITIONS:
Survey depth: ________m
Visibility: (Circle one) < 5m / 5-10m / >10m
Secchi: ________m
Air temp: ___________°C
Water temp (0-3m): ___________°C
(5-10m): ___________°C
Flood plume: Y / N
Suspended algal bloom: Y / N
Tide at survey time (low/mid/high): ___________

ASPECT: *(Select one option)* NW NE SW SE ☐
HABITAT: *(Select one option)* Lagoon A, Reef flat B, Crest C, Slope D ☐

BENTHOS:
Macroalgae: ________ %
Live coral: ________ %
Recently dead coral: ________ %
Live coral rock: ________ %
Coral rubble: ________ %
Sand: ________ %
TOTAL: ____100 %

BENTHOS

Macroalgae observations Present: Y / N Photos taken: Y / N

MACROALGAE TYPE:	Slime	Entangled / mat-like	Filamentous	Leafy / fleshy	Tree / bush-like	Total
Proportion of the total macroalgae cover	%	%	%	%	%	100 %
Average height (cm)*						

* Macroalgae height: A = 1-3cm B = >3-25cm C = >25cm

Coral observations Present: Y / N Photos taken: Y / N

CORAL TYPE:	Soft coral	Branching	Bushy	Plate / table	Vase / foliose	Encrusting	Mushroom	Massive	Total
Proportion of coral cover (live and recently dead)	%	%	%	%	%	%	%	%	100 %
Proportion of the above that is recently dead	%	%	%	%	%	%	%	%	

Coral bleaching Present: Y / N Likely cause: Temp. ☐ Salinity ☐ Both ☐ Unknown ☐ Photos taken: Y / N

CORAL TYPE:	Soft coral	Branching	Bushy	Plate / table	Vase / foliose	Encrusting	Mushroom	Massive
Proportion of the corals that are bleached	%	%	%	%	%	%	%	%
Most common level of bleaching severity *								

* Bleaching severity: 1 = bleached only on upper surface 2 = pale/fluoro (very light or yellowish) 3 = totally bleached white 4 = recently dead coral lightly covered in algae

IMPACTS

Coral disease Present: Y / N Algae: Y / N Photos taken: Y / N

Proportion of coral cover affected	CORAL TYPE:	Soft coral	Branching	Bushy	Plate / table	Vase / foliose	Encrusting	Mushroom	Massive
%	Black band disease								
%	Brown band disease								
%	White syndromes								
%	Other disease / tumours								

(Number of affected colonies)

Coral predation Present: Y / N Algae: Y / N Photos taken: Y / N

Proportion of coral cover affected	PREDATOR:	Total # adult	Total # juvenile	Soft coral	Branching	Bushy	Plate / table	Vase / foliose	Encrusting	Mushroom	Massive
				Number of scars							
%	COTS										
%	*Drupella*										

Recent coral damage Present: Y / N Algae: Y / N Photos taken: Y / N

Proportion of coral cover affected	CORAL TYPE:	Soft coral	Branching	Bushy	Plate / table	Vase / foliose	Encrusting	Mushroom	Massive
%	Number of affected colonies								
	Most common level of severity* *Insert code*								
	Possible cause** *Insert code (one only)*								

* Severity: 1 = Edge / tips 2 = Part / branches 3 = Whole colonies 4 = Reef structure

** Possible cause: A = Anchor D = Divers S = Snorkellers W = Weather / storm V = Vessel C = Animal X = Other U = Unknown

Rubbish Present: Y / N Photos taken: Y / N

RUBBISH TYPE:	Fishing line	Plastic	Netting	Rope	Other
Number of pieces of rubbish:					

Additional information *(For example: site conditions, impacts, sightings of protected species and comments on supplied photographs)*

06/2013

To submit your survey, go to **www.gbrmpa.gov.au/eye-on-the-reef** | Reply Paid PO Box 1379 Townsville QLD 4810 | Fax: (07) 4772 6093 | eyeonthereef@gbrmpa.gov.au

Figure 4.2. Reef Health and Impact Survey datasheet. The datasheet is used by participants in the Eye on the Reef network managed by the Great Barrier Reef Marine Park Authority.

The success of the observer network in meeting identified management needs (see section 4.2) is dependent on many observers visiting many different areas of the Marine Park. Large numbers of participants necessitates having a training and education program. An ongoing communication mechanism is also required so that managers can reward and reinforce participation. The training and education program is described next.

4.4 Training observers

The capacity building and communication process for RHIS has three parts: 1) e-learning and in-water training, 2) resources to assist with completing surveys, and 3) ongoing access to assistance and support. Everyone taking part in RHIS must complete the e-learning tutorial and has the option of attending an in-water practice session. The training and education ensures that all observers can accurately and efficiently undertake surveys and complete the form to a standard proficiency level. Having the tutorial online is critical, as this enables self-paced learning and adds cost-efficiency to the training and education process. People interested in participating first request a login ID for the online tutorial on the GBRMPA homepage (http://www.gbrmpa.gov.au/visit-the-reef/eye-on-the-reef/get-involved-with-eye-on-the-reef), which is provided following electronically signing a participation agreement.

The tutorial has four parts: a tutorial overview, 5 modules of curriculum, a final exam, and a section on data submission guidelines (Figure 4.3). The overview page describes the tutorial itself and how to use the interface. The 5 modules of curriculum are: 1 - Eye on the Reef Integrated Monitoring System; 2 - Introduction to the Great Barrier Reef; 3 - The Reef Health and Impact Survey Form; 4 - Recipe for a Reef Health and Impact Survey; and 5 - Reef Health Indicators (Figure 4.3). The introductory module (1) details the importance and value for managers and participants in undertaking the training and regularly completing RHIS forms at sites they visit once the training is complete. Each module has an introduction, a page on key learning objectives, video content specific to each module, several interactive downloadable materials and a series of review questions. Examples of module content include learning and practice sections on estimating percent cover, and identifying impacts and coral life-forms. The learning modules are followed by a 40 question final exam. Participants must answer 75% of the questions correctly to complete the tutorial.

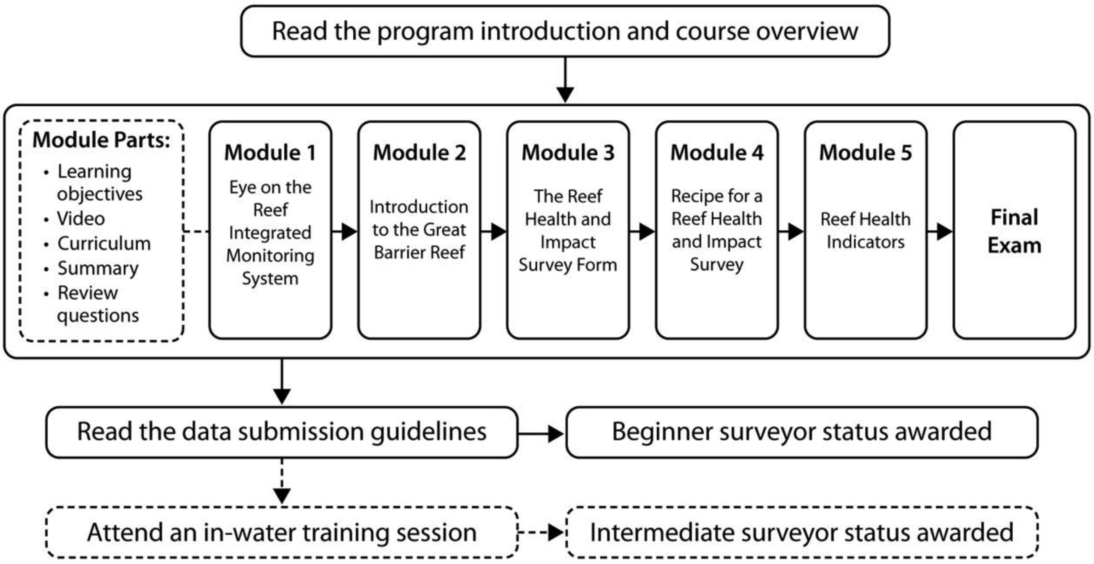


Figure 4.3. Structure of the e-learning tutorial and training process for Eye on the Reef. Observers must review and successfully complete the process prior to being certified as beginner or intermediate RHIS observers.

In-water practice sessions are offered 1-2 times per year to reinforce learning; these are mandatory for park rangers and optional for tourism staff and community participants. The in-water practice takes place over one day and lets participants put their e-learning into practice. Participants learn how many of their fin kicks equal roughly 5 m and practice some of the following skills: algae type and coral life-form identification, percent cover estimation, and key features to distinguish various impacts. During the in-water sessions, trainers also help participants use the visual aids and ID resources made available to all RHIS participants. The top of the front page of the waterproof RHIS visual aid describes the survey methodology (section 4.3.1) and has helpful tips and tricks for estimating percent cover (see Figure 4.4). The bottom half of the front page contains photos that aid in identifying benthos categories, algae types and coral life-forms (e-supplementary material). The back of the visual aid contains a decision-tree (e-supplementary material) that takes users through the process of identifying the various impact types (section 4.3.2) captured on the RHIS form. The decision tree is critical to ensuring the data provided by participants can meet the 4 management needs that underpin the program (section 4.2). Identifying impacts and surmising their causes is key for regular monitoring, assessing the severity and extent of impacts (see Chapter 5), and assessing whether a management action, like establishing no anchoring areas, is working (see Chapter 6). Other aids and resources made available include the guidebook *Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs (Beeden et al. 2008)*, and a web-accessible interactive PDF to aid in filling out the survey form. All RHIS participants have access to a RHIS coordinator and can call or email at any time with questions.

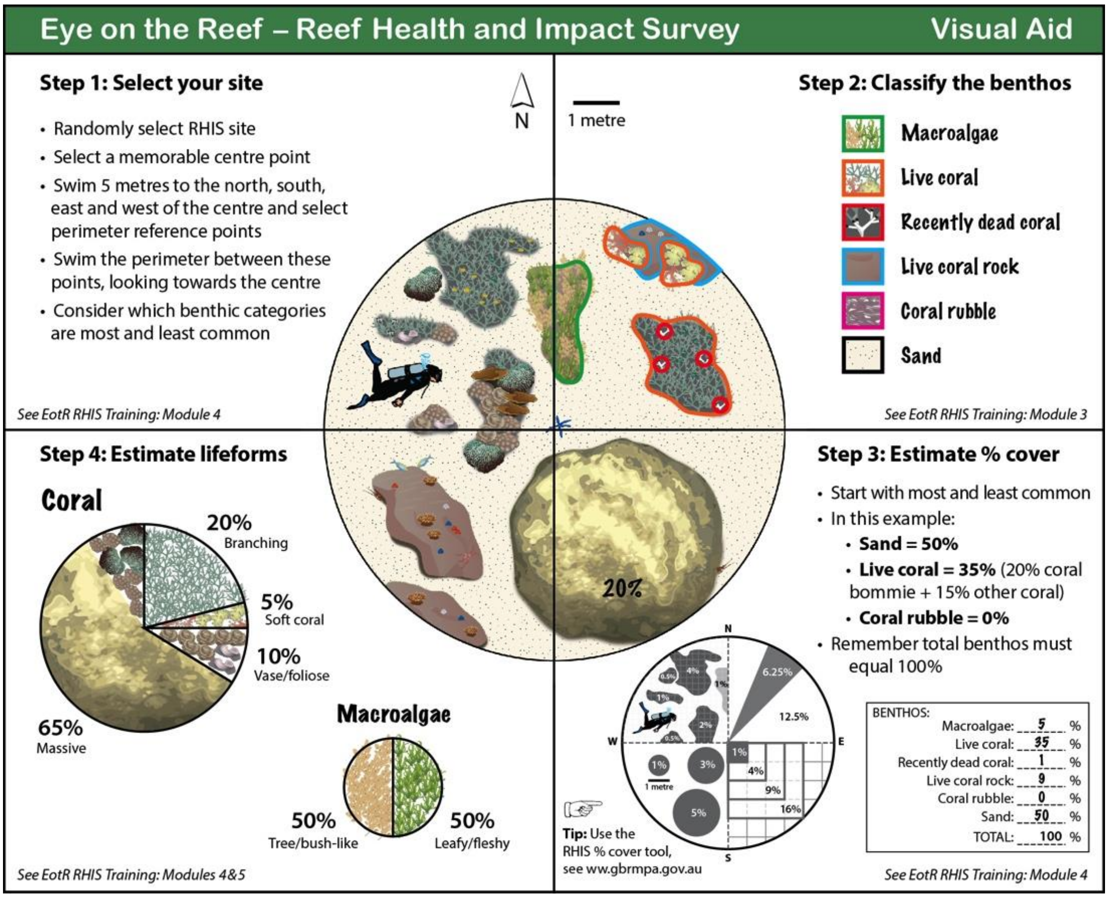


Figure 4.4. Underwater visual aid provided to participant observers. The visual aid assists observers to fill out the RHIS form (see also e-supplementary material). The four steps shown include: 1) site selection along the reef being surveyed, 2) classification of the benthos into 6 categories, 3) estimation of % cover of each benthic category using one of four approaches and 4) classification of coral life-forms and macroalgae types. Learning modules refer to the e-learning tutorial and training process described in Figure 4.3.

The online tutorial provides the necessary streamlined and standardised training required to build capacity amongst many participants. Once certified as observers, participants begin to undertake surveys; the survey network in the GBRMP produces thousands of surveys each year (see section 4.5). These data fulfil the needs managers have for dynamic information on reef health and impacts only if the data can be accessed and analysed. Bridging the common divide between monitoring and making management decisions is described next.

4.5 Informing decision-making and reinforcing participation

Ensuring survey data are accessible and interpretable by managers is a two-part process: submitting the data to central storage, and generating summary reports. For RHIS, participants enter their data through an online interface, essentially a database front end that looks just like the RHIS form (Figure 4.2). The information can be entered in 5-10 minutes for each survey. Having participants enter their own data is vital to the observer networks overall cost-efficiency and for data accuracy. Previously, monitoring programs managed by the GBRMPA used survey forms that could be folded and sent cost-free to managers by post. Forms were often returned incomplete, and many markings and explanatory notes were legible only to the writer. Online data entry by participants overcomes these issues, makes the data available for analysis nearly instantly, and ensures participants go through the process of checking their completed form against their memory of the site.

Online data submission and central data storage both reduce timeframes between data collection and the generation of reports managers need (Conrad & Hilchey 2011; Savan, Morgan & Gore 2003). For this reason, general ‘static’ database queries have been developed to automatically generate reports managers can use and provide to participants. To my knowledge, the reporting capability of the system developed to house and analyse RHIS survey data is unique in marine management. Three report types can be rapidly generated upon request: 1) activity reports, 2) annual survey summaries, and 3) reef health and impact summaries. The reports are PDFs containing images and text, and KML files viewable through Google Earth™, and each serves a different purpose, as follows.

1) The activity reports produced provide a data and graphics-based overview of participation: who has been submitting reports, from where, and can be over any specified timeframe such as the last week, month or year (Figure 4.5).

2) Annual summary reports are like activity reports as they describe participation and show the locations of completed surveys. The annual reports are polished one-page graphics that present a reef health and impact summary for July to June of the following year (Figure 4.6). The annual reports are shared with participants to reinforce the value of the information being collected and so that participation of tourism operators and community members can be showcased and shared with others. These strengthen relationships between managers and stakeholders, as they ensure participation involves a two-way information exchange (Conrad & Hilchey 2011; Danielsen et al. 2010; Savan, Morgan & Gore 2003).

(3) Reef health and impact summaries are survey reports for a selected timeframe. Reef health and impact data can be viewed for preset annual data or for any custom timeframe. Reports are generated as 'time aware' KML files for Google Earth^{TM}; these have a slide bar function enabling users to view the desired timeframe. Summaries of impacts can be viewed for coral bleaching, disease, predation, and coral breakage (Figure 4.6). These report outputs are how the EotR network fulfils the 'early warning system' need described in the introduction and shown within Figure 4.1. As examples, at any point in time, managers can view a 'snapshot' of the percentage of the substrate at reefs surveyed occupied by corals and the severity of impacts at the reef. For the KML files, the range in coral cover determines the size of the circle site marker (larger circle denotes higher cover), and the impact severity determines the colour, where grading shades indicate none and low impacts (green and tan) to severe and extreme (orange and red). The impact severity colours originate from a custom matrix for each impact that relates the most common damage severity level seen at the sites surveyed to the percentage of corals affected (see coral disease example in Figure 3.4). Minor impacts trigger only continued monitoring (R1 in the IRF box, Figure 4.1). Moderate, severe and extreme impacts trigger more spatially extensive assessments of impact severity (R2, 3 in Figure 4.1), and can trigger management actions to reduce stress (where possible), and support recovery processes (e.g. coral disease response levels and

actions in Chapter 3). When undertaken before and after management actions, the RHIS enable assessments of the effectiveness of management actions. Examples of events where RHIS and the EotR network were used to assess impact severity and management effectiveness are described within Chapters 5 and 6.

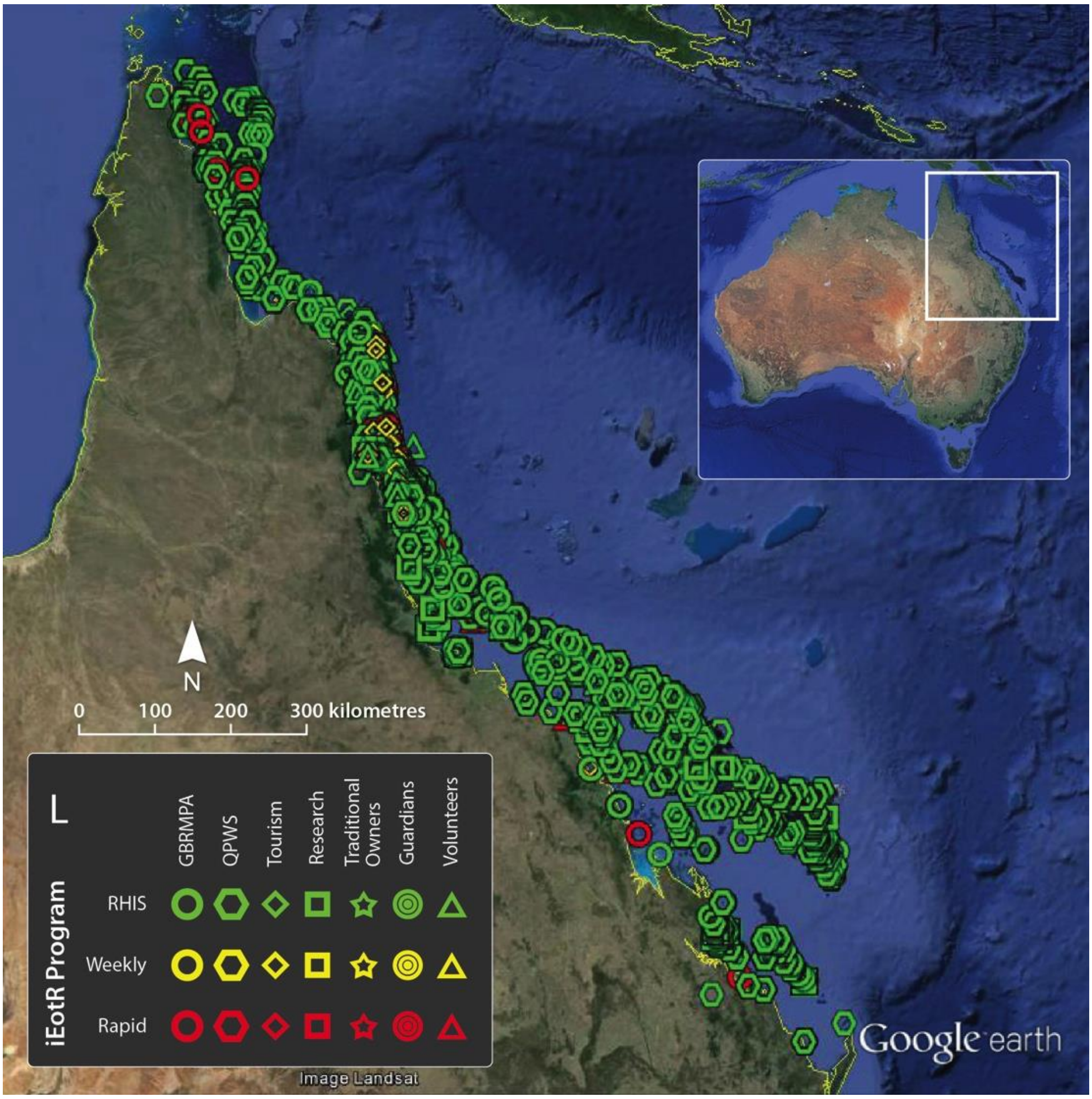


Figure 4.5. Map output from the EotR database showing participation of various agencies in the monitoring network. The map shows where surveys have been completed since use of the RHIS survey protocol commenced in 2009. As of 15th September 2014, 211 participants have surveyed a total of 628 different reefs in the Great Barrier Reef Marine Park.

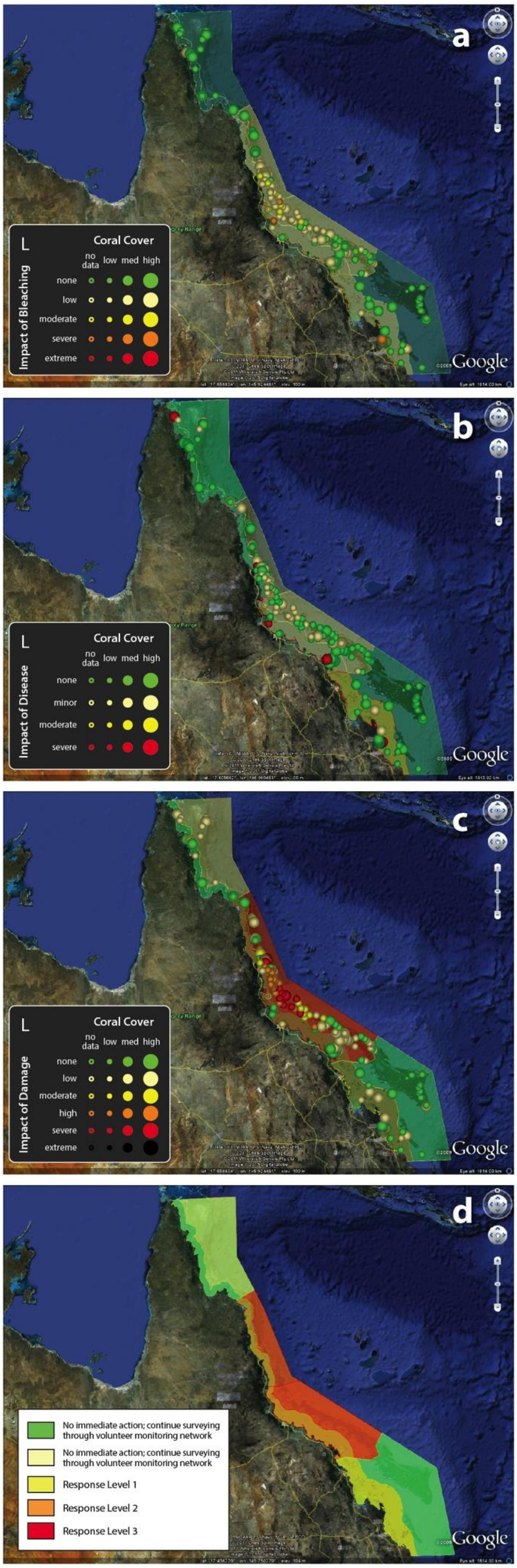


Figure 4.6. Maps of reef health impacts from the EotR database. These maps show reef health impacts for the 2011 summer (Dec 2010-Feb 2011); coral bleaching (a), coral disease (b), physical damage (c). Observational data from surveys are translated into dots of a size and colour dependent on the coral cover affected and severity of impacts, respectively. The extent and severity of impacts translate to five classes of management action (d) ranging from continuing to monitor conditions to Response Level 3 (see also Figure 4.1), which can involve both targeted monitoring and local-scale actions to support recovery processes.

4.6 Conclusion

While the RHIS protocol is tailored for use in the GBR, the approach could be readily customised to meet the needs of managers and conservationists working in other coral reef areas. In the GBR, the Eye on The Reef network fills a critical niche in a hierarchical monitoring scheme that complements professional monitoring schemes. Figure 4.7 depicts hierarchical monitoring within the GBR as a pyramid of stacked triangles. There are trade-offs associated with the type of monitoring conducted at each level. Two key examples are: as the expertise requirements increase, the number of reefs that can be surveyed decreases and, using non-expert observers sacrifices some precision and information detail but greatly increases spatial and temporal coverage and engagement/outreach opportunities (see the arrows in Figure 4.7).

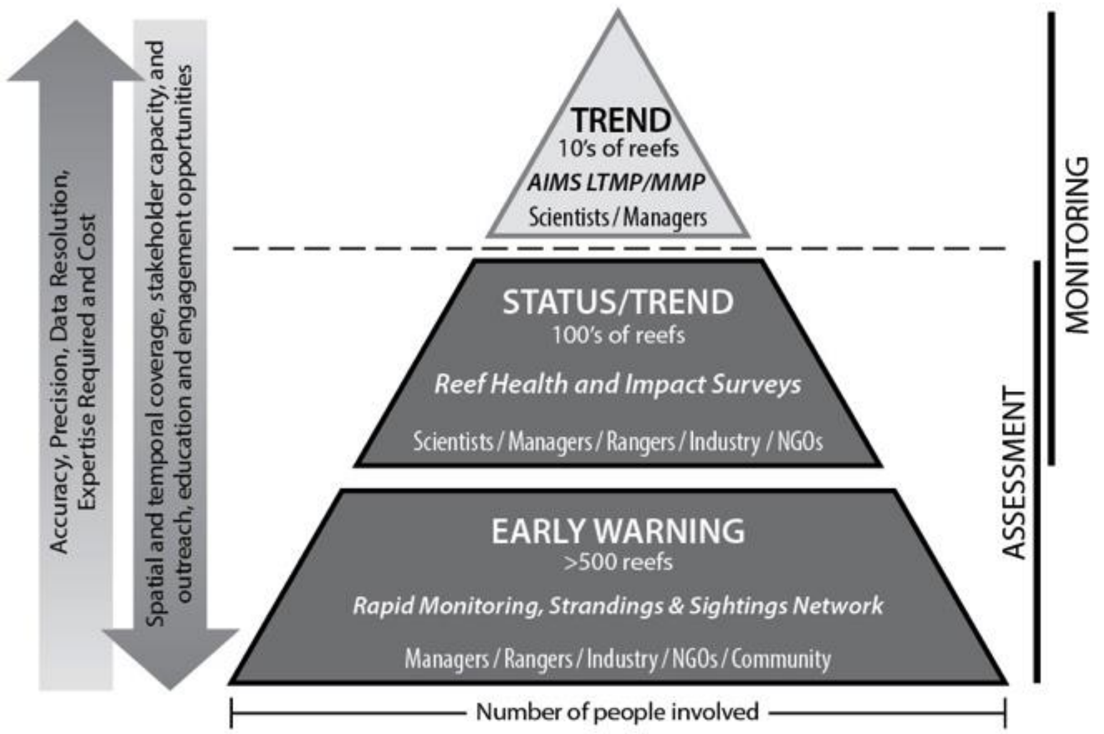


Figure 4.7. Pyramid describing hierarchical monitoring within the GBRMP. This diagram illustrates differences in the ways managers can use information from the different kinds of assessment and monitoring programs ongoing in the GBRMP (right side and titles in triangles). Only the EotR RHIS network of observers can regularly provide information related to status and trend from hundreds of reef locations. However, the opposing arrows highlight major trade-offs that would result from investment in a single kind of program, which clarifies why both professional and participatory monitoring programs are critically needed.

The trade-offs mean managers would lose critical opportunities to understand the system and take action if either professional or participatory monitoring programs operate in isolation. A key message emerging from running this program on one of the world's largest reef systems is that *only* a participatory monitoring network can cost-effectively provide information with broad spatial and temporal coverage. Between the 1st January 2009 and the 15th September 2014, 211 participants completed a total of 10529 Reef Health and Impact Surveys covering 628 different reefs (Figure 4.5). To ensure that this dataset continues to grow the GBRMPA is actively recruiting participants to the Eye on the Reef network via its Reef Guardian stewardship program.

Establishing a participatory monitoring network can have high start-up costs (Danielsen et al. 2009) but maintenance costs are usually low. Once participants are trained, the experiences in the GBR suggest that receiving regular reports requires: 1) matching the demands of the survey protocol to the time participants have and to the skill level attainable with training resources, and 2) ensuring a two-way exchange of information where managers provide reports back to participants that have provided data. When these key requirements are fulfilled, participatory monitoring networks can meet the information needs identified in the introduction, i.e., current and regular information on reef condition, impact detection and severity, and management effectiveness. These information needs are common to reef managers and conservationists, and meeting the needs is increasingly important to adaptively manage reefs in an era of increasing environmental pressures and uncertainty.

The upcoming chapters describe the use of the Reef Health and Impact Survey protocol and participatory monitoring network to quantify the impacts of a severe disturbance and to test the effectiveness of a management action.

CHAPTER 5

Impacts of severe tropical cyclone Yasi on the Great Barrier Reef

Diver from GBRMPA next to an overturned massive colony of *Diploastrea* exemplifying the structural damage resulting from waves generated during severe tropical cyclone Yasi.

This chapter describes the use of the survey protocol developed and described in Chapter 4 to assess the impacts of severe tropical cyclone Yasi, which crossed the Queensland coast as a category 5 storm on February 3, 2011, on coral reefs in the Great Barrier Reef.

Source References:

Beeden, RJ, Puotinen, M, Marshall, P, Goldberg, J, Dryden, J, Williams, G & Maynard, J (in review) ‘Impacts of severe tropical cyclone Yasi on the Great Barrier Reef’, submitted to *PLoS One*

Authority, GBRMP 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2808>

Authority, GBRMP 2013d, *Tropical Cyclone Risk and Impact Assessment Plan*, eds **RJ, Beeden**, JA, Maynard, J, Goldberg, J. Dryden & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2813>

Authority, GBRMP 2011, *Impacts of tropical cyclone Yasi on the Great Barrier Reef: a report on the findings of a rapid ecological impact assessment*, Great Barrier Reef Marine Park Authority, Townsville.

5.1 Abstract

Full recovery of coral reefs from tropical cyclone (TC) damage can take decades, making cyclones a major driver of habitat condition where they occur regularly. Since 1985, 44 TCs generated gale force winds (>17 m/s) within the Great Barrier Reef Marine Park (GBRMP). Of the hurricane strength TCs (H1 – Saffir Simpson scale; category 3 Australian scale), TC Yasi (2011) was the largest. In the weeks after TC Yasi crossed the GBRMP, managers and rangers assessed the extent and severity of reef damage via 858 Reef Health and Impact Surveys. Records were scaled into five damage levels representing increasingly widespread colony-level damage (1, 2, and 3) and reef structural damage (4, 5). Average damage severity was significantly affected by latitudinal location of the reef with respect to the TC track (north vs south of the cyclone track), reef shelf position (mid-shelf vs outer-shelf) and habitat type. More outer-shelf reefs suffered structural damage than mid-shelf reefs within 150 km of the track. Structural damage spanned a greater latitudinal range for mid-shelf reefs (400 km) than outer-shelf reefs (300 km). Structural damage was patchily distributed at all distances, but more so as distance from the track increased. Damage extended much further from the track than during other recent intense cyclones that had smaller circulation sizes. Just over 15% (3,834 km^2) of the total reef area of the GBRMP is estimated to have sustained some level of coral damage, with ~4% (949 km^2) sustaining a degree of structural damage. Based on intensity, size and persistence it

is likely that severe TC Yasi caused the greatest loss of coral cover on the Great Barrier Reef (GBR) in a 24-hour period since 1985. Severely impacted reefs have started to recover; coral cover increased an average of 10% between 2011 and 2014 on reefs within 100 km of the track. The RHIS protocol (developed in Chapter 4) was an ideal tool to rapidly assess the immediate impact of TC Yasi on the GBR, the legacy effects (e.g. coral disease abundance) and the recovery of affected reefs. The in situ assessment of impacts described in this study is the largest-in-scale ever conducted on the Great Barrier Reef following a reef health disturbance and highlights the important role a trained participatory monitoring network (Chapters 2 and 4) can play in assessing impacts on Reef health (Chapter 3) and targeting management actions to support ecosystem recovery (Chapter 6).

5.2 Introduction

Extreme winds during tropical cyclones (TCs, also known as hurricanes, typhoons) generate heavy seas that can devastate coral reef communities (Harmelin-Vivien 1994; Scoffin 1993). The types of damage to corals and reefs includes breakage of coral colony tips and branches, sand burial, dislodgement of large colonies, and structural damage, where sections of the reef framework are partly or wholly removed (Done 1992; Fabricius et al. 2008; Scoffin 1993). Recovery may take decades to centuries (Connell, Hughes & Wallace 1997; Hughes & Connell 1999) in cases of structural damage assuming access to a sufficient larval pool (Coles & Brown 2007; Hughes & Tanner 2000). When such damage reoccurs frequently, especially in combination with other disturbances and anthropogenic stress, coral cover may be lowered sufficiently to threaten the ability of reefs to sustain themselves as coral-dominated systems (Hughes 1994; Hughes et al. 2010; Hughes et al. 2007; McClanahan, Polunin & Done 2002). For example, recurrent cyclones combined with overfishing and coral disease have been a major driver of the decline of reefs in the Caribbean over the last three decades (Perry et al. 2013).

The Great Barrier Reef is regularly exposed to gale force (17m/s) or higher winds generated by TCs, averaging 4 days per year from 1985 to 2009 in the central GBR (Carrigan & Puotinen 2011). Where such TCs are intense or persistent enough or both, the heavy seas they generate can cause structural damage to coral reefs, as was recorded in field surveys after intense TCs Ivor in 1990 (Done 1992) and Ingrid in 2005 (Fabricius et al. 2008). These high-energy events leave a lasting legacy in the geological record, producing storm ridges that can be preserved for thousands of years (Scoffin 1993). Dating of such ridges throughout the GBR and adjacent coast provides evidence of repeated TC structural damage over the past 5,000 years (Nott & Hayne 2001). Cyclones are a major driver of habitat condition in the GBR; De'ath et al. (2012) attribute nearly half of the observed coral loss across the GBR from 1985-2012 to TC wave damage.

Intensity is only one factor affecting the potential of TCs to generate heavy seas capable of damaging coral communities. Although more intense TCs create faster maximum winds and higher maximum wave heights than less intense cyclones and are characterised by lower central pressures (Holland 1980; Young 2003), the overall area encompassed by a cyclone's circulation may be more important in determining its destructiveness (Powell & Reinhold 2007). For a given intensity, large TCs extend extreme conditions over much greater distances than small TCs (100s vs 10s of km – (Knaff, Longmore & Molenar 2014; Merrill 1984). In general, intense TCs can be any size (Merrill 1984), although near the northeast Australian coast, TC intensity tends to peak when TCs are small (Knaff, Longmore & Molenar 2014). Recent studies of TC damage to coral reefs often assume that structural damage is generally not found beyond a certain distance away from the track determined by cyclone intensity (e.g. 100km (Gardner et al. 2005); 90 km (Manzello et al. 2007)), or by intensity and side of the track (160 km (Edwards et al. 2011)). To date, there are no published studies presenting field survey data on the spatial extent of wave damage to coral reefs from a TC that is both large and intense.

TC Yasi crossed the Australian east coast on 3 February 2011 and made landfall on the Queensland coast at the highest intensity since 1918 (Australian Government Bureau of Meteorology 2011). With an estimated extent of gale force winds more than 600 km wide, TC Yasi was also notably large (Figure 5.1), posing challenges for comprehensively mapping the spatial extent of the damage caused to coral reefs. However, when TC Yasi crossed the coast, I had just finished integrating mechanical damage into the Reef Health and Impact Survey (RHIS) protocol for the Great Barrier Reef Marine Park Authority's (GBRMPA) Eye on the Reef participatory monitoring network (see Chapter 4, (Beeden, RJ et al. 2014)). Having trained managers, rangers and participating researcher teams available to use the protocol meant that a large number of reefs could be rapidly assessed spanning the entire potentially affected area.

My objective in this chapter was to demonstrate the capacity of non-specialist observers to quantify impacts following a major disturbance. The impact and recovery assessment for TC Yasi provided a valuable opportunity to fulfil this objective. Other published field surveys after TC Yasi looked for evidence of damage at only 2 (Lukoschek et al. 2013) and 4 reefs (Perry et al. 2014). This study first compares the characteristics of TC Yasi with other TCs that have generated gale force winds in the GBR Marine Park (GBRMP) between 1985 and 2014, and then presents and discusses the results of the impact assessment and subsequent recovery surveys. The study clearly demonstrates the capacity of the network of non-specialist observers to use the RHIS protocol to quantify impacts and recovery following a major reef health disturbance.

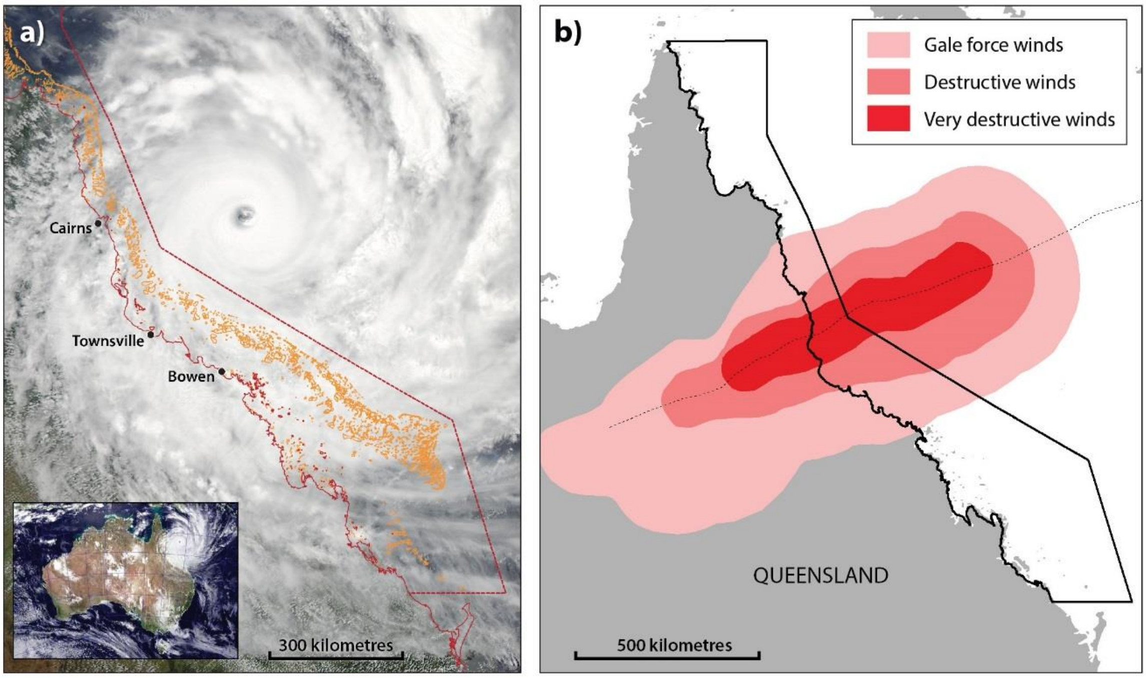


Figure 5.1. Spatial extent of TC Yasi with wind zone boundaries. (a) Satellite-based photograph of TC Yasi on February 2, 2011 prior to crossing the Queensland coast between Townsville and Cairns on February 3 (images courtesy of the Australian Government Bureau of Meteorology (BoM). (b) Boundaries of gale force, destructive and very destructive winds from BoM; the extent of gale force winds north to south along the GBR exceeded 600 km.

5.3 Materials and Methods

Data from the Australian Government Bureau of Meteorology were used to compare TC Yasi's key characteristics to each of the 43 other TCs that produced gale force (>17 m/s) winds in the GBRMP between January 1985 and September 2014. The potential for a TC to cause structural damage to reefs is driven by three key factors: the TC's intensity, size, and duration of extreme conditions near reefs ('persistence'). To capture this, each cyclone was classified based on its maximum intensity (maximum surface wind speeds in m/s), its average size (mean radius from the eye of the storm to the outer edge of gale force winds in km), and its persistence (total hours of gale force or higher winds within the GBRMP). Intense TCs are those that reach hurricane force (wind speeds of 33 m/s; central pressure <970 hPa; category 1 on the Saffir Simpson scale, category 3 on the Australian cyclone scale). The mean gale radii of large TCs exceed 300 km, while radii of small TCs are less than 150 km (Merrill 1984). Gale force wind duration was estimated by calculating the cyclone-generated wind speed across the GBR every hour during each TC and counting the number of hours it met or exceeded gale force conditions. Cyclone generated wind speeds were reconstructed at a 4 km resolution using a parametric TC wind model based on Holland et al. (2010) , with an asymmetry correction from McConochie et al. (2004) and scaled to the gale radii (Puotinen et al., in review). Each TC's intensity, size and persistence were plotted on a conceptual diagram of structural wave damage potential.

The RHIS protocol described in Chapter 4 was used to document the geographical extent, severity and patchiness of damage to reefs exposed to extreme winds (and consequent rough seas) during TC Yasi (Beeden, RJ et al. 2014). Teams from GBRMPA, QPWS, the Australian Institute of Marine Science (AIMS), and the tourism and fishing industries completed 858 surveys at 76 reefs within five weeks (between 10 February and 17 March 2011) of TC Yasi crossing the Queensland coast (3 February 2011, Figure 5.2). The reefs surveyed included nearly 10 percent (73 / 775) of those located within TC Yasi's gale force, destructive or very destructive wind boundaries (Figures 5.1b, 5.2) and three reefs beyond these zones. Surveys spanned the continental shelf (n_{inner}=15 reefs, n_{middle}=35 reefs, n_{outer}=26 reefs), and extended from 150km north (weak side) to 350 km south (strong side) of the TC track. Teams completed at least three surveys for at least three sites around each reef, including a range of habitat types (lagoon, reef flat, crest, slope or bommie fields). Surveys were undertaken on snorkel and SCUBA.

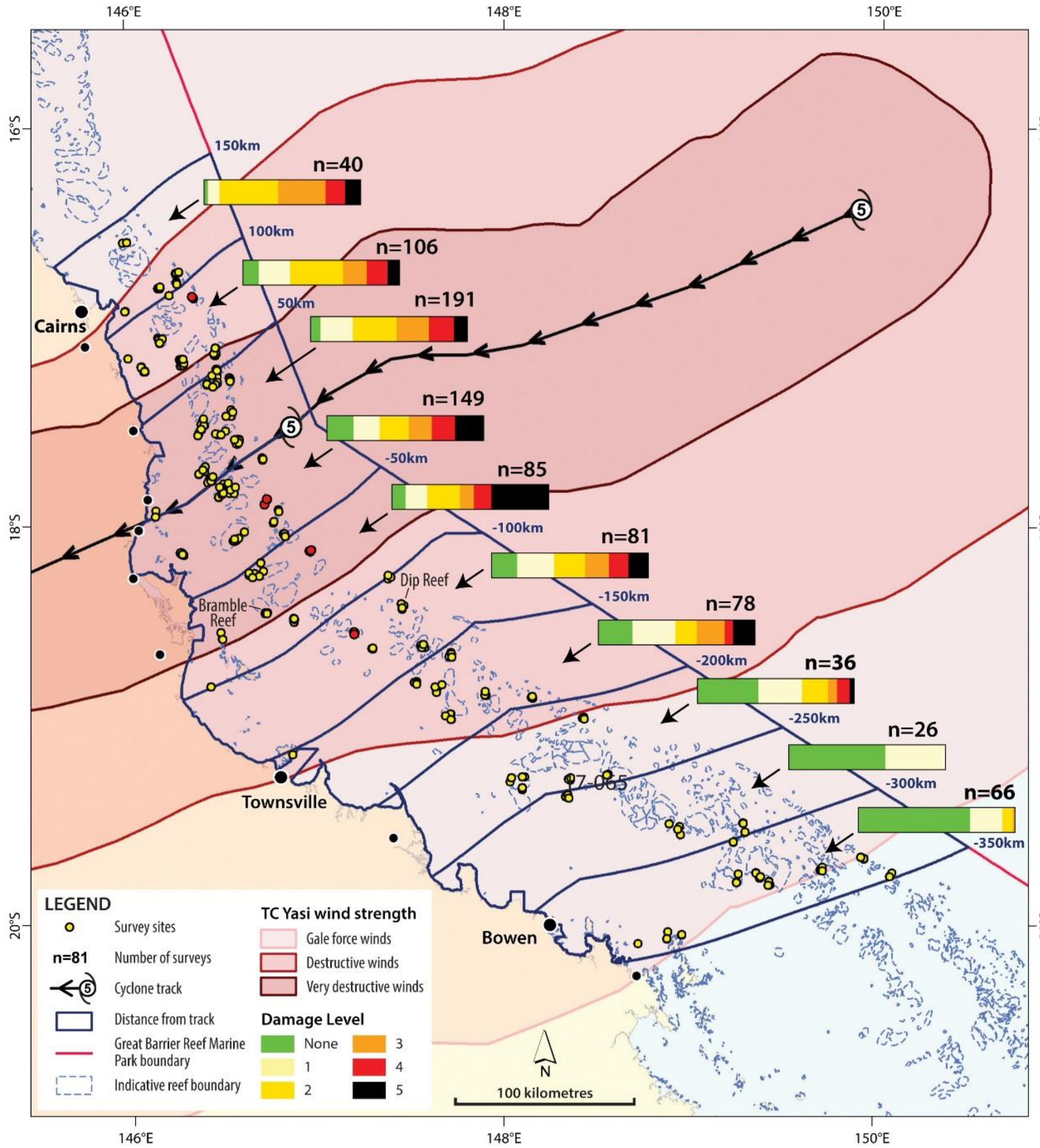


Figure 5.2. TC Yasi survey site locations (surveyed February 10 to March 17, 2011). Bar charts for each 50 km Marine Park segment north and south of the TC track represent the proportion of surveys that had each of 5 levels of damage (see legend on figure). Locations in red denote reefs where >60% of surveys recorded structural damage (level 4 or 5); the two labeled reefs (Bramble and Dip reefs) show the locations of reefs photographed in Figure 5.7.

Damage matrix	Damage Extent						
Damage severity description	Score	0%	1-10%	11-30%	31-50%	51-75%	76-100%
None	0	0	0	0	0	0	0
Tips / Edges	1	0	10	30	50	75	100
Branches / Parts	2	0	20	60	100	150	200
Colonies	4	0	40	120	200	300	400

Damage Levels	
0	No damage
1	Minor coral damage
2	Moderate coral damage
3	High coral damage / Minor reef damage
4	Severe coral damage / Moderate reef damage
5	Extreme coral damage / High reef damage

Figure 5.3. Cyclone damage matrix. Damage extent and severity scores in light blue represent the survey area damaged (Damage extent) and the dominant type of colony-level damage observed (Damage severity description). Damage levels 1, 2 and 3relate to coral damage, while 4 and 5 relate to reef/structural damage. See Figure 5.4 for representative examples and descriptions of each damage level.

For these assessments, team members estimated the proportion of coral cover damaged, and classified the most common level of impact severity observed as one of the following: None, Tips/Edges, Branches/Parts, and Colonies. A damage impact matrix was developed to integrate the extent and severity scores for each survey into one of five levels of damage (Figure 5.3). The matrix and damage levels were developed to be comparable to those developed by AIMS to assess the impact of TC Ingrid (Fabricius et al. 2008). The five damage levels used encapsulate both colony and reef damage. Damage Levels 1 and 2 indicate partial colony mortality. Damage Levels 3, 4 and 5 indicate the increasing extent of complete colony mortality and reef framework damage. Of these, levels 4 and 5 are referred to throughout as structural damage. Figure 5.4 presents pictures of damage that are representative of each of the five damage levels.

Survey data were collated in 50-km segments from 150 km north to 350 km south of the track (10 segments/distance groups). Within these segments, the percentage of surveys that recorded each of the five damage levels was calculated. To estimate the area of coral reef affected at each damage level, the proportion of each level of cyclone damage seen within the surveys was extrapolated to the known reef area within each of the 10 distance groups. Estimates were then produced of the percentage of the total reef area within the Marine Park (24,839 km^2) impacted by TC Yasi at each damage category level (Figure 5.2). Data were collated to identify the percentage of surveys on each reef that recorded structural damage. This provided a measure of the patchiness of structural damage, with low and high percentages indicating isolated (patchy) and widespread (uniform) structural damage, respectively.

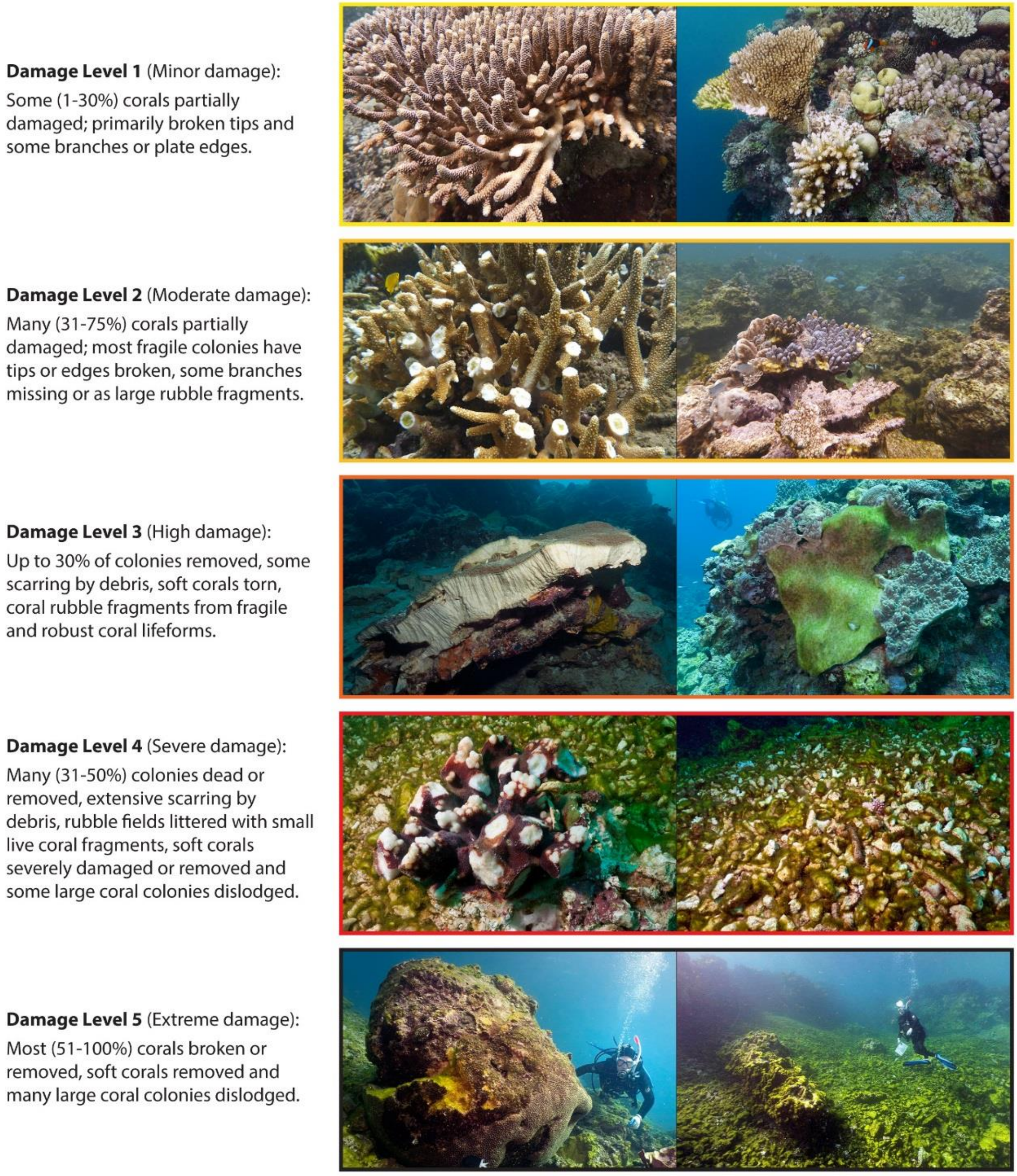


Figure 5.4. Representative photos of the 5 damage levels used in the impact assessment and analysis. The damage levels used follow the matrix in Figure 5.3, which combines damage extent with the dominant type of colony-level damage observed.

Damage levels for surveys within each 50-km segment were also averaged and a custom coded bootstrap routine with R 2.15.3 (R Development Core Team, www.R-project.org) was used to generate 95% confidence intervals, using resampling with replacement (10,000 times) of the 10 distance groups. This method generates estimates of error while accounting for unequal effort among the 10 groups and pools all data (no discrimination between habitat or shelf position). A permutational analysis of variance (PERMANOVA) was also used to test the effects of three fixed factors on the mean level of damage experienced: side of track (two levels: north/south of the eye), shelf position (two levels: mid-shelf and outer-shelf), and habitat (4 levels: lagoon, reef flat, crest and slope). The independent effects of each factor, their possible interactions, and all post-hoc pairwise comparisons across levels were calculated using PERMANOVA+, based on a Bray-Curtis similarity matrix, 9999 permutations of the raw data under a reduced model, and Type III (partial) sums-of-squares.

Recovery surveys were conducted between 2012 and 2014 at sites from 150 km north to 200 km south of the cyclone track (the area with most damage). The recovery surveys were conducted in the same manner as the impact assessments using the RHIS protocol. Percent change was calculated for all benthic cover classifications between 2011 and 2012-2014.

5.4 Results and Discussion

Of the 44 cyclones crossing the GBRMP between 1985 and 2014, TC Yasi was the only cyclone to cross the region when both very intense and large (Figure 5.5). The combination of high intensity and large circulation size increased the probability of structural damage and the likelihood that damage would be spread across a larger area than typical. In contrast, more than half (27, 60%) of the 44 TCs that produced gale force winds in the GBR since 1985 (when detailed satellite records became available) posed a no or very low risk of structurally damaging reefs. These storms did not generate extreme sea conditions, were not sufficiently intense or large, or were not sufficiently persistent near reefs. Just over one-third (30%, i.e. 13) of the TCs in the study period were intense, large and persistent enough to pose a high or very high risk of structural reef damage (Figure 5.5). Of these TCs Larry was the most intense however it was small and short-lived and hence the risk of widespread structural reef damage was diminished. Of the ten TCs that posed a high risk of structural reef damage the three most intense systems crossed the GBR in the past five years. Their overlapping combined tracks are likely to have caused structural damage to very large proportion of the GBR and full recovery may take decades to centuries (Done 1992; Fabricius et al. 2008; Hughes & Connell 1999; Hughes et al. 2010;

Mumby et al. 2011; Pearson 1981; Puotinen, Done & Skelley 1997). Although TC Yasi was only the third most intense, the last cyclone to make landfall at a similar size and intensity did so nearly a century ago in 1918 (Australian Government Bureau of Meteorology 2011). TCs more intense than TC Yasi (central pressures < 920 hPa versus TC Yasi's minimum hPa of 929) track within the GBR only about once every 200-300 years (~0.5% probability of occurrence in a given year; (Nott & Hayne 2001)).

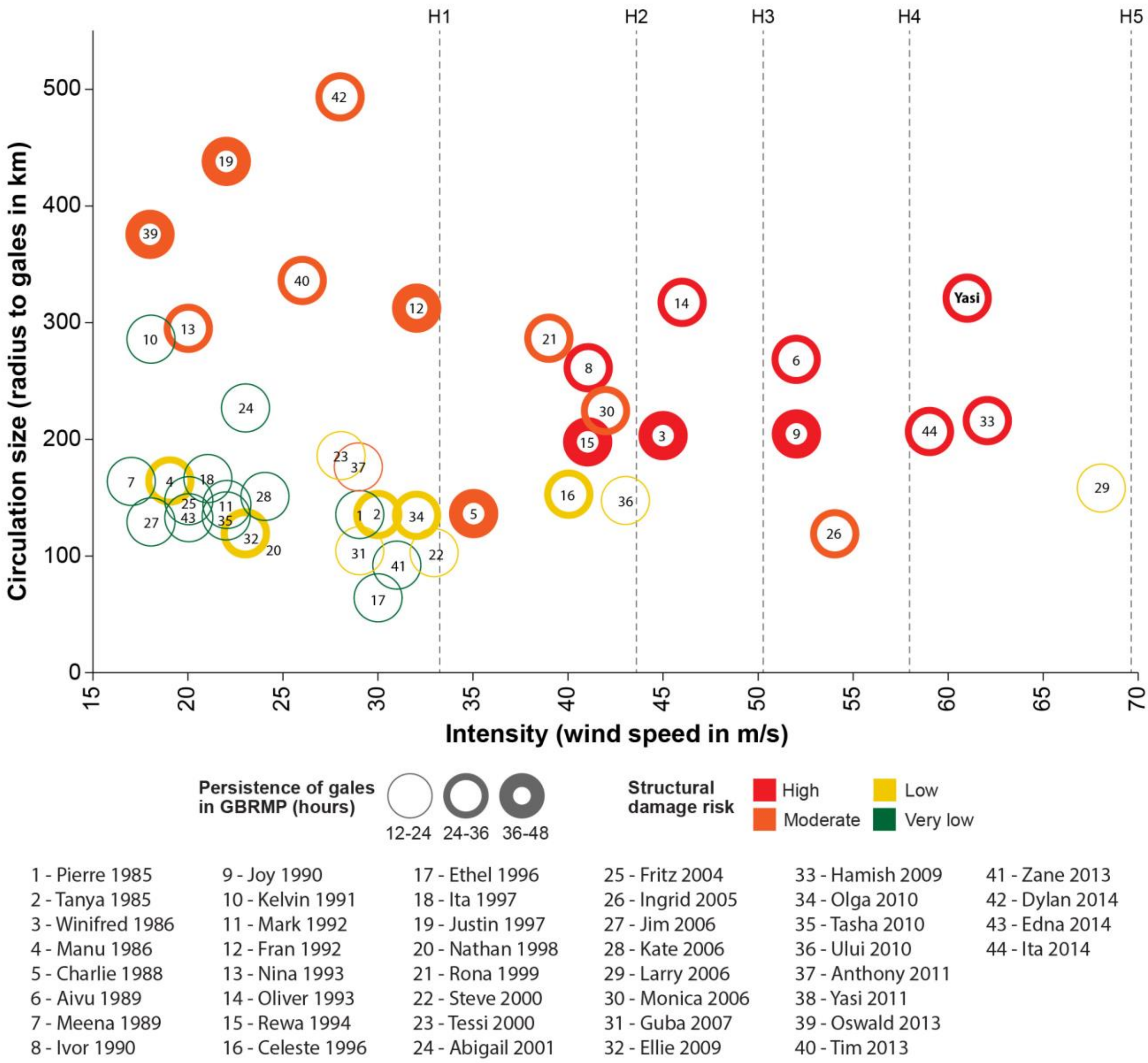


Figure 5.5. Conceptual diagram of damage potential for TCs that generated >1 hour of gale force winds in the GBRMP between January 1985 and September 2014. The 44 TCs are classified with respect to their intensity (wind speed in m/s) along the horizontal axis and their circulation size along the vertical axis (average radius to gales in km). Dotted lines illustrate the Saffir-Simpson Hurricane Scale categories. Colour coding depicts the risk of structural damage to reefs in the GBR. Of the 44 TCs Yasi was the largest very intense system to affect the GBR resulting in a very high risk of extensive structural damage across an extended area.

The impact assessment undertaken following TC Yasi using the RHIS protocol represents the most spatially extensive field survey of TC impacts on coral reefs ever conducted and reported (858 surveys of 76 reefs, ~10% of the 775 reefs within the gale force wind boundary, see Figure 5.2). Damage was observed throughout the 89,090 km^2 area of the Marine Park exposed to damaging (gale force to very destructive) winds during TC Yasi, an area spanning approximately 4 degrees of latitude (Figures 5.1, 5.2). Damage from TC Yasi ranged from minor tissue injuries at the edges and tips of fragile coral colonies to total removal of all sessile organisms and abrasion and fracturing of the reef substrate. In total, just over 15% (3,834 km^2) of the 24,839km^2 reef area within the Marine Park is estimated to have sustained some level of coral damage, with nearly 4% (949 km^2) of reef area sustaining severe coral damage and some degree of structural damage (Table 5.1).

Table 5.1. Total and percentage reef area affected within each damage level. Damage levels are described in Figure 5.3 and illustrated in Figure 5.4.

Damage Level	Damage Level Descriptions	Total Reef Area Affected (km^2)	Proportion of Affected Reef Area Within the Marine Park (%)
Level 0	No Damage	21,005	84.5
Level 1	Minor Coral Damage	1,388	5.6
Level 2	Moderate Coral Damage	933	3.8
Level 3	Severe Coral Damage	564	2.3
Level 4	Severe Coral Damage and Moderate Structural Damage	447	1.8
Level 5	Extreme Coral Damage and High structural Damage	502	2.0

Structural damage (levels 4 and 5) extended as far as 150 km to the north and 250 km to the south of the cyclone track. This demonstrates that structural damage from an intense and large TC extends farther than the typically reported distance thresholds (i.e., 90km (Manzello et al. 2007), 100 km (Gardner et al. 2005), 160 km (Edwards et al. 2011)). At sites with structural damage (levels 4 and 5, Figures 5.2 and 5.3), few corals escaped substantial physical injury, and many were so severely damaged that only their bases or remnant sections remained attached to the reef. The majority of large soft corals either suffered substantial tissue loss or were completely removed, as indicated by layers of spicules formed where the coral had been attached to the substrate. Extensive fields of freshly formed rubble were seen, including large numbers of coral fragments still covered in live tissue. At the worst affected sites, extensive areas of reef structure were comprehensively scoured. Few corals or other sessile organisms remained attached to the reef structure and some very large corals, likely to be hundreds of years old, were dislodged and overturned (Figure 5.2, pictured in Figure 5.4).

The extensive field data set collected following TC Yasi demonstrates that a single large and intense cyclone can severely damage coral communities over a vast area within a very short timeframe (~ a day). Using percent coral cover recorded at sites where little to no damage occurred as a proxy for pre-TC Yasi coral cover, the overall average coral cover loss (pre-TC Yasi cover – post-TC Yasi cover) at reefs surveyed was calculated to be 2.5±2.7%. Coral cover loss varied considerably among the ten 50-km distance segments, and was greatest (7.03%) at 100 km north of the track, where both pre-TC Yasi coral cover and average damage severity were high (Figure 5.6). Current rates of decline in annual coral cover across the GBRMP since 2006 are estimated to be ~1.4% per year (De'ath et al. 2012), and from 1985 to 2012, an annual mortality rate of 1.6% was attributed to cyclones in potentially affected areas (De'ath et al. 2012). Accordingly, the 2.5% mean coral cover loss estimated for TC Yasi is about 40% higher than typical annual losses for TCs in the GBRMP since 1985. It is important to note that several of the years from 1985 to 2012 included multiple cyclones, yet the coral loss from a single large and very intense TC (Yasi) was almost twice as high as the typical yearly loss. Given the vast extent of area affected by TC Yasi, the rate of coral loss may have been even higher had the greatest impacts not occurred in an area where coral cover was already low prior to the TC (e.g. comparing historical central GBR coral cover in De'ath et al. 2012 with Figure 5.6).

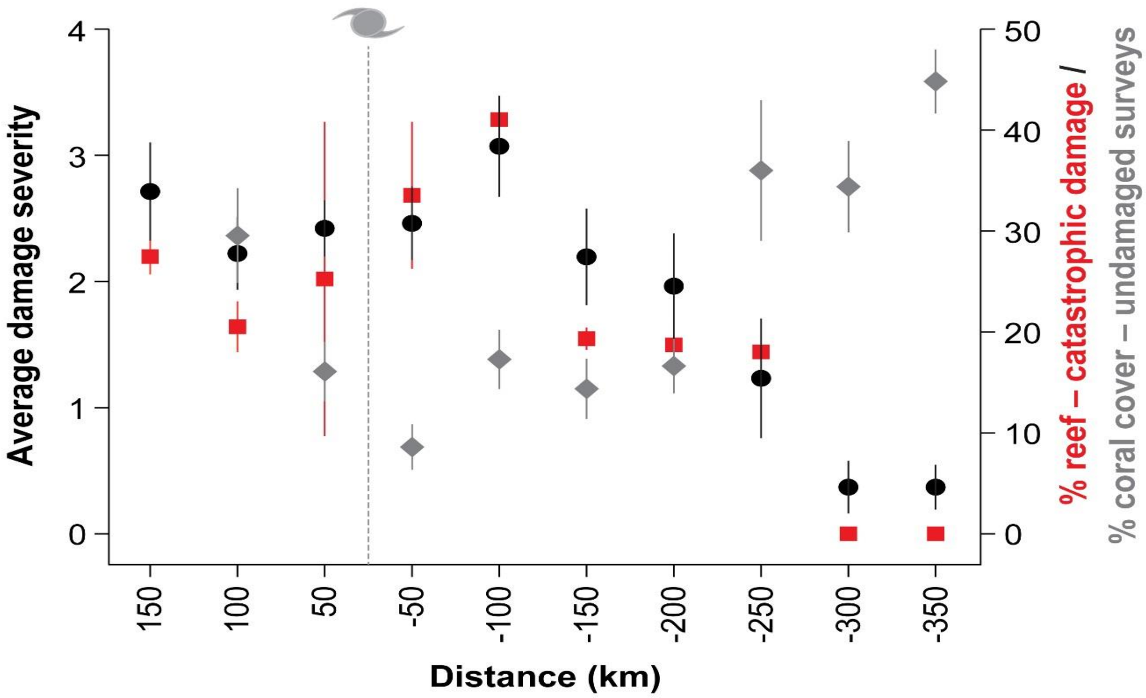


Figure 5.6. Average damage severity (CI 95%) (black circles) in each of the ten 50 km segments of the GBRMP surveyed (see Figure 5.2, surveys Feb-Mar, 2011). The percentage of the reef structurally damaged (damage levels 4 or 5, Figures 5.3 and 5.4) is also shown (±SE) (red squares), along with the % coral cover (±SE) (grey triangles) at undamaged sites at the time of surveys for the 50 km segments for which the undamaged survey sample size is greater than one (excludes 150 km north). The cyclone symbol denotes the location of the track of the cyclone eye.

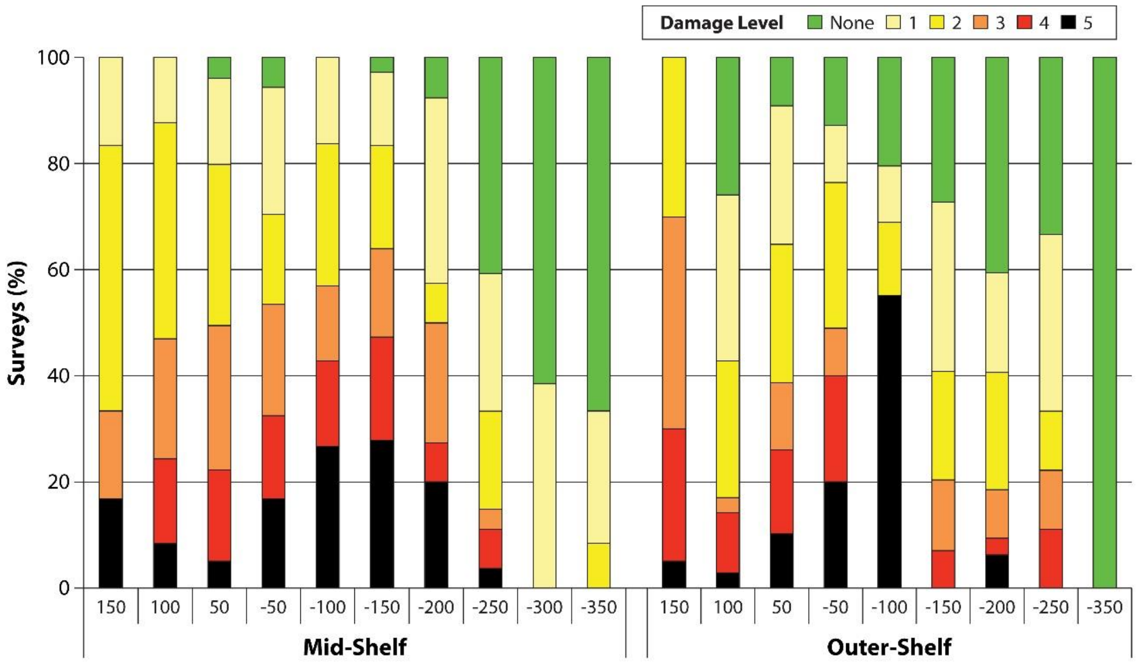


Figure 5.7. Proportion of surveys that recorded each level of cyclone damage at each shelf position for each 50 km segment (Figure 5.2) of the Marine Park. Damage level descriptions can be found in Figures 5.3 and 5.4.

Average damage severity did not significantly differ among the seven 50-km segments from 150 km north to 200 km south of the cyclone track based upon the overlapping standard error bars in Figure 5.6. Average damage peaked 100 km south of the track (3.09±0.19) but was not significantly greater than in the segment 150 km north (2.73±0.18). The proportion of sites with structural damage was roughly equal for all three 50-km segments north of the track (24%, 21% and 23% for the northern 50, 100 and 150km segments, respectively). Within 50 and 100 km of the cyclone track, the prevalence of both high coral damage and structural damage was greater to the south (high damage: 33% of reefs, structural: 47% of surveys) than to the north (high damage: 24% of reefs, structural: 21% of surveys) of the track (Figure 5.2). South of the cyclone track, average damage (± SE) declined rapidly as distance from the track exceeded 200 km (Figure 5.6). Accordingly, the proportion of surveys recording colony rather than structural damage levels 1-3 or no damage increased with distance south of the track, from 33% of reefs up to 50 km south to >90% beyond 250 km (Figures 5.6, 5.7). No structural damage was recorded for surveys of reefs south of 250 km (Figures 5.6, 5.7).

Reef habitat, shelf position and location relative to the side (north/south) of the cyclone track all influenced damage severity, but their affects varied according to characteristics of each of the other two factors (PermANOVA: Pseudo-$F_{5,754}$=3.2054, p = 0.003). In pairwise comparisons to determine which factors contributed significantly to this interaction term, interactions between side of track and habitat (Pseudo-$F_{5,754}$=3.8805, p<0.01) and between habitat and shelf position (Pseudo-$F_{5,754}$=2.1667, p<0.05) were significant, but patterns in damage severity at shelf positions were not significantly different between sides of the track (Pseudo-$F_{1,754}$=1.0043, p>0.05). At outer-shelf reefs north of the cyclone track, lagoon habitats (mean damage level=3.269), reef flats (2.857) and reef crests (2.778) all suffered more damage than reef slopes (1.643) (t=4.96, p<0.001; t=3.12, p<0.01; t=2.34, p<0.05 [respectively]). However, there were no significant (p>0.05) differences in average damage between habitats for mid-shelf reefs north of the cyclone track. Nor were there any significant differences in average damage between habitats for outer-shelf or mid-shelf reefs south of the cyclone track (p>0.05).

Distance from the cyclone track influenced the severity of damage recorded (Figures 5.6, 5.7). The prevalence of the worst structural damage (level 5) peaked at outer-shelf reefs south of the track in the 100 km segment, where level 5 damage was recorded in more than half of surveys (Figure 5.7). This was double the prevalence of such damage in outer-shelf reefs in the comparable 100 km segment north of the track (Figures 5.6, 5.7). However, at least one instance of severe structural damage was observed at a greater number of mid-shelf (17) than outer-shelf (13) reefs located between 150 km north and south of the track. However, the total number of surveys (across all 50-km bands) that recorded structural damage was higher for mid-shelf (47) than outer-shelf (38) locations (Figure 5.7).

Structural damage to corals from TC Yasi was spatially extensive, with high levels recorded at 24% of reefs surveyed and moderate levels recorded at 66.2% of reefs surveyed. The spatial distribution of structural damage was extremely patchy, as is characteristic of cyclones (Harmelin-Vivien 1994), even for intense TCs (e.g., TCs Ivor (Done 1992), Ingrid (Fabricius et al. 2008)). Only four (5.3%) of the reefs surveyed showed structural damage at 60% or more of the sites surveyed. These uniformly devastated reefs (Hopkinson, Unnamed 18-023, Unnamed 17-065 and Pellowe; see red circles depicting sites on each of these reefs in Figure 5.2) were located within the highly destructive and destructive wind zones defined by the Australian Bureau of Meteorology (see Figure 5.1), ranging from 100km north to 150 km south of the track, and primarily on the outer continental shelf (inner: 0 reefs, middle: 1 reef, outer: 3 reefs; see Figure 5.2). At these reefs, coral cover remaining after TC Yasi was typically less than 20% (Hopkinson: 14%, UN18-023: 19%, UN17-069: 17%, Pellowe: 33%). The full range of damage types was seen at most other reefs surveyed from 150 km north of the track to 250 km south.

In both the very destructive and destructive wind zones (Figure 5.1), there were sites where structural damage was observed within 50 m of sites that escaped completely unscathed (Figure 5.8). Such patchiness highlights that the amount of TC-generated wave energy actually reaching a given part of a reef within the complex GBR setting depends on the location of nearby reefs and land masses, and the incoming wave direction and tidal currents (Young & Hardy 1993). Wave energy is then transformed as it interacts with the variable topography characteristic of reefs and their colonies (Monismith 2007). The likelihood of structural damage from a given level of wave energy is greater where colonies of mechanically vulnerable shapes (e.g. branching, plate morphologies) are both prevalent (Madin & Connolly 2006) and large, given that vulnerability increases with colony size (Madin et al. 2014). Furthermore, TC Yasi tracked through the central GBR, which is frequently exposed to TCs (Carrigan & Puotinen 2011, Puotinen et al. in press). As a consequence, the total coral loss is likely to have been less at sites with a recent history of cyclone damage (little coral left to damage; (Hughes 1989), most notably TC Hamish which tracked north to south through much of the GBRMP at high intensity in 2009.

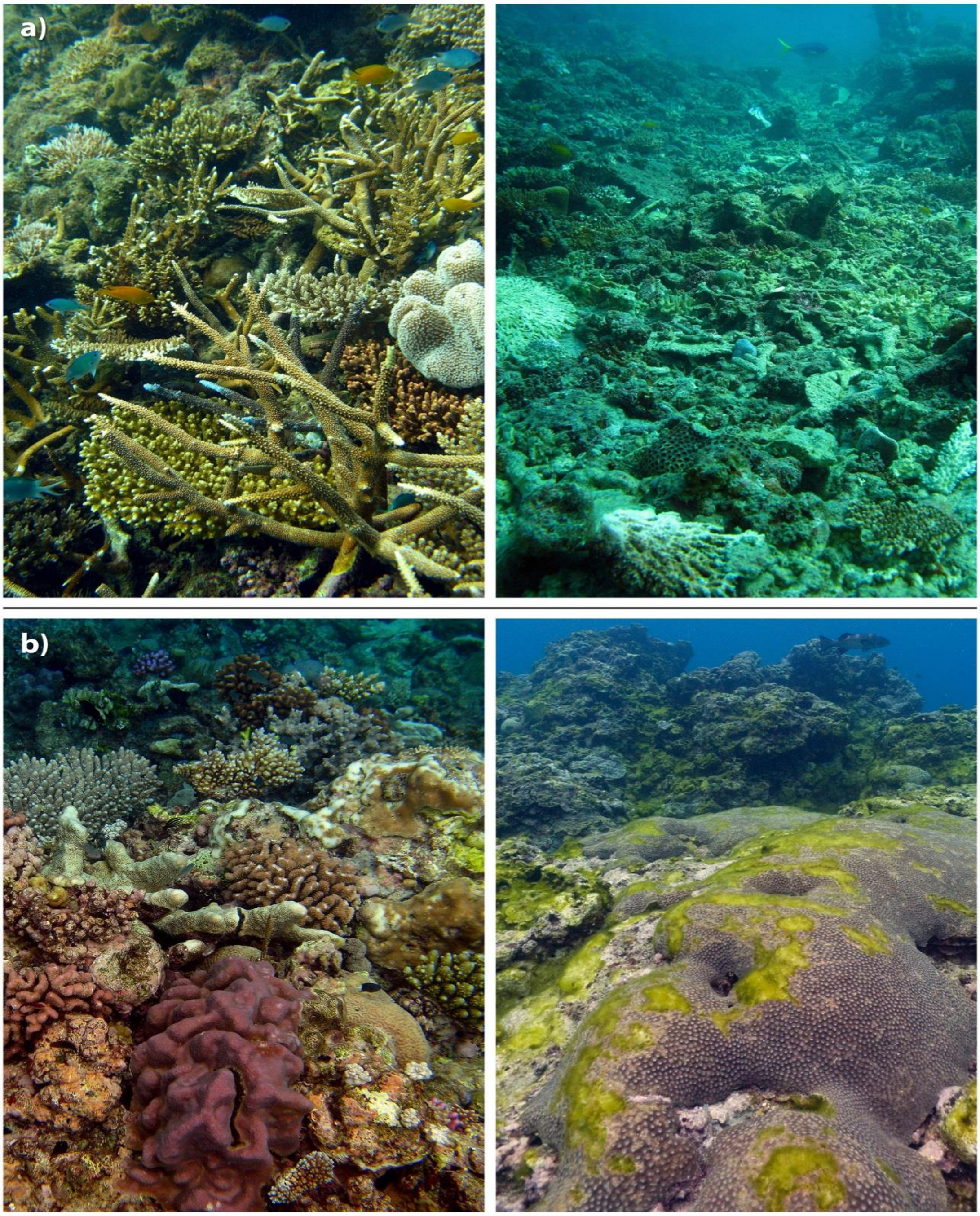
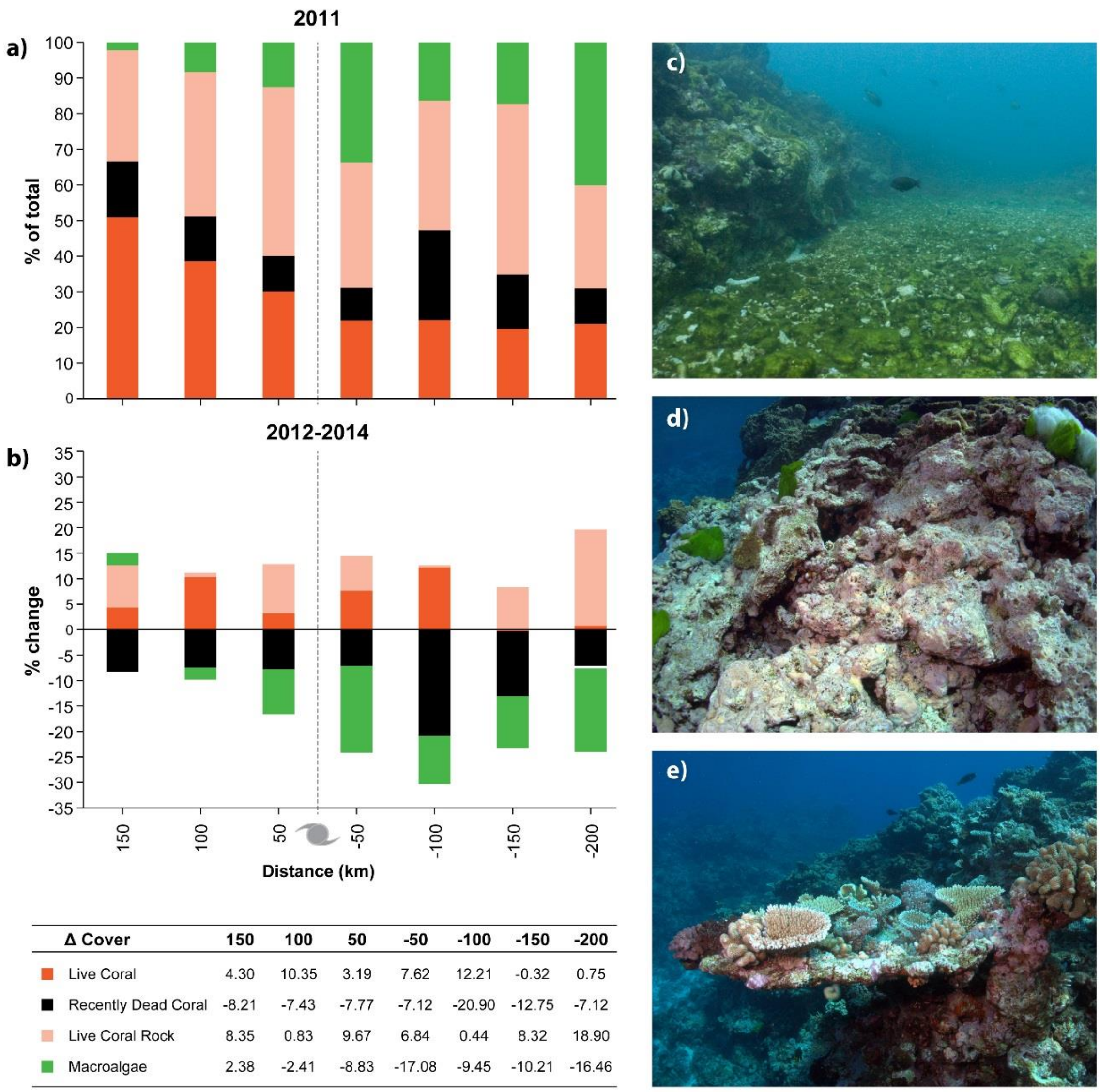


Figure 5.8. Pairs of photographs taken within 50 m showing the patchiness of damage at (a) Bramble Reef in the very destructive wind zone; left – Damage Level 0, Right – Damage Level 5, and (b) Dip Reef in the destructive wind zone Damage Level 1, Right – Damage Level 5. See Figure 5.1 for destructive and very destructive wind zone boundaries, Figure 5.2 for reef locations and Figure 5.4 for Damage Level illustrations.

During the impact assessment surveys, extensive algal growth was observed on many of the damaged reefs. Green filamentous algae were observed growing over remnant coral fragments and injured colonies, and blanketing large areas of damaged reef substrate. Dense algal growth was seen on reefs up to 200 km south of the cyclone track (Figure 5.9c). The morphology of the algal growth varied with depth, taking the form of a low matt on mid and lower reef slopes, and dense stands of long filaments on the upper slope and reef flat. During the impact assessment, algal cover varied from 6.65% (100 km north) to 34.50% (200 km south of the track). Algal cover declined in all 6 of these segments between 2011 and the recovery surveys of 2012-2014 (2.41% in the northern 100 km segment and 16.46% in the southern 200 km segment, Figure 5.9b). Conversely, coral cover increased in nearly all segments from 150 km north to 200 km south between 2011 and 2012-2014, with increases of 10.35% and 12.21% at sites 100 km north and south of the track, respectively. The only exception was in the southern 150 km segment (-0.32%), where no change in coral cover was detected. Since TC Yasi, the average change in coral cover from 150 km north to 200 km south of the track was an increase of 5%. The percent of the benthos identified as recently dead coral also declined between 2011 and the recovery surveys of 2012-2014; most had transitioned to either live coral rock or live coral (Figure 5.9c, d).



Δ Cover	150	100	50	-50	-100	-150	-200
Live Coral	4.30	10.35	3.19	7.62	12.21	-0.32	0.75
Recently Dead Coral	-8.21	-7.43	-7.77	-7.12	-20.90	-12.75	-7.12
Live Coral Rock	8.35	0.83	9.67	6.84	0.44	8.32	18.90
Macroalgae	2.38	-2.41	-8.83	-17.08	-9.45	-10.21	-16.46

Figure 5.9. Patterns in benthic categories immediately following TC Yasi and 1-3 years later. a) Proportion of the benthos comprised of live coral, live coral rock (includes crustose coralline algae and turf algae covered substrate, see Chapter 4), recently dead coral, and macroalgae in the 6 weeks following TC Yasi crossing the Marine Park in 2011. b) Percent changes between 2011 and 2012-2014 for each category, where positive values correspond to increases and negative values to decreases. Images depict: c) algae blooms following TC Yasi in 2011, d) the transition from recently dead coral to live coral rock, and e) coral recruitment and recovery at Helix Reef.

Despite the ecosystem-scale significance of TC Yasi, notably the widespread but patchy damage it caused throughout 15.5% of the GBRMP reef area, early signs of recovery are now evident. The majority of sites surveyed still had remnants of living coral in 2011, and increases in coral cover have been seen in all but one of the 50 km segments from 150 km north to 150 km south of Yasi's track since 2011. Between the impact assessment (2011) and recovery surveys (2012/2014), extensive overgrowth by filamentous algae rapidly subsided (Figure 5.9a, b) and recently dead coral has been covered, in large part, by crustose coralline algae. Crustose coralline algae can facilitate larval recruitment (reviewed in Birrell et al. 2008; Doropoulos et al. 2012) and thereby enhance the recovery of damaged coral reefs (Figure 5.9a,b). The presence of multiple signs of recovery in the three years since TC Yasi crossed the GBRMP is promising. However, continued recovery will depend on successful larval recruitment (Cantin et al. 2009; Lukoschek et al. 2013), regrowth of surviving colonies and future disturbance frequencies. Return to pre-TC Yasi coral cover levels is likely to take 10 years or more at severely damaged sites and recovery to pre-cyclone species diversity may take even longer. Disturbance frequency will be a major driver of recovery rates, thus the current outbreak of crown-of-thorns starfish (COTS, *Acanthaster planci*) (De'ath et al. 2012) in the region poses a serious threat to the pace and extent of recovery of affected reefs.

Recent research suggests that TC activity along Australia's east coast was significantly lower during the past century than over the past 550 years (Haig, Nott & Reichart 2014). This is in line with projections that the overall frequency of TCs in the region is likely to decline as the climate warms (reviewed by Knutson et al. 2010)). The recent spate of intense TCs crossing the GBRMP (TCs Ingrid 2005; Monica 2006; Larry 2006; Hamish 2009; Ului 2010; Yasi 2011; Ita 2014) is in stark contrast to the extreme rarity of such TCs from 1970 to 2003. No TCs crossed the GBRMP and Queensland Coast at greater than category 3 on the Australian scale in this period (Puotinen 2007; Puotinen, Done & Skelley 1997). This has led to speculation that the intensification of TCs (fewer TCs overall, but more of them at higher intensity) projected for the southwest Pacific under global warming (Abbs et al. 2006; Leslie et al. 2007; Pearce et al. 2007; Walsh, Nguyen & McGregor 2004) is already occurring in the GBR region. Holland and Bruyère (2014) argue that global warming has already substantially increased the proportion of very intense (Saffir Simpson category 4 and 5) TCs globally and regionally since 1975 but that the rate of intensification of TCs is likely to slow. In contrast, cyclones with large circulation areas did not become more prevalent globally or locally from 1978-2011 (Knaff, Longmore & Molenar 2014). There is currently no evidence to suggest large cyclones will occur more frequently as the climate warms (Knutson et al. 2010). Furthermore, potential changes to the spatial distribution of TC tracks globally and in the southwest Pacific is uncertain (Knutson et al. 2010). However, even if large TCs remain rare within the GBR, a greater proportion of TCs are predicted to be intense in the future (Knutson et al. 2010). This indicates an increased likelihood that the large TCs that do cross the GBR in the coming decades will do so at high intensity - similar to TC Yasi. If so, the typical annual rate of coral loss from TCs reported in De'ath et al. (2012) may rise in the future.

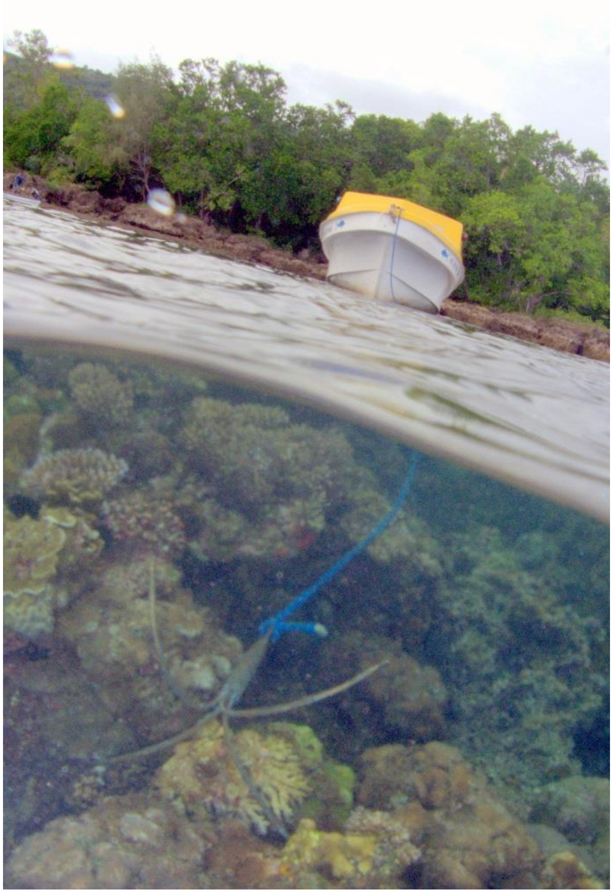
The impact assessment detailed in this chapter is the largest-in-scale ever conducted on the GBR following a reef health disturbance. The need for such assessments is likely to increase, given that spatially extensive coral bleaching events (Van Hooidonk & Huber 2012; Van Hooidonk, Maynard & Planes 2013) and intense cyclones are projected to become more frequent (Knutson et al. 2010; Pearce et al. 2007). Currently, more than 200 participants in the GBRMPA's Eye on the Reef participatory monitoring program use the RHIS protocol and submit data regularly on reef condition and impacts from 100s of reefs in the GBRMP (see Chapter 4, Beeden, RJ et al. 2014). In combination with regular reporting, completing targeted impact assessments following disturbances like intense cyclones (Authority, GBRMP 2013a, c, d and e) within the GBRMP provides managers with a dynamic understanding of reef condition and impacts. Understanding spatial patterns in damage severity enables managers to target local-scale actions to support reef resilience and recovery. Examples of such actions include: crown-of-thorns starfish culls, active reef restoration and the establishment of special management areas or temporary fishing closures. Such local-scale actions are increasingly needed (reviewed in (Sale 2008)) and, in the GBR, can complement Reef-wide strategic initiatives (Anthony et al. 2014), like the Reef Water Quality Protection Plan (Reef Plan 2013; www.reefplan.qld.gov.au) and the re-zoning of the Marine Park in 2004 to include habitat from a range of representative habitat areas (Day 2002; Fernandes et al. 2005).

Large intense cyclones like TC Yasi have been very rare over the last ~100 years but may occur with greater frequency in the coming decades under climate change. The results of the impact assessment presented in this chapter demonstrate a number of points that have implications for current and future management (1) The spatial extent of structural damage from TC Yasi was great, far greater than was documented in the GBR following the smaller but nearly as intense TCs Ivor (1992) and Ingrid (2005), and caused an unusually high rate of coral loss. (2) Damage at all levels was extremely widespread, but the most severe damage (structural damage) was highly patchy within all wind zones. (3) Such patchiness can facilitate future recovery, and many early signs of recovery have already been observed; algal blooms have subsided, crustose coralline algae are covering dead coral (live coral rock category in RHIS, see Chapter 4), and corals are actively recruiting and recovering. Overall, these three primary results lead to the conclusion that, where they occur, large intense TCs are among the biggest drivers of coral reef condition and patterns of recovery. TC Yasi probably caused the greatest loss of coral cover in any 24-hour period since formal monitoring of the GBR began in the 1980's.

Without the development of a strategic plan for responding to Tropical Cyclone impacts (Authority, GBRMP 2013e), the RHIS protocol, training system and participatory monitoring network, and Eye on the Reef (EotR) database (Chapter 4), the full impact of TC Yasi could not have been adequately assessed to inform responsive adaptive management actions. Furthermore, while follow-up surveys of reefs in the worst affected area have revealed encouraging early signs of recovery, RHIS data from reefs in the Cairns to Lockhart River region collected since 2011 reveal the extent of risk that cumulative impacts pose to full recovery. RHIS and other EotR program surveys indicate that crown-of-thorns starfish are now moving into the area worst affected by TC Yasi. In addition, TC Ita, which crossed the GBR as a category 4 system in April 2014, may have affected recovering corals and limited their reproductive capacity. The complex web of cumulative impacts and their combined potential to affect recovery from severe disturbances highlights the critical importance of establishing systems that provide dynamic information on reef condition. Such information is now beginning to be used to guide crown-of-thorns starfish control actions to protect remaining coral cover in the TC Yasi impact area. The impact assessment and recovery analysis documented in this Chapter will aid the targeting of these and future actions to support recovery. As discussed in Chapters 3 and 4, evaluating the effectiveness of actions to support recovery is an essential requirement of adaptive management. Evaluation can also be accomplished using the tools developed in Chapters 2, 3 and 4. A multi-year example of how this has been achieved for a local scale action to support reef recovery and resilience following multiple Reef health impacts in Keppel Bay is the subject of Chapter 6.

CHAPTER 6

No-anchoring areas reduce coral damage in an effort to build resilience in Keppel Bay, southern Great Barrier Reef



Anchors can badly damage corals, especially in frequently visited areas.

This chapter describes the use of the RHIS protocol developed and described in Chapter 4 and implemented in Chapter 5 to assess the effectiveness of no-anchoring areas, established in 2008 in Keppel Bay to support reef resilience.

Source Reference:

Beeden, RJ, Maynard, J, Johnson J, Dryden, J, Kininmonth, S & Marshall, P 2014b, 'No-anchoring areas reduce coral damage in an effort to build resilience in Keppel Bay, southern Great Barrier Reef', *Australasian Journal of Environmental Management*, vol. 21, no. 3, pp. 311-319, doi: 10.1080/14486563.2014.881307

6.1 Abstract

The natural resilience of coral reefs and their ability to resist and recover from disturbance may be supported by managing user access, including regulating the anchoring of vessels. The process of targeting such a site-based local management action and evaluating its success is central to managing adaptively. Here I describe an example of such a management action that was initiated in Keppel Bay in the southern Great Barrier Reef (GBR). No-anchoring areas (NAAs) were selected based on evidence of severe anchor damage relative to other sites. The four locations selected are areas of high visitation, where interpretive signage and the management effort to support reef resilience create the additional benefit of enhancing community outreach. Surveys following the establishment of NAAs indicate reduced anchor damage inside all four no-anchoring areas, from ~80 cases per 1000 m^2 in 2008, to <10 cases per 1000 m^2 in 2012. Anchor damage also declined between 2010 and 2012 at three of the four control reefs adjacent to the no-anchoring areas. This case study is unique and foundational in that this is the first time that supporting reef resilience was explicitly used as the motivation for local-scale management in the GBR. Follow-up engagement with community and stakeholder groups demonstrates that the process has also led to an increase in reef awareness and stewardship. In combination the management action and community stewardship offer an efficient flexible strategy to support reef health and enhance recovery following disturbances.

6.2 Introduction

Since its establishment in 1975, the Great Barrier Reef Marine Park Authority (GBRMPA) has implemented several strategic initiatives to support the resilience of ecosystems within the GBR Marine Park (GBRMP). For example, the Great Barrier Reef Marine Park Zoning Plan 2003 protects representative biodiversity and there are ongoing efforts to improve water quality under the joint Queensland and Australian Governments' Reef Water Quality Protection Plan (Reef Plan 2013). In some areas of the GBRMP, regional Plans of Management and Special Management Areas (SMAs) complement ecosystem-wide initiatives. Plans of Management and SMAs govern activities in areas of highly concentrated use and visitation like Cairns and the Whitsunday Islands. Local-scale actions, such as permit conditions and spawning closures are also being implemented to reduce known stresses caused by specific human activities. However, as yet, there are few examples where follow-up surveys have evaluated the effectiveness of a local-scale management action.

Reefs in the Keppel Islands are good candidates for evaluating a localised management action. The Keppel Islands are a group of 16 continental islands 15 km off the coast of Yeppoon in the southern GBR. The fringing coral reefs surrounding these islands have moderate to low diversity of fish and coral communities (Thompson et al. 2011), high average coral cover (Figure 6.1a, Authority 2009), and consist of corals with growth rates higher than seen elsewhere in the GBR (Diaz-Pulido et al. 2009). Since 2000, however, the Keppel Bay region has experienced a 140% growth in tourism coupled with a 33% increase in recreational boat use (Authority, GBRMP 2008a, b).

This expansion of human activities and potential impacts has coincided with a number of environmental disturbances. Corals were stressed due to severe bleaching that followed anomalously warm sea surface temperatures in 1998, 2002 (Elvidge et al. 2004) and 2006, resulting in localised mortality (Johnson, Marshall & Authority 2007). Most reefs demonstrated strong recovery after these bleaching events, but since 2008, reefs have been repeatedly exposed to major flood plumes. The nearby Fitzroy River flooded in 2008, 2010 and 2011, and low salinity flood plumes caused many corals to bleach and some to die. Corals were also stressed during this time by high turbidity associated with the flood plumes caused by the extreme rainfall events (Thompson et al. 2011). The highly visible coral bleaching event in 2006 coupled with the desire of the local community to take action to support reef recovery made the area an ideal location to trial a resilience-based management action. The subsequent cumulative effects of the flood plumes on the Keppel Bay reefs highlighted the importance of ongoing monitoring and provided valuable insights into the use of resilience as a guiding principle for adaptive management to support reef recovery.

Higher incidence of anchor damage generally occurs in areas popular with boaters (Dinsdale & Harriott 2004). Anchor damage was observed at a third of sites surveyed in Keppel Bay in 2007 shortly after the 2006 major coral bleaching event (e.g., Figure 6.1b; Authority, GBRMP 2008a). Boaters in the area usually use Danforth, reef-pick or mushroom style anchors, and the boats are mostly 6-12 m powerboats and 8-15 m sailboats. The Danforth and reef-picks hold fast but often pull coral and other invertebrates off of the substrate when pulled out of the water. Mushroom anchors are less common but even more damaging as these bounce up and down on the reef as the boat above moves with the surface water motion. Physical damage to corals caused by anchors can be identical to that caused by severe storms like cyclones, albeit on a far smaller scale. Physical damage to corals can increase susceptibility to disease and bleaching and can lengthen recovery timeframes following disturbances (Haapkylä et al. 2013; Hawkins et al. 1999; Lamb et al. 2014; Lamb & Willis 2011). Expected ongoing increases in recreational use suggest anchoring will continue to add stress to the already vulnerable fringing reefs in Keppel Bay.

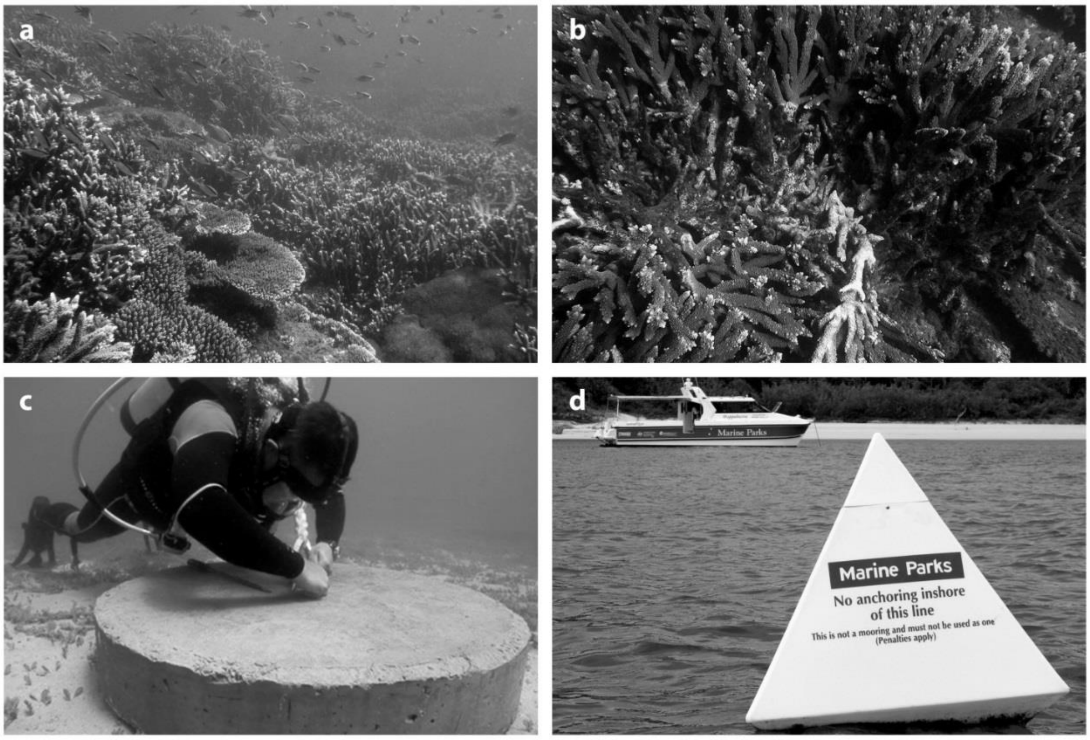


Figure 6.1. Photo panel of reefs, anchor damage and moorings in Keppel Bay. (a) The diverse high coral cover reefs characteristic of the Keppel Bay (from Sloping Island), (b) damage to a branching *Acropora* colony caused by anchoring at Humpy Island, (c) the installation of the no-anchoring area markers underwater at Humpy Island, (d) and the buoys used to mark the boundaries of the no-anchoring areas at Big Peninsula.

The GBRMPA has been examining strategies to enhance the resilience of vulnerable coral reef ecosystems. In 2008, a working group that included local managers, community members, and Natural Resource Management bodies decided that No

Anchoring Areas (NAAs) would be trialled in the Keppel Bay area (Figure 6.1c, d). The NAAs deter boaters from anchoring, reducing physical stress on corals in the area and supporting the capacity of corals to recover from other disturbances (Day 2002).

In this chapter, my objective was to use the RHIS protocol (Chapter 4) to evaluate whether a local-scale management action, specifically the establishment of NAAs, could reduce anchor damage at highly visited sites in the Keppel Bay area. Supporting reef resilience was the explicit motivation for the action (a first in the GBR) and was communicated as such to stakeholders and participating community members. This study analyses the effectiveness of the NAAs against the 2008 baseline assessment using RHIS data collected at the NAA and control reefs of Keppel Bay since 2009. This chapter also includes a discussion of the increasing importance of using local-scale actions to support reef resilience as disturbance frequencies increase under climate change (reviewed in (Anthony et al. 2014). The study findings also support the case that the participation of community members and stakeholders increased support for the NAAs once implemented and has increased reef stewardship in the Keppel Bay area.

6.3 Materials and Methods

6.3.1 Site selection

The process used to select sites for the NAAs was unique and participatory. Sites were selected late in 2008 following an assessment of the relative resilience of reef sites in the Keppel Bay area (Maynard et al. 2010). A 'Resilience Assessment and Capacity Building' workshop was convened that included managers, scientists, local community members and stakeholders (Maynard et al. 2010). Attendees participated in assessing the resilience of reefs at 31 sites and reviewed the results to select suitable sites to trial NAAs. Four sites met the criteria, i.e. they had: (i) low to medium resilience relative to other sites, (ii) high levels of anchor damage, (iii) high usage and good visibility to the public, and (iv) high accessibility for managers and rangers to install and patrol the NAAs (Figure 6.1c, d). The selected sites are at Humpy and Barren Islands, and Big Peninsula and Monkey Beach on Great Keppel Island (Figure 6.2). The four sites cover areas ranging from 2.4 to 15.4 hectares, which are delineated by Reef Protection Marker (RPM) buoys displaying the NAA signage (Figure 6.1d).

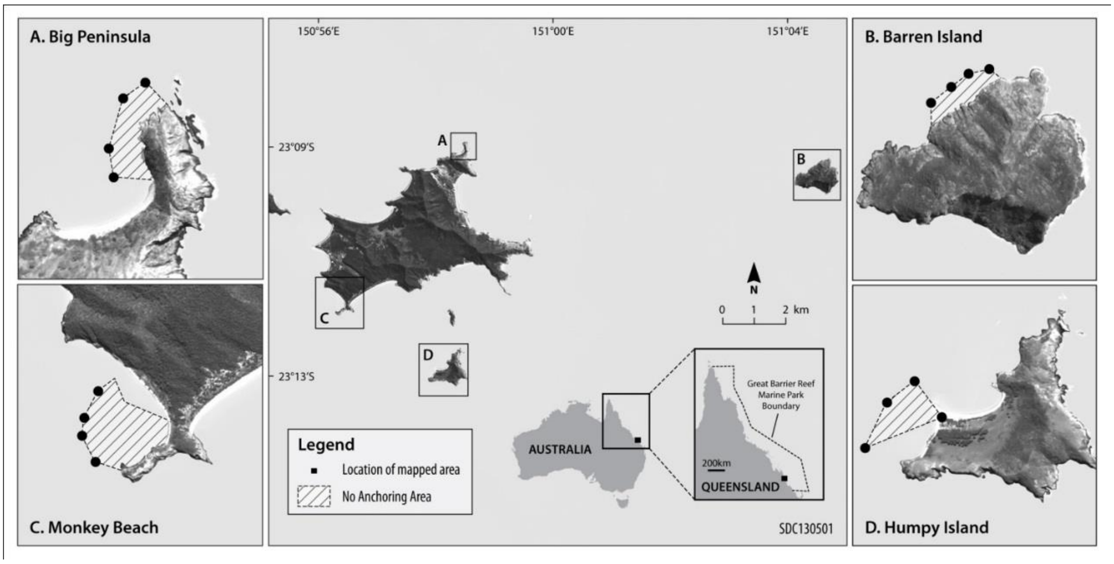


Figure 6.2. Map showing no-anchoring area locations established within the Keppel Bay of the southern Great Barrier Reef. No-anchoring areas are located (a) near the northern tip of Great Keppel Island at Big Peninsula, (b) near a campground at Humpy Island, (c) at a popular sailing stop on the south-western shore of Great Keppel Island at Monkey Beach, and (d) on the northern shore of Barren Island.

6.3.2 Survey Methods

Belt transect surveys of habitat within the proposed NAAs were undertaken in 2008 to establish baseline condition prior to installation of the NAA markers in 2009. Follow-up surveys were conducted for the NAAs and control sites on adjacent reef habitats (control sites) in 2010, 2011 and 2012. In 2008, a fixed area was set of 100 m x 10 m and observers assessed benthic condition and counted every occurrence of anchor damage within the 1000 m^2 survey area. During subsequent survey years, observers used the GBRMPA's new Reef Health and Impact Survey (RHIS) protocol (Chapter 4). The RHIS data was scaled to anchor damage instances per 1000m^2 to enable comparison with baseline observations. I led the observation team every year; and trained new team members to the program standard in partnership with co-authors using the RHIS training program (see Chapter 4). All team members could readily identify cases of anchor damage. The RHIS protocol enables observers to capture replicate assessments of reef condition (including impacts such as anchor damage) at multiple locations within each site. Control sites were also surveyed from 2010–2012 at locations adjacent to the NAAs at Humpy and Barren Islands and near Monkey Beach and Big Peninsula (control sites at Miall and Sloping Islands).

The RHIS protocol requires observers to search for a consistent reef habitat to survey, which in this study was sloping reef areas from 4-12 m. Observers then complete multiple randomised 5m radius circle plot surveys using the RHIS protocol detailed in Chapter 4. The observers survey the area enclosed by the perimeter, recording their estimates of benthic cover and signs of impacts, including cases of anchor damage. For all surveys and all survey years, observers recorded evidence of anchor damage rather than the number of damaged colonies. This is because of the difficulty of distinguishing colonies, as many of these reefs are dominated by monospecific stands of branching *Acropora* that are not clearly delineated into separate colonies. A ‘case’ of anchor damage is a discrete observation of damage, such as a hole in the reef surrounded by broken branches, or an area of broken branches (Figure 6.1b). A minimum of three RHIS were undertaken inside and outside each of the NAAs during the 2010–2012 surveys.

Trends in mean anchor damage through time were compared graphically (1) between all NAA sites combined versus all control sites combined, for each of the four survey years, (2) among sites and among years within a site for NAAs, and (3) among sites and among years within a site for control sites. For the first comparison, counts of the number of anchor damage cases from the 2008 and subsequent RHIS were averaged for those completed inside the NAAs (n_{2008}=4 surveys, n_{2010}=21 surveys, n_{2011}=40 surveys, n_{2012}=24 surveys) and for those at adjacent control sites (n_{2010}=26, n_{2011}=22, n_{2012}=29). For the second and third comparisons, counts of anchor damage were averaged at the site level across the four years for surveys completed inside NAAs and at control sites, respectively. For all comparisons, anchor damage counts from RHIS were converted to density values (counts per 1000 m^2) for comparison with the data collected in 2008 (circle survey area is 78.5 m^2, therefore damage counts were multiplied by 12.74 to give areas of 1000m^2). The switch to the RHIS protocol was made in 2010 because that year RHIS became the standard protocol used by managers and scientists participating in the GBRMPA’s Eye on the Reef monitoring program. In 2010, the RHIS protocol and the 100 x 10 m belt transect approach used in 2008 were compared. During swims on the first survey day, anchor damage counts from the two approaches were within 10% when converted to a density per 1000 m^2, as described above. The two approaches to assessing the severity of anchor damage were found to be comparable, partially because the NAAs are very small (less than 0.25 km^2 in all cases) and because no location within the NAAs is a better anchorage than any other. Anchoring is random and well represented using both survey approaches.

6.4 Results and Discussion

Anchor damage declined following installation of the four NAAs in Keppel Bay. The average number of anchor damage cases per 1000 m^2 across all NAAs exceeded 80 in 2008, prior to installation of the marker buoys. By 2010, average anchor damage counts within NAAs declined to less than 25% of levels observed in 2008 (~20 per 1000 m^2, Figure 6.3a), and <10 cases were observed at NAA sites in 2012 (Figure 6.3a). When each of the four NAAs were compared with their respective control sites, average anchor damage within NAAs by 2012 was less than 10% of levels observed in 2008 (Figure 6.3b). By location, mean (±SE) anchor damage declined by up to 21-fold between 2008 and 2012, from 32 to 2.56 (± 2.56) cases at Barren Island, 64 to 0 cases at Humpy Island (but see below), 167 to 8.01 (± 8.01) cases at Big Peninsula, and 51 to 16.03 (± 14.28) cases at Monkey Beach (Figure 6.3b). Most of the decline in anchor damage cases at NAA sites occurred between 2008 and 2010. Overlapping error bars for levels of anchor damage observed between 2010 and 2012 indicate that the mean number of cases in these years are not significantly different. Average anchor damage counts also declined at most control sites adjacent to NAAs from 2010–2012 (but not at Big Peninsula). The up to 15-fold declines in anchor damage cases at control sites from 2010 to 2012 included declines from 83.33 (± 48.40) to 23.81 (± 10.99) at Barren Island, 31.34 (± 21.16) to 2.14 (± 2.14) at Humpy Island, and from 51.28 (± 45.02) to 4.81 (± 3.37) at Monkey Beach (Figure 6.3c). No decline was observed at the control site for the Big Peninsula NAA (from 19.23 (± 13.14) to 17.63 (± 9.36)). However, of the four control sites, this site is furthest from the no-anchoring markers of the NAA, thus the no-anchoring markers are least likely to deter boaters from anchoring at this location. The data indicate the NAAs are effective in reducing damage to corals. Interestingly, control site data and anecdotal reports from the local marine advisory committee suggest that the consultation process has increased public stewardship of Keppel Bay reefs, and may be the cause of the observed reduction in anchor damage in some adjacent control areas.

Coral cover declined between 2010 and 2012 at all sites, but still exceeded 25% in 2012 at all sites except Humpy Island, where cover declined from 80 to 0% (Thompson et al. 2011). While the decline in the average number of anchor damage cases at Humpy Island between 2008 and 2010 can be attributed to the establishment of the NAA, it is unclear whether compliance with the NAA continued in subsequent years due to the loss of nearly all corals at this site. Evidence from the other NAA sites suggests, however, that if there were still corals at Humpy Island, they would probably have been damaged by anchors far less frequently from 2011-2012 than prior to the NAA being established in early 2009.

Anchor damage is likely to remain low at the four sites where NAAs were installed, as well as at adjacent control sites, providing the markers (see Figure 6.1d) are well-maintained and that local communities continue to comply with their intent. Although small in scale, the benefit of NAAs is that they actively address a locally significant damaging process that can undermine reef recovery post-disturbance. A study of ecological recovery after the 2006 bleaching event in the Keppel Bay showed that coral recovery was strong after 2006 due primarily to four factors: the rapid regeneration of remnant coral tissue, very high competitive ability of corals in the Keppel Bay area that allows them to out-compete macroalgae, a natural seasonal decline in the dominant species of macroalgae, and an effective marine protected area (Diaz-Pulido et al. 2009). Coral colonies not damaged by anchors are certainly more likely to be resilient than corals that are severely damaged. In an era of increasing disturbance frequency and cumulative impacts targeted local-scale actions offer an important, feasible strategy for managers to address the challenge with ‘cumulative actions’ that limit controllable pressures to enhance natural recovery.

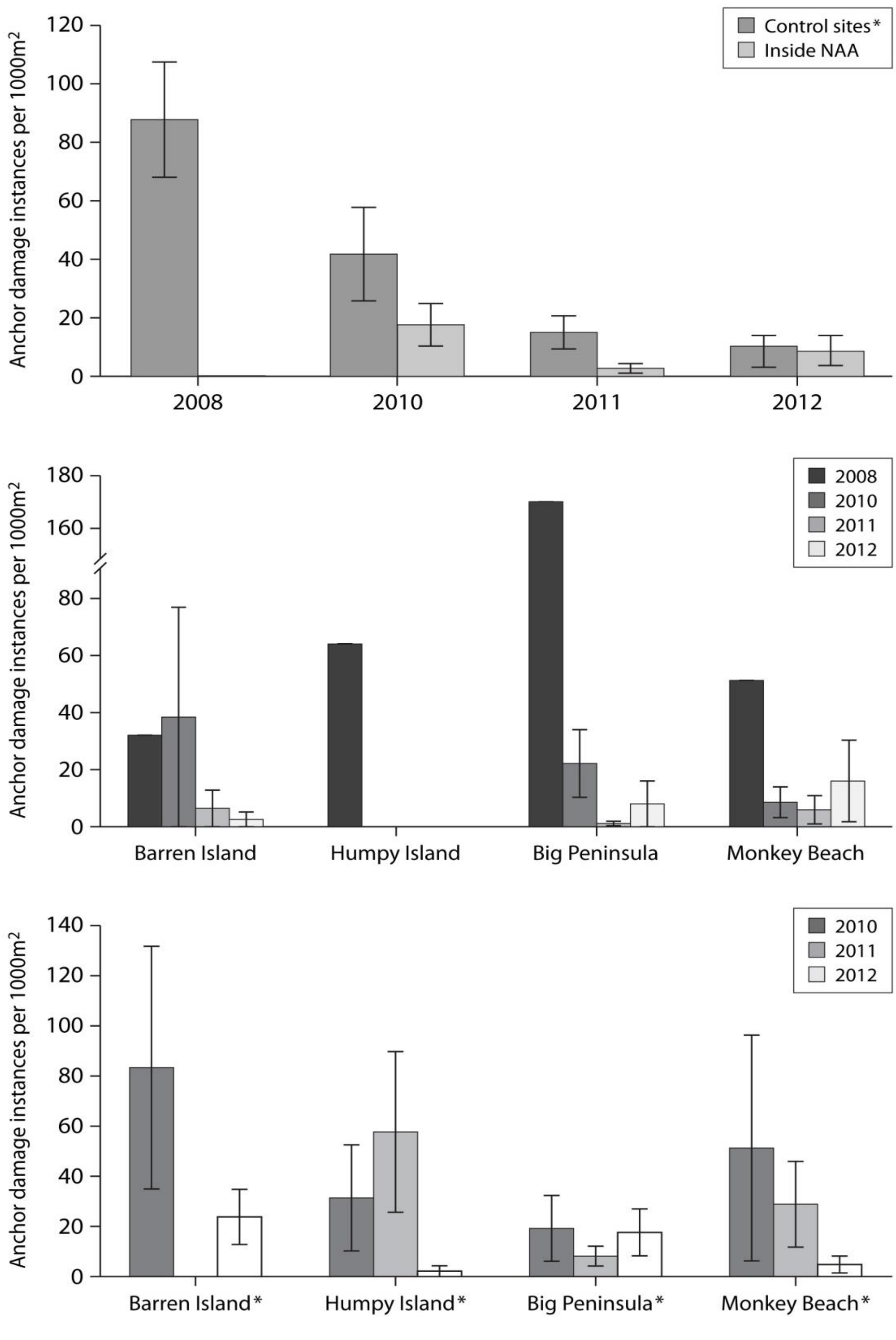


Figure 6.3. Number of anchor damage cases within and near No Anchoring Areas (NAAs) in Keppel Bay, 2008-2012. (a) Temporal trends based on pooled data for all NAA versus control sites per survey year, where sites in 2008 were pre-NAA marker installation. Comparisons of anchor damage among years at each of the four reefs for (b) NAAs, and (c) control sites. Error bars are SE. In (b), SEs are not shown for 2008, as the means are based on a single survey at each site.

Coral reefs in Keppel Bay have been impacted by flooding every year during recent years and, as a result, are now considered to be in a ‘poor’ state (Thompson et al. 2011). Some reef sites monitored by the Australian Institute of Marine Science (AIMS) marine monitoring program (MMP), like Humpy Island, were so severely impacted by the 2011 flood event that they have shown no signs of recovery (Thompson et al. 2011). For these reefs, recovery may depend upon larval supply from adjacent reefs (Hughes et al. 2000). However, AIMS MMP monitoring data may indicate another reason for this poor recovery; settlement of larvae on the reef has been limited in recent years, even when fecundity of adult corals is high (Thompson et al. 2011; Thompson & Dolman 2010). Monitoring of natural reef substrata suggests that high larval settlement onto tiles is not translating into abundant juvenile corals on the reef. Larvae are either avoiding settling onto available natural substrata or are not surviving, even though they are clearly present and viable on settlement tiles (Thompson et al. 2011). It is likely that the recovery of coral reefs in Keppel Bay is dependent on a dual mechanism of larval recruitment and growth of surviving fragments, making protecting live coral critical. Efforts to continue to improve water quality are critical, as many studies suggest larval survivorship can be adversely affected by poor water quality (Fabricius 2005; Humphrey et al. 2008).

A number of benefits have emerged from community engagement in the local-scale management action of establishing NAAs in Keppel Bay. The initial workshop meetings and follow-up meetings with the Local Marine Advisory Committee are part of an ongoing two-way exchange between managers and stakeholders about this project. Frequent opportunities have been created in recent years to discuss the demonstrated effectiveness of the NAAs and the need for local-scale actions to support reef resilience with community members. The local community has embraced the project, is clearly complying with the intent of the NAAs, and has been communicating outcomes from the project to others visiting Keppel Bay. The process of establishing the NAAs, their demonstrated effectiveness, the signage describing their intent and the ongoing engagement process have increased reef awareness and stewardship. Anchor damage is declining dramatically at areas within and near the NAAs, demonstrating marker buoys are positively changing boating behaviour.

Another benefit of the ongoing engagement with community members is the implementation of the Marine Aquarium Industry's Stewardship Action Plan (Pro-vision Reef 2013) following the 2011 floods (Figure 6.4a). Data collected while surveying for anchor damage were used to develop the boundaries for a voluntary moratorium on aquarium collection (figure 6.4b and 6.4c). The collectors themselves aim to limit the impact of their industry on reefs in the Keppel Bay area by not collecting when reefs are recovering from stress events, including flood-induced coral bleaching. The establishment of a voluntary action by fishers that remained in place for more than 12 months was an unexpected positive consequence of the ongoing dialogue between managers and stakeholders. The industry stewardship plan laid out the strategy and criteria under which Pro-vision Reef members would change their working practices to support reef recovery. The delivery of dynamic health information across Keppel Bay (in the form of RHIS data from the NAA and control sites) provided Pro-vision Reef with a trusted source of data upon which they established the moratorium's spatial and temporal boundaries. In combination with the NAA's, which serve as a 'stick' that prompts reefs users to take care when anchoring, the broader suite of variables collected using RHIS served as a 'carrot', triggering industry staff to turn their plan into an action that supports the recovery of the resources which support their business.

This project used relatively simple technology to target anchoring, a locally significant impact, to reduce damage to corals at high visitation sites in Keppel Bay. The success of no-anchoring areas is demonstrated by the fact that there is now virtually no anchor damage to corals in these areas, and by the level of community participation in the process and their support for the initiative. The no-anchoring areas are effective in reducing anchor damage on coral communities and can positively influence their resilience to other disturbances, albeit at a small scale. Targeting direct management action (in this case NAAs) to areas of known resilience potential (Maynard et al. 2010) offers a realistic opportunity to inform conservation strategies (Game et al. 2008) to enhance outcome. At a larger scale, the voluntary moratorium response of the aquarium collection industry to the reef health information collected before and after a major flood impact serves as an important example of how a dynamic understanding of reef health can rapidly prompt indirect yet significant actions (e.g. community stewardship) to support ecosystem recovery. Co-management guided voluntary actions by reef stakeholders may prove to be a cost-effective way of supporting reef resilience, following increasingly frequent impacts, which enjoy an unprecedented level of community support. In summary this project provides a case study of resilience-based participatory local management that can be applied elsewhere in the GBR and in other reef ecosystems.

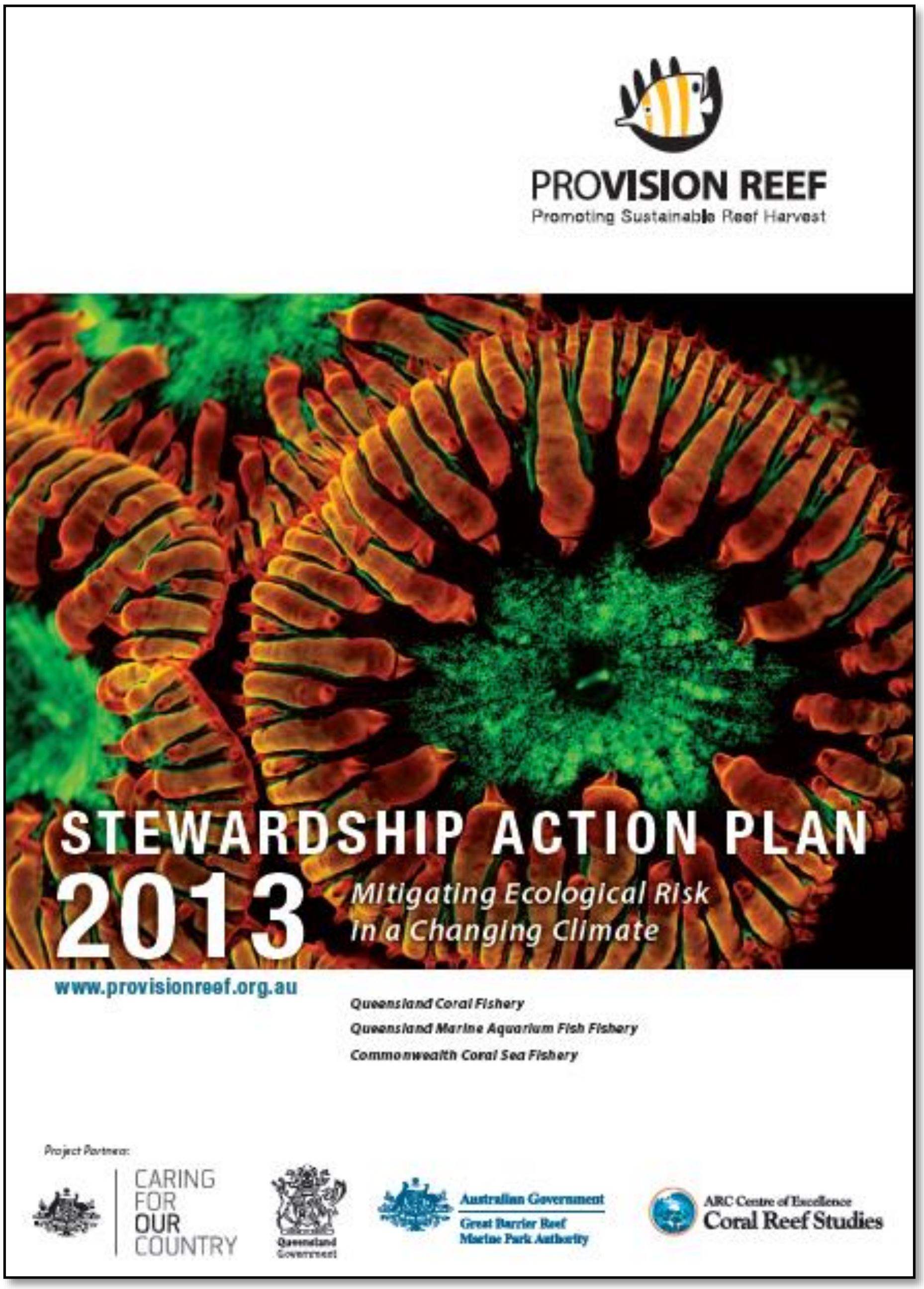


Figure 6.4a. Pro-vision Reef Stewardship Action Plan 2013. The voluntary moratorium implemented following the 2011 flood impacts on reefs in Keppel Bay was established based on the strategies and objectives in the 2009 Stewardship Action Plan. The 2009 plan has since been further refined into the current 2013 plan illustrated here.

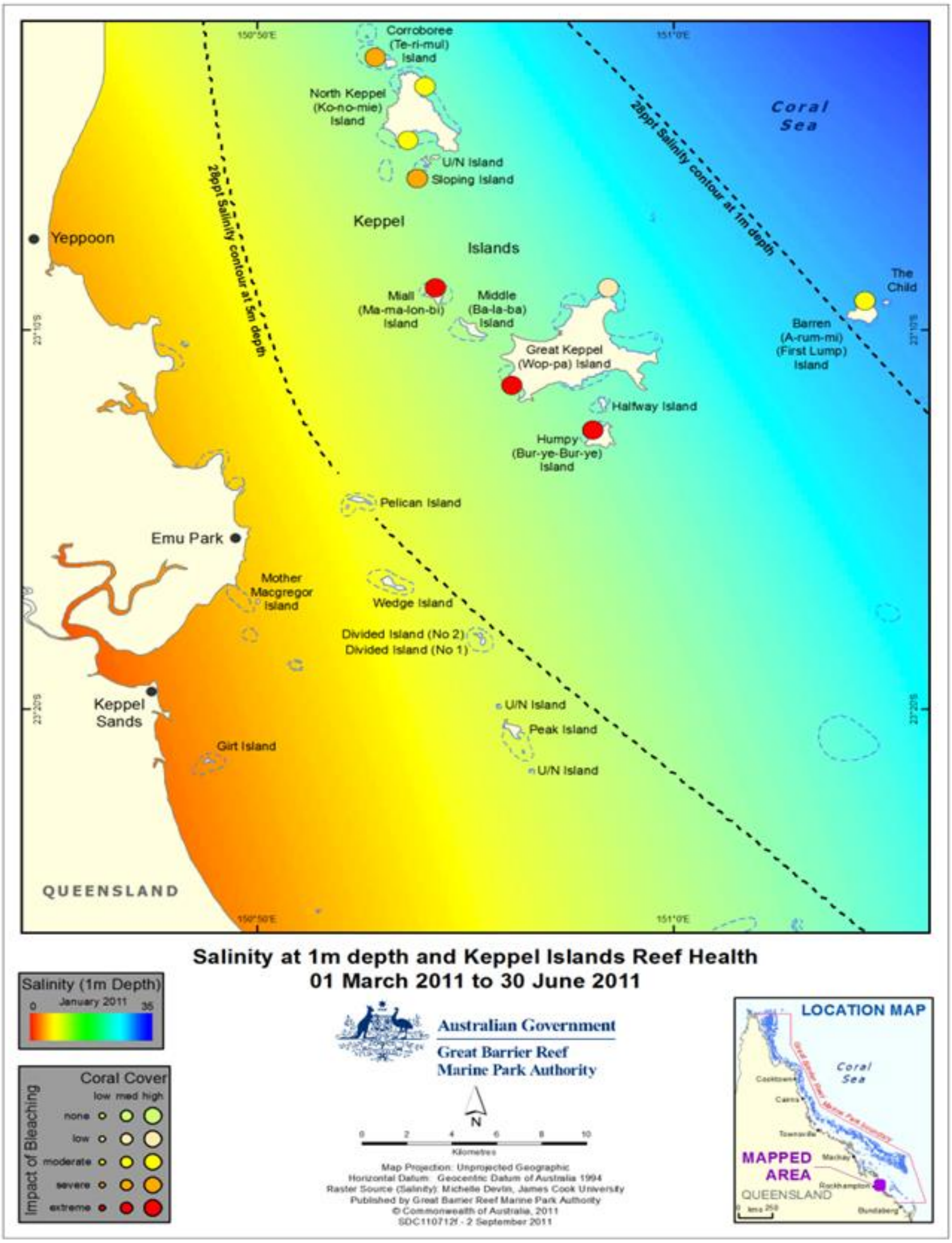


Figure 6.4b. Patterns of salinity exposure (colour-coded areas) and RHIS assessments (colour-coded circles) at reefs in Keppel Bay exposed to varying levels of salinity following the SE Queensland floods in 2011. The dotted lines represent depth contour salinity gradients that are likely to result in coral mortality. RHIS data were collected in the months following the flood plume. Dot sizes indicate the average coral cover recorded at each site. The colour of each dot denotes the degree of impact.

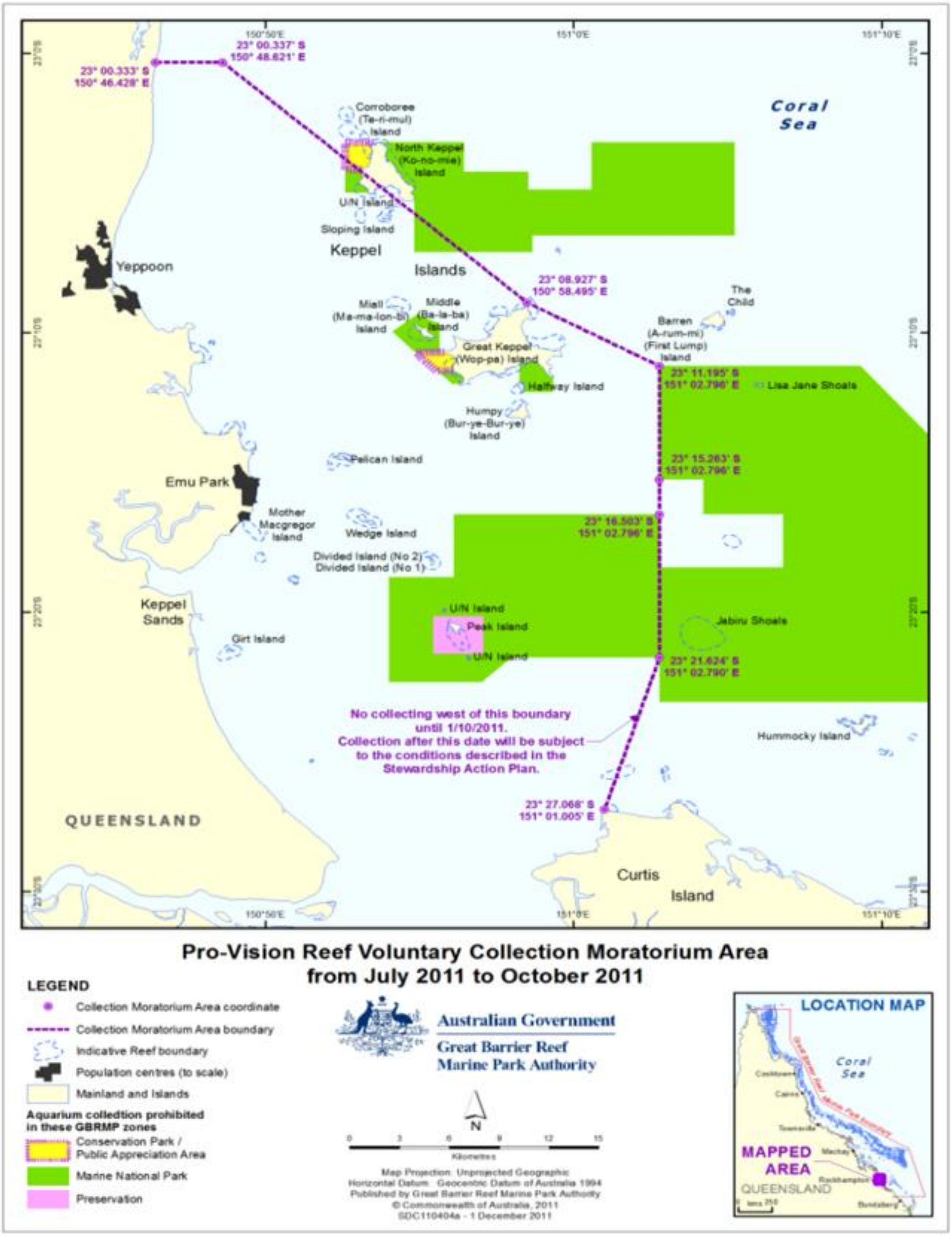


Figure 6.4c. Pro-vision Reef Voluntary Collection Moratorium Area in Keppel Bay. The dotted line on the map illustrates the area within which no aquarium industry collection occurred following the 2011 flood impacts. The lines were agreed upon by GBRMPA and the coral collecting industry based on RHIS data. The initial moratorium period was extended several times and lasted until late 2012.

CHAPTER 7

Summary and conclusions

7.1 Content summary

With well documented declines in coral reef health already apparent around the world, conventional approaches such as marine spatial planning are struggling to maintain ecosystem values, goods and services. Resilience-based management represents the most credible and practical strategy to adapt current management practices to address the challenges of the future. Resilience focused adaptive management actions that support coral reef resistance and recovery will buy time while the global community works out how it will address the ultimate cause of decline, the cumulative and interactive effects of anthropogenic impacts, (including increasing greenhouse gas emissions) that threaten humanity perhaps to an even greater degree than coral reefs. To be effective, adaptive management requires regular evaluation of actions and the human and environmental drivers of ecosystem condition. Such evaluations necessitate gathering information dynamically on drivers and conditions, especially given disturbance frequencies and magnitudes will increase as the climate changes. The provision of dynamic information on reef condition is therefore vital to inform resilience-based management decisions, particularly in vast marine systems like the Great Barrier Reef (GBR). During my candidature I developed and produced the following tools to manage and enhance the resilience of coral reefs, all of which are currently in use at the Great Barrier Reef Marine Park Authority (GBRMPA):

(1) An underwater field guide that is building capacity among rangers, tourism operators and community volunteers to distinguish among coral diseases and other reef health impacts in the Indo-Pacific based on visible signs (Chapter 2).
(2) A strategic framework for responding to coral disease outbreaks that includes thresholds that trigger various adaptive management actions, and describes unique communication challenges that outbreaks pose for managers (Chapter 3).

(3) An integration of participatory coral reef monitoring programs in the Great Barrier Reef Marine Park (GBRMP) to include a new Reef Health and Impact Survey protocol, online training package and a web-enabled data management system that provides dynamic information to managers via automated reporting (Chapter 4).
(4) A spatially comprehensive impact assessment following severe TC Yasi, which informed management responses by classifying damage using a custom matrix inclusive of both impact extent and severity (Chapter 5).
(5) A multi-year evaluation of the effectiveness of a resilience-based management action used in the Keppel Bay to mitigate anchor damage, that also built stewardship among local community members and industry through outreach and consultation (Chapter 6).

Chapter 2 starts to build the case made throughout the thesis that dynamic information on reef health can only become available to managers at the scale of the Great Barrier Reef (GBR) if capacity is built among regular reef visitors to assess and monitor reef condition and impacts. A key issue is that many impacts on coral reef health are cryptic, ephemeral and readily confused with other impacts. Chapter 2 describes the process by which a field guide was produced that enables observers to recognise characteristic signs of compromised coral health on Indo-Pacific Reefs. A decision tree was developed to aid the differential diagnosis of diseases and other reef health impacts using the visible characteristic signs of each impact. The guide, entitled Underwater Cards for Assessing Health on Indo-Pacific Reefs, was published in 2008 by the Global Environment Facility's Coral Reef Targeted Research program. The original print run of the guides rapidly sold out and is now in use throughout the Indo-Pacific and Australia.

The development, distribution and current use of the field guide has fulfilled the first objective identified for this thesis; "*Create a guide that builds capacity to identify coral disease and assess reef health impacts.*" A second version of the field guide is currently being prepared that will have: new and more images, descriptions of types and severity levels of mechanical damage, a new field survey method, and graphics produced while completing the work presented in Chapter 3. The process by which the guide was developed was extremely collaborative and inclusive of managers, scientists and community members. Leading and learning from this process early on in my candidature set the stage for the direction and manner in which the rest of my thesis work was undertaken.

In the year that followed the production of the guide, the *Underwater Cards* were used in the GBR to help managers, rangers and tourism staff distinguish among diseases and reef health impacts. Since 2009, this enhanced capacity among non-specialist observers has provided an early warning system for disease outbreaks. The value of this kind of early warning system is described in the strategic framework for responding to disease presented in Chapter 3. The strategic framework enables managers to use remote sensing and field observations to produce a near real-time estimate of outbreak likelihood and impact severity if an outbreak does occur. Descriptions of all of the following are included in the framework: 1) routine tasks required to estimate outbreak likelihood and risk, 2) conditional responsive actions that could be implemented to assess the severity and extent of impacts, 3) actions that could be taken to minimise coral mortality, and 4) the unique communication challenges for reef managers posed by disease and disease outbreaks. Development of the framework led to the establishment of outbreak thresholds for key coral diseases found in the Great Barrier Reef region that are likely to result in significant mortality. Automated coral disease outbreak alerts are now created within the GBRMPA based upon the outbreak thresholds that were developed while writing the response framework.

The development and implementation of the framework has helped to shift views of managers working at GBRMPA to appreciate the increasing need for a more holistic evaluation of coral reef health. The prime example of this is that the response framework provides the theoretical underpinning of the annually updated GBRMPA Coral Disease Risk and Impact Assessment Plan, which is a core component of the Authority's operational Reef Health Incident Response System. The strategic disease response plan and adaptive management framework was published in *Environmental Management* in 2009. The theoretical work in this area, published paper and the resultant operational Impact Assessment Plans at GBRMPA all demonstrate that the second thesis objective has been met: "*Develop a response framework for managers for coral disease that links information on status to management actions*."

After developing the Disease Risk and Impact Assessment Plan (Chapter 3), colleagues and senior managers within the GBRMPA agreed with the case that I made that participatory monitoring can significantly enhance our capacity to adaptively manage the GBR. The basis for making the case was that in 2009 managers only had access to really detailed information on reef condition and impacts from the 48 sites surveyed once every two years by the AIMS Long Term Monitoring Program. Chapter 4 opens by stating that only a large network of observers can dynamically provide information with sufficient spatial and temporal coverage to enable managers to respond to impacts, support recovery and plan strategically. By 2009, participatory monitoring had been taking place in the GBR in various forms for ~10 years. Between the late 1990's and 2009, rangers completed surveys occasionally, the public could report sightings of various fauna, and tourism operators participated in the early version of the Eye on the Reef program and reported observations of bleaching via BleachWatch. A key shortcoming of having all of those programs was that training materials and approaches varied among the programs, as did datasheets. Furthermore, web-enabled data entry capability and central data storage had not been developed, and there were no automated reporting systems in place to ensure that participants received reports and managers could access well presented data summaries. All of those issues have been resolved during the last five years of my candidature under my direction and Chapter 4 describes this part of my research.

The key first step in this journey was to iteratively develop the 'Reef Health and Impact Survey' (RHIS) protocol. Hundreds of rangers, managers, researchers, tourism operators and community volunteers now use the method, largely because it was developed collaboratively to ensure people could be efficiently trained to undertake the method effectively within their time constraints. An online and field-based training program and materials, coupled with a web-enabled database that has a user-friendly interface have been successful in recording management relevant information on the health of more than 625 reefs. The database can automatically produce a range of Google Earth™ based interactive summaries of reef condition and impacts and participation in monitoring. The resulting 'integrated Eye on the Reef' (iEotR) program was named in reference to its historical foundation and public face 'Eye on the Reef'. The program integrates the new RHIS method, training, data entry/storage, and automated reporting. The great advance for management of the GBR is that we now have a hierarchical monitoring scheme whereby: fauna sightings data can be provided for 1000's of locations, condition and impacts are assessed at 100's of locations annually (RHIS and tourism Eye on the Reef), and detailed information on trends in condition and impacts is provided for 10's of locations by the specialist observers of the AIMS LTMP.

In the last couple of years, the integrated Eye on the Reef program has become the primary mechanism by which the GBRMPA gathers up-to-date information on coral reef health and impacts in the Marine Park. Managers at the GBRMPA have never before had access to even 10% of the information on reef condition and impacts that is now available to us through the integrated Eye on the Reef network. This is very exciting because the scene is now set to use the information to guide resilience-based management decision-making within the GBRMP. The objective for Chapter 4 was probably the most ambitious of all of those set in the early part of my candidature and this objective has been fully met: "*Iteratively develop and refine a monitoring protocol that enables rapid assessments of reef health by a range of observers complemented by a data storage and reporting system that meets management information needs.*"

Opportunities arose to use the RHIS protocol following a severe tropical cyclone (Chapter 5) and to evaluate the effectiveness of a management action (Chapter 6) in the years that followed establishing the integrated Eye on the Reef network (Chapter 4). Chapter 5 tells the story of tropical cyclone Yasi, which was unique when it crossed the Park on February 3rd of 2011, in being both very severe and large in circulation size. The observer network established in the preceding years had already been trained to undertake RHIS so the GBRMPA was positioned to implement the largest-scale impact assessment conducted to date in the Marine Park. Analysis of data from 882 RHIS at 76 reef locations revealed cross-shelf variation in the severity of mechanical damage caused by the storm, as well as patterns in impact severity with respect to direction (north and south) and distance from the cyclone eye. The results of the analyses and the body of work overall has helped the scientific and management community better understand spatial damage patterns following really severe cyclones. A key conclusion from this work is that more coral was lost in the 24-hour period in which TC Yasi crossed the Park than in any other 24-hour period in at least the last 30 years.

Being able to conduct so many surveys so quickly ensured the GBRMPA was the authoritative source of information on the patterns in cyclone impacts and their implications for the Great Barrier Reef. Being this source of information for politicians, reef stakeholders and the public is a key goal of the Reef Health Incident Response System developed while I was finishing the framework for responding to coral disease described in Chapter 3. Aside from using RHIS and the integrated Eye on the Reef network to understand the impact patterns and communicate such knowledge, follow up surveys in 2012 and 2013 have helped us understand impact legacy and recovery. Results from the recovery surveys include that: some sites suffered to a greater extent from cyanobacteria and macroalgae blooms after the storm, disease prevalence was greater at sites that were impacted severely but still had corals to be affected by disease (J. Lamb pers. comm.), and fast-growing corals have recruited and are growing at most severely affected sites. Reef health assessments that include coral diseases offer important insights into the legacy of individual impacts like TC Yasi and may serve as a measure of both cumulative impacts and their resilience status (McClanahan et al. 2012). Results from the impact assessment I developed and led following TC Yasi are in review at *PLoS ONE* and were shared in 2011 in a GBRMPA technical report. Further, a Tropical Cyclone Risk and Impact Assessment Plan (TCRIAP) was developed under my direction in 2013. In the final months of my candidature, I led the implementation of the TCRIAP after TC Ita crossed the northern GBR on April 11th 2014. The impact assessment following TC Yasi and resultant manuscript, report and Risk and Impact Assessment Plan demonstrate that the objective set for Chapter 5 has been met: *Demonstrate the capacity of non-specialist observers to quantify impacts following a major disturbance.*

Understanding spatial patterns in the severity of impacts following TC Yasi helped the GBRMPA communicate information about the event, as I describe above, and helped to target local-scale actions to support recovery. After actions are implemented, the integrated Eye on the Reef network can help managers to evaluate the effectiveness of the actions, through the analysis of data arising from completing RHIS. Chapter 6 reviews a recent example from the southern Great Barrier Reef in which RHIS were used to assess the effectiveness of no-anchoring areas (NAAs). Some of my colleagues installed marker buoys in 2008 to demarcate NAAs at four locations in Keppel Bay (offshore of Yeppoon, Queensland) after they had undertaken an analysis of the relative resilience of reef sites in the area. The NAAs were established at sites with high relative resilience where anchor damage was found to be severe relative to other sites in the area and where signage could be used to ensure the NAAs also served as an education and outreach mechanism. I led teams of managers from GBRMPA and rangers from Queensland Parks and Wildlife to complete RHIS within the NAAs and at control sites from 2010-2012. Declines in anchor damage, expressed as damage instances per 100 m^2, were immediately apparent in 2010 and virtually no anchor damage was seen within the NAAs by 2012. It was surprising to see that anchor damage also declined at nearby control sites so the marker buoys and signage are clearly changing boating behaviour positively in the areas near NAAs as well as within NAAs.

Importantly, managers from the GBRMPA (me and my colleagues) consistently engaged with the communities of Keppel Bay and Yeppoon prior to the NAAs being installed and in the months and years that followed. There is evidence that the frequency and consistency of these exchanges with community members has built reef stewardship in that area. As a prime example, the aquarium fishing industry established a voluntary moratorium on fishing during and following the low salinity induced coral bleaching event caused by the major Fitzroy river flood in 2011. The account of my work in Keppel Bay presented in Chapter 6 clearly fulfils the Chapter objective: *Use the protocol developed and the participatory monitoring network to test the effectiveness of a management action,* but also serves as a practical case study example of how the effectiveness of a management action can be evaluated by having non-specialist observers undertake RHIS. The exciting part of having shown this in Keppel Bay is the resulting precedent for using the observer network and survey protocol to assess management effectiveness and that will guide the use of the network/protocol in this way in future years. The content within Chapter 6 was published in the *Australasian Journal of Environmental Management*.

The Keppel Bay story in Chapter 6 explains that there are multiple benefits for managers (and management of the Reef) as a result of involving community members in monitoring coral reef condition and impacts. In a sense, the Keppel Bay story is the story of my thesis and the story of how adaptive management is meant to work. By building capacity among non-specialists to monitor reef condition and impacts (Chapters 2-5, Figure 7.1) managers can target, evaluate and refine actions (Chapter 6) to support reef resilience and recovery. Two-way exchanges of information between managers and reef stakeholders and community members are required for the full benefits of the adaptive management process to be realised, as was shown in the Keppel Bay (see also inner arrows in Figure 7.1). Indeed, communication is absolutely vital to being able to manage adaptively, resulting in both direct (reduced damage) and indirect (community support) outcomes. Programs I developed, integrated and refined during my research study are now facilitating a range of ways for managers and reef stakeholders to communicate, resulting in benefits for both parties and for coral reefs.

Figure 7.1. Cycle of adaptive resilience-based management and the final thesis content. The thesis chapters describe inter-related (outer arrows) programs of work (outer circles) coral reef managers can invest in that, as a whole, ensures reefs can be managed adaptively to support resilience (inner circle) as long as managers and reef stakeholders engage and communicate (inner arrows).

7.2 Future directions in resilience-based management

Corals live within a very narrow range of environmental conditions. It is for this reason precisely that coral reefs are the most sensitive ecosystems to climate change. Sea levels, sea temperatures and sea chemistry are already changing in ways that negatively affect the capacity of stony corals to settle, grow and calcify, and persist through time. These changes are projected to continue and they result in both chronic/gradual as well as acute stress to corals (Anthony & Maynard 2011; Anthony et al. 2014; Baldock et al. 2014; Mumby et al. 2011; Van Hooidonk, Maynard & Planes 2013). All of this stress compounds the ever-increasing anthropogenic stress in many reef areas. This means that coral reef managers, like myself, have the challenging task of reducing rates of decline in coral reef condition and dependent ecosystem services while environmental pressures radically increase (Authority, GBRMP 2009, 2014). That is a realistic rather than pessimistic view and, more importantly, as a working coral reef manager, the view is both pragmatic and necessary. By this I mean that managing expectations is critical to building and maintaining the political and social will that will be required to implement the range of actions that can give reefs the best chance of persisting as the climate changes.

We need to shift from basing management decisions on historical data and trends (the current paradigm) to being both prospective and proactive to properly manage expectations of politicians and reef stakeholders. Such a shift has already begun in the GBRMP under the Outlook reporting requirements of the 2011 revisions to the Great Barrier Reef Marine Park Act 1975. It is also a view I share with the insurance industry, probably far and away the best industry at assessing and understanding risk. Last June, the Geneva Association, an insurance industry research group, released a report outlining the evidence of climate change and describing the new challenges insurance companies will face as the climate changes. The report states: "*In the non-stationary environment caused by ocean warming, traditional approaches, which are solely based on analyzing historical data, increasingly fail to estimate today's hazard probabilities.*" I think it is useful to combine this premise with what is probably the single most important investment strategy used in all financial markets; 'cut your losses and let your profits run'. In keeping with this logic, coral reefs may be best served by managers seeing their management area as a sort of 'battlefield triage' clinic in which reefs with the best chance of persisting are given the highest rather than lowest priority. We can increasingly focus conservation efforts at reef sites with lower relative exposure to disturbances (relative refugia) and sites with greater relative resilience potential (based on local conditions and ecological characteristics, e.g. low exposure to cumulative impacts and fast reproduction and growth rates see (Anthony et al. 2014; Beeden, R et al. 2014b; Maynard et al. 2010; McClanahan et al. 2012; Van Hooidonk, Maynard & Planes 2013)). Concurrently, we can decrease our investment of effort at highly vulnerable reef sites that have little chance of persisting long enough for the benefits of our actions to even manifest. This means additional investment to supplement large-scale, long-term (strategic) actions that reduce exposure, with local-scale, short-term (tactical) actions that support recovery. Importantly, the success of such an approach will depend on ensuring that priority is genuinely based upon the likelihood a reef will persist in preference to those that are the most politically, socially, culturally and economically convenient to protect (see Devillers et al. 2014).

The challenge for managers of large coral reef systems is knowing where and when to implement tactical actions to best effect. Even with recent advances in remote sensing and monitoring technologies, managers are often required to make decision based upon very limited information. Furthermore, much of the information that is available from long-term trend monitoring is analogous to the image provided by the rear view mirror in a car. While it undoubtedly provides valuable insights into how reefs have arrived at their current state, it only provides a very limited, time delayed rear windscreen view of the current environment that severely limits decision making regarding where to go next. Rather like the insurance industry, what is really needed is a far higher resolution real-time front windscreen view coupled with a modelling based equivalent of a global positioning system (GPS) navigation tool that highlights potential paths, enables managers to set a course and then adapts to changes in direction. Such a system would operationalise resilience thinking in a way that would empower reef managers to make the best possible choices in an increasingly uncertain future.

Within the context of the broader resilience vision, the results of my thesis work have already greatly enhanced managers' capacity to target local-scale, short-term actions to support recovery in the GBR. The network of observers participating in Eye on the Reef monitoring is now providing information on reef condition and impacts from hundreds of reefs every year. Also, scientists working in collaboration with my team at GBRMPA are mapping exposure to waves generated during cyclones, temperature stress severe enough to cause bleaching, and flooding in ways not possible five years ago. The consequence is that we are starting to dynamically understand condition and exposure and can actually adaptively manage by responding to impacts with targeted actions to support recovery. This is a very exciting capacity to have helped create in what remains the world's largest management agency tasked solely with managing a coral reef area. As is the case with any research area, addressing challenges and making advancements has identified new challenges and created some new opportunities. Some of the most important of these opportunities include:

1) Dynamic assessments of resilience potential by querying data provided by the Eye on the Reef Network to produce composite scores for sites surveyed, based on variables that can serve as resilience indicators.
2) Creating an annually updated spatial database and associated interactive tool that reports on exposure of coral reef areas to environmental disturbances and making this accessible to the research and management community and public.
3) Combining the application of (1) and (2) to trial management actions that can minimise mortality associated with coral disease on highly valued reefs, as well as at relative refugia and reefs with greater relative resilience potential.

Taking advantage of these opportunities will form the focus of the research objectives of my work with the GBRMPA over the coming years. The final days of my candidature find me certain that the greatest opportunity of all is that the public is becoming increasingly aware of the threat posed to coral reefs by climate change. Many coastal community members are dependent enough on coral reefs to care and want to know how to help. In Queensland we are already translating their desire and willingness to help into the capacity to help co-manage and conserve coral reefs by participating in monitoring and outreach programs I have worked to integrate and refine. These programs are underpinned by ongoing and effective communication between managers and reef stakeholders that serves both to inform and to stimulate stewardship. As an overarching summary of the body of my work, an important outcome is that I have contributed to implementation and tightening of the adaptive management cycle now guiding management actions at GBRMPA. We are empowering people that depend on coral reefs to participate in their management by providing data we are using in near real-time to better conserve those reefs to the benefit of both the reefs and dependent people. As a consequence, the outlook for the Great Barrier Reef in an era of climate change is perhaps just a little better.

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APPENDIX 1

Underwater cards for assessing coral health in the Indo-Pacific

Appendix contains the entire content of the *Underwater Cards for assessing coral health in the Indo-Pacific* described in Chapter 2. The cards were published in 2008 by the Global Environment Facility's Coral Reef Targeted Research program.

The cards were designed around a decision tree that separates coral diseases and other reef health impacts by their characteristic signs. The decision tree was designed to serve as a visual colour coded index that enables users to differentially diagnose coral health impacts and their likely causes. The decision tree is followed by colour indexed pages that detail the characteristic signs of each coral health impact, and other impacts that they may be readily confused with. All, bar one of the content pages, follows a standard format with bullet points summarising key information on the left of each page and illustrative images on the right. An additional page of images for the coloured band diseases was added on the basis of user feedback.

The *Underwater Cards* also provide instructions on their use, and outline a range of methods that can be employed to assess coral disease abundance, prevalence and / or progression. The Cards conclude with a waterproof datasheet used by coral disease researchers to determine coral disease prevalence. The cards were constructed from lightweight flexible plastic, with a durable clear cover to protect them from the elements and from being scratched when stored with other survey equipment. The cards were sized to fit in a large SCUBA buoyancy compensation device pocket. The entire first print run of the *Cards* sold out by 2010; a new version will be released late in 2014.

spine

Coral Reef Targeted Research & Capacity Building for Management

2008

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Underwater Cards for Assessing Coral Health on

Indo-Pacific Reefs

Underwater Cards for
Assessing Coral Health on Indo-Pacific Reefs

Roger Beeden[1,2], Bette L. Willis[1], Laurie J. Raymundo[3], Cathie A. Page[1], Ernesto Weil[4].

How to use these cards

Coral Disease

Coral reefs are under increasing stress globally from a number of causes, including climate warming, poor water quality and over-fishing. Disease outbreaks not only result in coral loss, but they also cause significant changes in community structure, species diversity and reef-associated organisms.

Coral diseases potentially impact both well-managed and unmanaged reefs. However, strategies for dealing with disease outbreaks are currently non-existent. The increasing frequency with which diseases influence and alter reef communities means they must be considered and incorporated into management plans.

The CRTR Disease Working Group

The CRTR *Disease Working Group* has been funded by the Coral Reef Targeted Research & Capacity Building for Management Program (CRTR) to advance understanding of coral disease in a number of key areas.

In particular, the CRTR *Disease Working Group's* research is providing a greater understanding of the ways in which coral diseases can alter reef function and the conditions under which outbreaks may occur. Documenting abundance and prevalence of disease and monitoring changes in disease through time are key steps in understanding how factors like ocean warming and deteriorating water quality may affect disease dynamics.

To assist with our objectives, the CRTR *Disease Working Group* has produced these Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs so that recreational, professional and scientific divers can all assist with gathering information on the occurrence of coral diseases.

By using these cards, you can:

- Learn to identify Indo-Pacific coral diseases and survey techniques for measuring coral disease prevalence;
- Gather information on the distribution and abundance of coral diseases on local reefs;
- Monitor the health of local coral reefs and identify potential drivers of disease abundance;
- Contribute to a world-wide data base on coral disease;
- Help to conserve the world's coral reefs.

How to use these cards

These cards start with a decision tree for assessing the health status of Indo-Pacific corals. The decision tree is colour coded to assist with navigation through the cards. After reviewing all disease descriptions and images to gain an overview of the range of signs of disease and compromised health, the following steps will enable you to assess the health status of a coral. Note that a variety of factors other than disease (e.g. predation, grazing) cause lesions.

1. Decide if a coral shows signs of tissue loss (red section), tissue discolouration (blue section), anomalous growth (green section) or some other sign of compromised health (yellow section).
2. At each level in the key for the coloured section selected, decide which category best describes the signs observed.
3. Go to the appropriate coloured section in this card set to check disease images and descriptions.
4. Record your observations on the data sheet provided at the end of this card set.

The CRTR Program is a partnership between the Global Environment Facility, the World Bank, The University of Queensland (Australia), the United States National Oceanic and Atmospheric Administration (NOAA) and approximately 50 research institutes and other third-parties around the world.

GEF THE UNIVERSITY OF QUEENSLAND AUSTRALIA Coral Reef Studies

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spine

Indo-Pacific Coral Health – Decision Tree

Tissue Loss – Predation — 1
- 1a. Predation (PRD) – e.g. fish, snail, starfish feeding scars

Tissue Loss – Non-Predation – Coloured Band Diseases — 2
- 2a. Skeletal Eroding Band (SEB)
- 2b. Black Band Disease (BBD)
- 2c. Brown Band Disease (BrB)

Tissue Loss – Non-Predation – No overlying band of coloured material — 3
- 3a. Ulcerative White Spots (UWS) – focal tissue loss
- 3b. White Syndromes (WS) – irregular tissue loss
- 3c. Atramentous Necrosis (AtN) – grey-black material overlies irregular area of tissue loss

Tissue Discolouration – White — 4
- 4a. Bleaching (BL) – environmentally induced partial or whole colony bleaching
- 4b. Focal Bleaching (FBL) – early stage of UWS or unexplained spots
- 4c. Non Focal Bleaching (NFBL) – unusual bleaching patterns, e.g. patches, stripes

Tissue Discolouration – Non White — 5
- 5a. Pigmentation Response (PR) – coral response to a challenge (not a disease)
- 5b. Trematodiasis (TR)

Growth Anomalies — 6
- 6a. Explained Growth Anomalies
- 6b. Unexplained Growth Anomalies

Compromised Health — 7
- 7a. Pigmentation Response (see 5a. above)
- 7b. Unusual Bleaching Patterns (see 4c. above)
- 7c. Competition – Aggressive Overgrowth – e.g. cyanobacteria, *Terpios* and *Cliona* sponges, red filamentous algae
- 7d. Sediment Damage
- 7e. Flatworm Infestation

Diseases in Other Reef Organisms — 8
- 8a. Examples for Crustose Coralline Algae & Gorgonians

Indo-Pacific – Decision Tree

Coral Reef Targeted Research & Capacity Building for Management

① Tissue Loss – Predation

1a. Predation

Crown-Of-Thorns Starfish (COTS)

(*Acanthaster planci*)

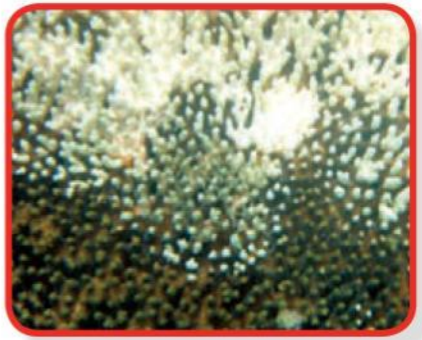
- Adult COTS are up to 80cm in diameter, covered in numerous sharp 4-5cm spines and have up to 21 arms;
- **Australia:** COTS are typically grey with tinges of red on their spines and body;
- **Asia Pacific:** COTS may be more brightly coloured – bright blue or purple varieties;
- COTS feed directly on living coral tissue;
- Feeding usually starts from the colony edge on plates or colony base on branches;
- Feeding causes rapid tissue loss, exposing large patches of white skeleton.

Key ID characteristics:

- Feeding scar often has a scalloped border on plate corals;
- Border may show visible strings of tissue and mucus;
- Starfish usually seen in area (check under nearby colonies);
- Feeding scars on neighbouring colonies.

Commonly confused with:

- White syndromes, which typically advance more slowly, so white areas smaller;
- Bleached areas, which still have tissue present;
- *Drupella* scars, which expose smaller areas of white skeleton.



1a. Predation

Drupella (*Drupella cornus*)

- *Drupella cornus* snails may vary in colour from pink (1) to dark red (2) when they are covered with encrusting coralline algae;
- Feeds at night from base of branches or edge of colony;
- Tissue loss typically slower than for COTS (*Acanthaster planci*) predation;
- Tissue loss from base upward, exposing small patches of white skeleton when snail densities are low;
- Typically prefers *Acropora* species.

Key ID characteristics:

- Feeding scar often has irregular border – shredded strings of tissue may be visible;
- *Drupella* snails usually shelter under colony or near base during day;
- *Drupella* snails are often found on neighbouring colonies if not immediately visible beside the feeding scars.

Commonly confused with:

- COTS scars, which are larger areas of white skeleton;
- Bleached areas, which still have tissue present;
- White syndromes, which tend to have more regular fronts.

1a. Predation

Coralliophila (*Coralliophila sp.*)

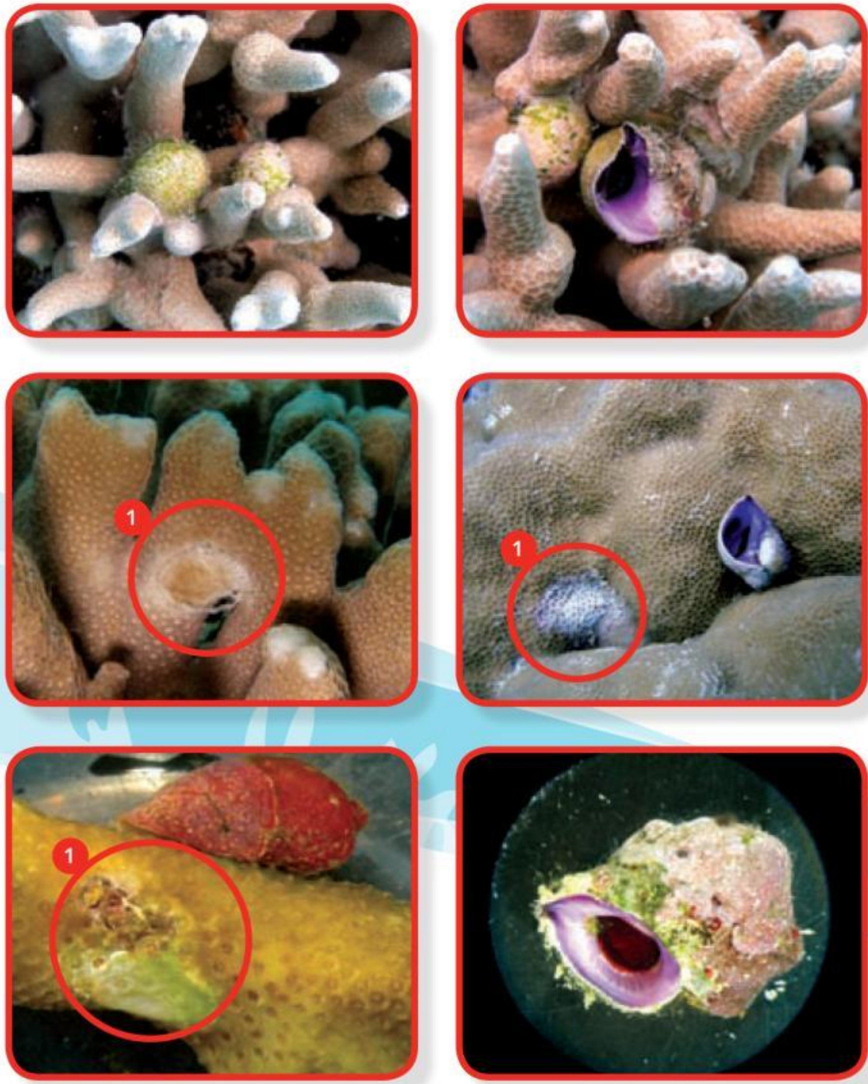
- *Coralliophila sp.* snails typically have a violet or purple aperature;
- Snails are typically sedentary and are firmly attached to the coral;
- *Coralliophila sp.* cause little coral tissue loss, but may drain energy resources required to heal the wound over extended periods of time;
- Feeding wounds may be a potential entry point for disease causing organisms.

Key ID characteristics:

- A characteristic small ovoid feeding wound is typically present if the snail is removed from the coral; 1
- Typically found feeding on *Porites*, particularly branching species.

Commonly confused with:

- *Drupella* snails, which move as they feed exposing areas of white skeleton.



1 Tissue Loss – Predation

1a. Predation/Grazing

Fish Bites

- Distinctive, regular scars: gouges, scrapes "bite" marks that may involve damage to coral skeleton;
- Scars typically white if relatively fresh;
- Scars may become colonised by algae.

Key ID characteristics:

Parrotfish scars

- Large scrapes sometimes focused along colony ridges or growth anomaly tissue; 1
- Common on massive *Porites*.

Trigger/Pufferfish scars

- Small regular, paired rectangular bite marks; 2
- Less damaging to coral than parrot fish bites.

Damselfish scars

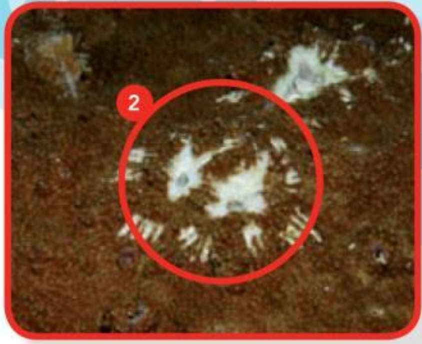
- Irregular patches of tissue loss colonized by algae farmed by damselfish; 3
- Common on branching *Acropora* species.

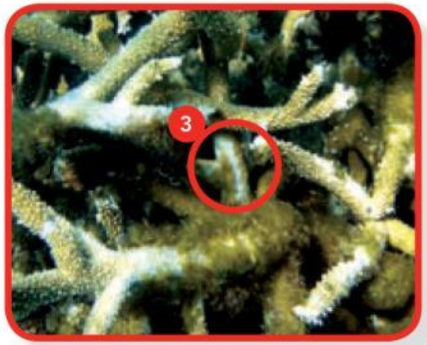
Butterflyfish scars

- Butterflyfish use their narrow elongated mouth to selectively remove coral polyps;
- Feeding scars may not be clearly evident;
- Butterflyfish may transfer diseases to the coral.

Commonly confused with:

- Usually easy to identify.





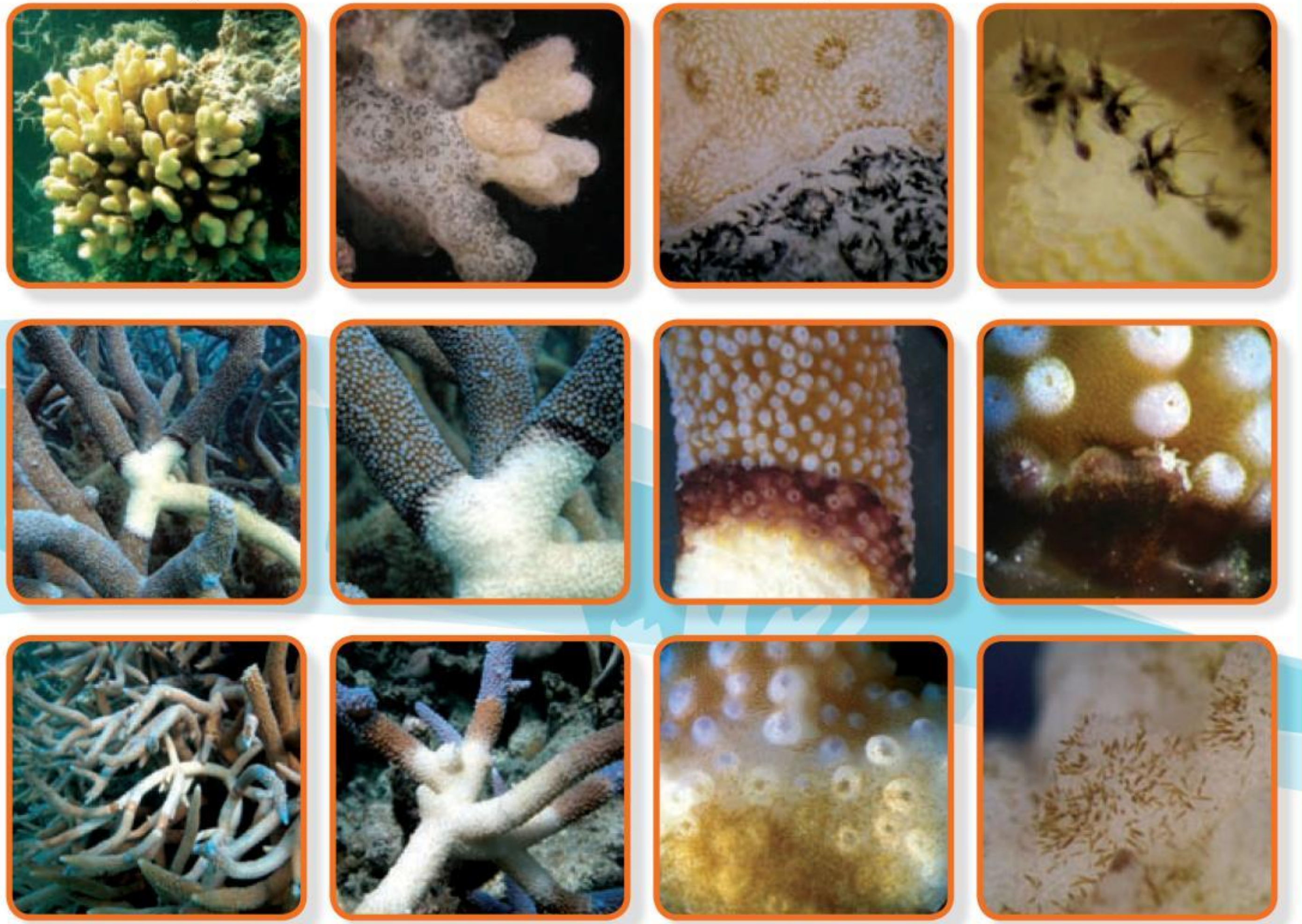
Coloured Band Diseases

Colony | Branch | Polyp | Microscope

Skeletal Eroding Band (SEB)

Black Band (BBD)

Brown Band (BrB)



Coloured Band Diseases

2a. Skeletal Eroding Band (SEB)

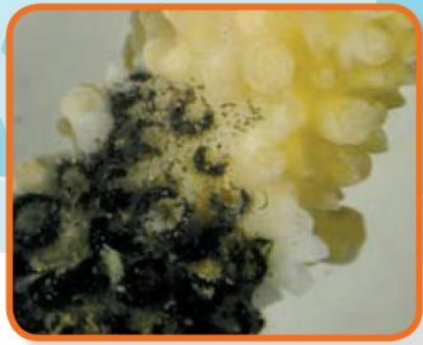
- Diffuse, speckled black or dark green band at tissue-skeleton interface;
- Exposed skeleton behind tissue front speckled by empty "housings" of the boring ciliate, ***Halofolliculina corallasia***;
- Exposed skeleton eroded in appearance;
- Diffuse, scattered patches of ciliates on bare skeleton without band formation may indicate secondary infection.

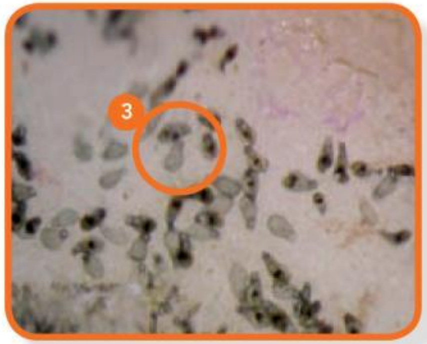
Key ID characteristics:

- Black "specks" often clustered within corallites; (1)
- Sessile ciliates within "housings" comprise band;
- Microscopically, two "antenna-like" pericytostomial wings visible; (2)
- Empty, black "housings" left behind as the disease front advances, creating speckling; (3)
- Relatively slow rate of progression (~0-6mm/day);
- Common throughout the Indo-Pacific, affecting a wide range of coral families.

Commonly confused with:

- Black Band Disease, which does not have speckled appearance.





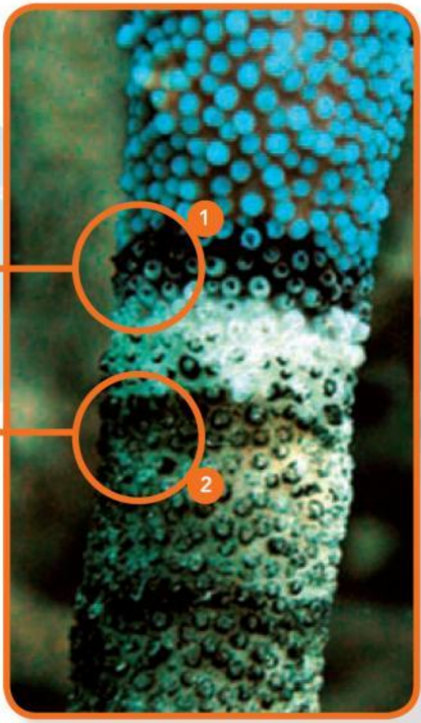
Coloured Band Diseases

2b. Black Band Disease (BBD)

- Discrete, dark band at interface between live tissue and exposed skeleton, at times directly overtopping live tissue; 1
- Band colour can vary from black to reddish-brown;
- Exposed skeleton is white (no speckling) behind band;
- Skeleton distant to tissue front becomes progressively brown as colonized by fouling community.

Commonly confused with:

- Skeletal Eroding Band (SEB), which is differentiated by speckled appearance of exposed skeleton; 2
- Dark bands between competing corals. 3



Key ID characteristics:

- Microscopically, thread-like cyanobacteria and bacteria comprise black band;
- Moderate rate of progression (~4-8mm/day on staghorns; ~1-4mm/day on plates);
- Common throughout the Indo-Pacific, affecting a wide range of coral families.

Coloured Band Diseases

2c. Brown Band Disease (BrB)

- Discrete brown band at interface between live tissue and extensive areas of exposed, white skeleton;
- Bands composed of ciliates and vary from light to dark brown with ciliate density;
- Narrow white band may be present between live coral tissue and brown band;
- Skeleton distant to tissue front becomes progressively brown as it is colonized by the fouling community; indicates progressive tissue loss.

Key ID characteristics:

- Mobile ciliates (Class: Oligohymenophora; subclass: Scuticociliatia) visible under a microscope and may contain engulfed zooxanthellae giving brown appearance;
- Rapid rate of progression (20-100mm/day recorded);
- Affects a wide range of families throughout the Indo-Pacific, but commonly affects staghorn and plating species of *Acropora*.

Commonly confused with:

- White syndromes (WS) when ciliate densities are low. Check for brown tinges macroscopically or ciliates microscopically.







3 Tissue Loss – Non-Predation

No Distinct Band (of overlying material) Focal Tissue Loss

3a. Ulcerative White Spots (UWS)

- Multifocal patterns of tissue loss that expose spots of bare white skeleton;
- Lesions typically small (<1cm diameter), regularly ovoid and may start as bleached spots; a coral may contain both bleached lesions and lesions devoid of tissue;
- Lesions may coalesce to create larger patches of tissue loss.

Key ID characteristics:

- No signs of associated micro-organisms at live tissue-bare skeleton interface;
- Commonly affects *Porites*, but also *Montipora, Echinopora,* favids and *Heliopora.*

Commonly confused with:

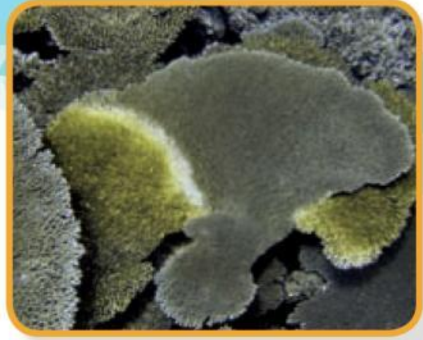
- Focal bleaching, which is distinguished by the presence of tissue in white areas.




Irregular tissue loss

3b. White Syndromes (WS)

- Diffuse patterns of tissue loss that expose bands or patches of bare white skeleton abutting live tissue.

No Distinct Band

White Syndromes (WS) cont...

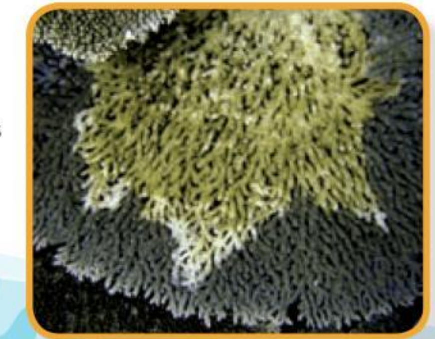
- Potentially caused by a range of pathogens and/or environmental stressors;
- May be visible colour gradient from bare white skeleton to brown as fouling community develops – indicates progressive tissue loss;
- Margins of lesions may be linear, irregular or annular (ring-like).

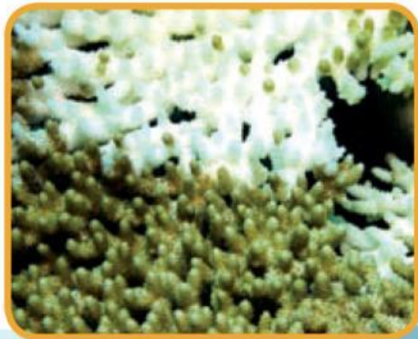
Key ID characteristics:

- No signs of associated micro-organisms at live tissue-bare skeleton interface;
- Apoptosis (programmed cell death) may be involved;
- Tissue loss may progress rapidly (≤20mm/day);
- Tissue bordering WS lesion may be coloured by coral pigmentation response; (1)
- Commonly affects plate species of *Acropora* and a range of other genera.

Commonly confused with:

- Brown band (BrB), particularly when ciliate densities are low. Look for brown tinges;
- Bleaching, which is distinguished by the presence of tissue;
- Atramentous necrosis, which develops distinctive grey film;
- Ulcerative White Spots, on massive *Porites*, which are small, multi-focal lesions.





No Distinct Band Irregular Tissue Loss (with overlying material)

3c. Atramentous Necrosis (AtN) (Black Death)

- Multifocal patterns of tissue loss that expose spots or patches of bare white skeleton subsequently colonized by a distinctive dark fouling community;
- Lesions typically start as small (<1cm diameter) bleached spots, which may coalesce to create larger patches of tissue loss; (1)
- In the final stages, lesions may develop a white film overlying black deposits giving them a grayish appearance.

Key ID characteristics:

- Black sulphurous-smelling deposit accumulates under white film of bacterial filaments giving lesions a greyish-black appearance;
- Commonly affects *Montipora* but also recorded on *Acropora, Echinopora, Fungia, Merulina* and *Turbinaria*.

Early stages commonly confused with:

- Multifocal bleaching, which is distinguished by the presence of tissue;
- Ulcerative white spots, which do not result in characteristic grey-black lesions;
- White syndromes, which do not result in characteristic grey-black lesions.

(3) Tissue Loss – Non-Predation

4a. Bleaching (environmentally induced)

Partial/Whole Colony

- Colony to reef-wide loss of symbiotic algae (zooxanthallae);
- Associated with environmental stress (e.g. thermal, light, salinity).

4b. Focal Bleaching

Spots

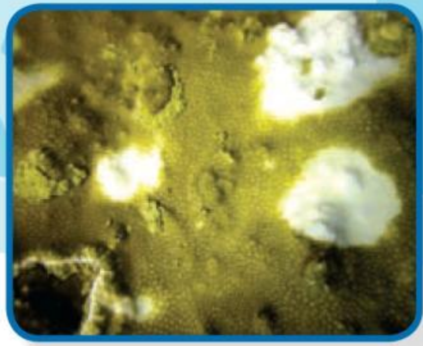
- Multifocal patterns of bleaching scattered over colony;
- Borders between bleached patches and healthy tissue are often discrete;
- May be the first stage of Ulcerative White Spot or Atramentous necrosis;
- Commonly recorded on *Porites, Montipora* and *Acropora*.

Key ID characteristics:

- Coral is alive, hence polyps visible;
- Skeleton is not eroded nor colonized by algae because tissue is present.

Commonly confused with:

- Ulcerative White Spot, which is distinguished by the absence of tissue;
- Atramentous necrosis (Black Death), which is distinguished in final stages by characteristic grey-black lesion.



4c. Non Focal Bleaching (unusual bleaching patterns)

Patches

- Unusual, diffuse patterns of bleaching that do not appear to be a specific response to thermal or other environmental stress;
- Borders between bleached patches and typically coloured tissue are often discrete;
- Recorded on massive species of *Porites*.

Stripes

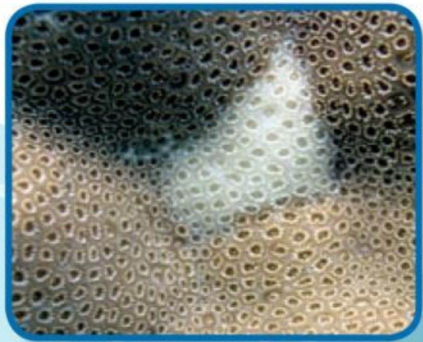
- Unusual, diffuse patterns of bleaching that do not appear to be a specific response to thermal or other environmental stress;
- Borders between bleached stripes and tissue with typical colouration are often discrete;
- Recorded on *Pachyseris*.

Key ID characteristics:

- Coral is alive, hence polyps will be visible;
- Skeleton is not eroded nor colonized by algae because tissue is present.

Commonly confused with:

- White syndromes, which are distinguished by the absence of tissue in white areas.



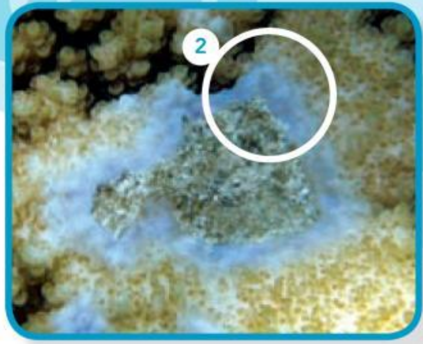
Tissue Discolouration Non-White

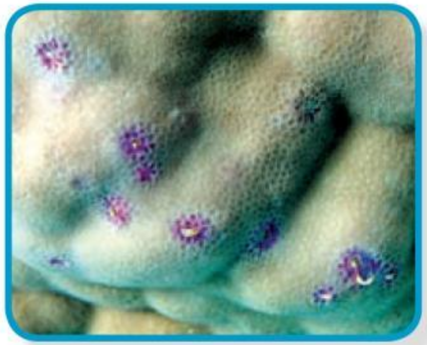
5a. Pigmentation Response

- Coral tissue bordering lesion is brightly coloured, typically:
  - pink or purple in *Porites* sp.; (1)
  - blue in *Acropora* sp.; (2)
- Lesion may be swollen or thickened;
- Pigmentation may form lines, bumps, spots, patches or irregular shapes depending on cause of lesion;
- Lesion may be caused by borers, competitors, algal abrasion, fish bites, breakages, etc.

Key ID characteristics:

- Pigmentation appears to be a type of "inflammation" response mounted by coral;
- Pigmented tissues typically associated with a healing response rather than progressive tissue loss;
- Suggests coral health is compromised, but is not itself a sign of disease.





Tissue Discolouration

Pigmentation Response cont...

Commonly confused with:

- Trematodiasis, which is distigiuished by encysted trematodes.

5b. Trematodiasis

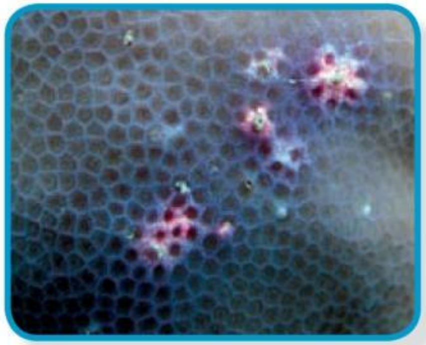
- Multifocal, distinct pink to white small (1-2mm) areas of tissue swelling;
- Swelling of one or a few polyps in response to encysted parasitic trematode; (1)
- Trematode cysts are often clustered;
- Life cycle – Trematode cysts are eaten by butterflyfish then excreted and eaten by a gastropod which then infects the coral;
- Only recorded on *Porites* to date.

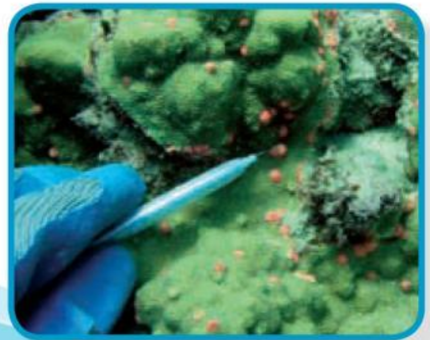
Key ID characteristics:

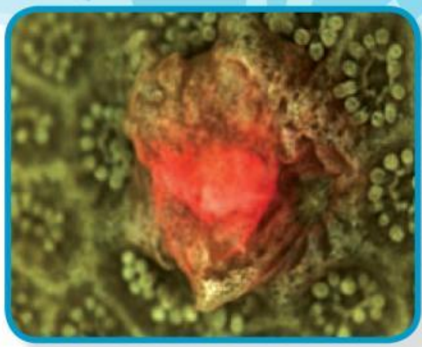
- Heavy infestations result in reduced growth and reproduction of the coral host.

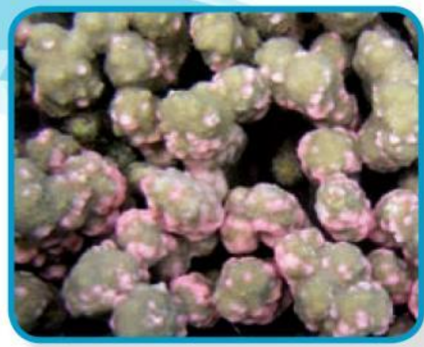
Commonly confused with:

- Pigmentation response, but distinguished by distinct small nodules of tissue swelling and presence of trematode cyst when examined microscopically.









6a. Explained Growth Anomalies

Invertebrate Galls

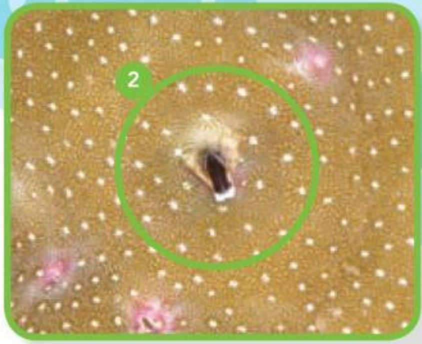
- Focal to multifocal skeletal deformations associated with an invertebrate
  e.g. crab, (1)
  barnacle; (2)
- Deformations are typically raised and caused by skeletal depositions around resident invertebrate in unusual patterns that are characteristic for each invertebrate.

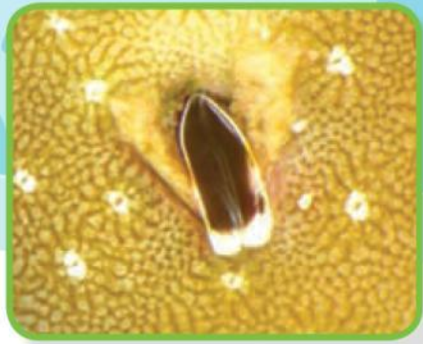
Key ID characteristics:

- Invertebrate may be present inside the gall or within the colony;
- Galls have characteristic shapes and features that are usually easy to identify;
- Crab galls are commonly observed on *Seriatopora* and *Stylophora*.

Commonly confused with:

- Other growth anomalies.





6b. Unexplained Growth Anomalies

Enlarged Structures

- Focal to multifocal, circular to irregularly shaped lesions comprising abnormally arranged, enlarged skeletal elements (corallites, ridges, valleys);
- Typically protudes above colony surface and surface rugosity visibly differs from healthy tissue;
- Pigmentation may be normal or slightly pale (suggesting reduced zooxanthellae densities);
- Tissue may die in irregular patches, and bare skeleton may be colonized by epibionts;
- Includes gigantism and areas of accelerated growth.

Irregular White Plaques

- Focal to multifocal, circular to irregularly shaped lesions comprising abnormally arranged, often highly disorganized skeletal elements (corallites, ridges, valleys);
- Pigmentation may be normal, lighter (reduced zooxanthellae) or completely absent (loss of zooxanthellae);
- Corallites smaller, fewer than in healthy tissues, or absent, resulting in structure resembling a white plaque;
- Includes chaotic polyp development.

7c. Competition – Aggressive Overgrowth

Live coral tissue overgrown by a vartiety of organisms

Cyanobacteria

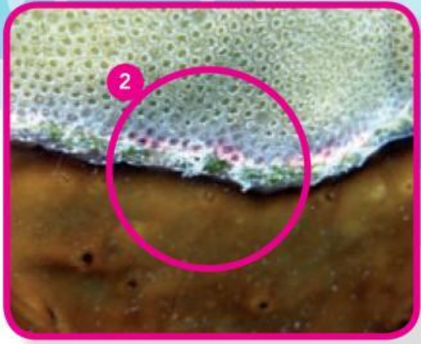
- Mats or tufts of fine algal filaments that attach to surface of coral and smother tissue;
- Algae (cyanobacteria) may vary widely in colour – dark grey, reddish orange and yellow;
- Bubbles of photosynthesis/respiration products may be present in the algal mats. (1)

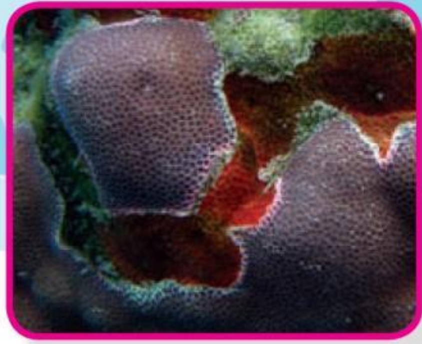
Sponges

- *Terpios* and *Cliona* sponges progressively kill and overgrow exposed coral skeleton;
- A zone of white exposed skeleton between sponge and coral may be evident. (2)

Red Filamentous Algae

- Filaments embed in surface mucus and accumulate sediment;
- Tissue adjacent to filaments may bleach.





Multiple Compromised Health Signs

- Combination of algal filaments, pigentation response, surface mucus and accumulated sediment. 3

7d.Sediment Damage

- Diffuse area of tissue loss associated with fine sediment accumulating in hollows on coral surface and on coral polyps and tissue;
- Common in turbid water.

Key ID characteristics:

- Sediment deposition visible;
- May be accompanied by mucus secretion and pigmentation response.

Commonly confused with:

- Usually easy to identify.

7e.Flatworm Infestation

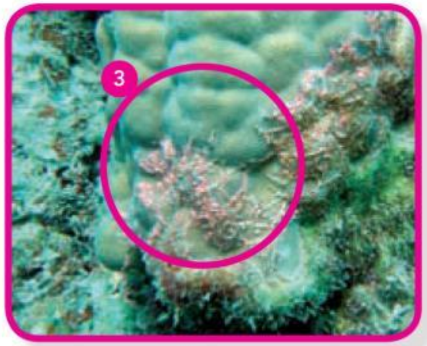
- Surface of coral covered by mobile, ovoid, brown flatworms, notably in the genus *Waminoa*;
- Brown colouration due to endosymbiotic dinoflagellates.

Key ID characteristics:

- Microscopically the brown flatworms are speckled white.

Commonly confused with:

- Usually easy to identify.

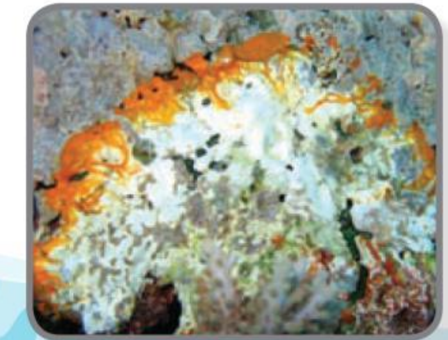


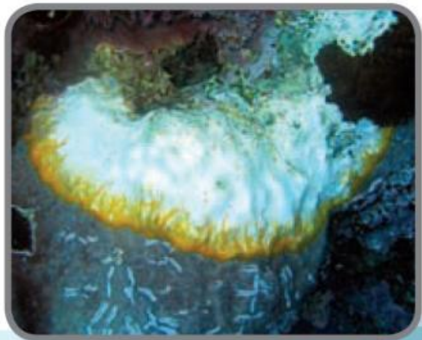
8a. Diseases Affecting Other Reef Organisms

Crustose Coralline Algae

Coralline Lethal Orange Disease (CLOD)

- Characteristic orange band.



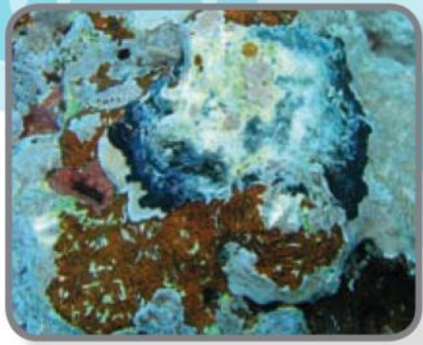


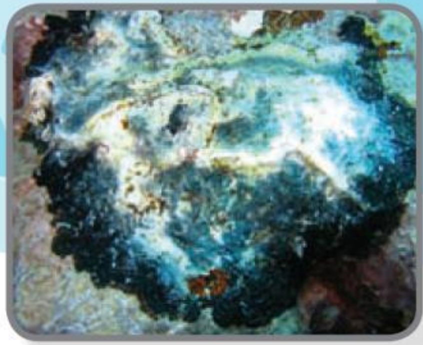
Crustose Coralline Algae (CCA)

Black Fungal Disease

Commonly confused with:

- Usually easy to identify.





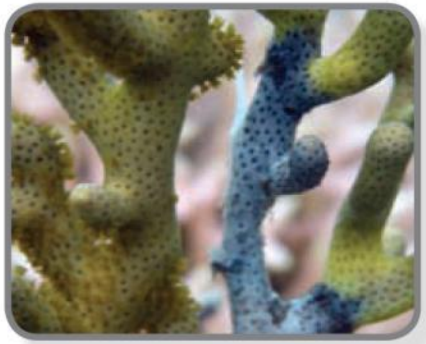
ISIS Gorgonians

Black necrosing syndrome

- Black/grey necrotic tissue;
- Tissue necrosis and loss;
- Skeleton exposed as necrotic tissue is lost.

Commonly confused with:

- Usually easy to identify.



Recording & Reporting

Underwater Cards - Options for Recording & Reporting Observations of Coral Disease

Qualitative observations of coral disease

At the simplest level, it is useful to photograph and / or record details of corals that are diseased or show signs of compromised health. The following data could be recorded:

Date & Recorder: ____________________

Site/Habitat/Depth: ____________________

Disease/compromised health sign: ____________________

Growth form/Genus/species of coral: ____________________

Photo name(s) & number(s): ____________________

Additional observations (e.g. #corals/species affected): ____________________

____

____

Quantifying observations of coral disease

Disease abundance: Recording the number of cases of disease per unit area without recording all healthy corals gives a measure of disease abundance. ***To quantify disease abundance:***

1. Select an appropriate area (e.g. 20m x 2m belt transect);
2. Select appropriate replication (e.g. 3 belt transects per site);
3. Record all corals showing signs of disease or compromised health on the data sheet at the end of this guide;
4. Calculate mean (± SE) number of disease cases per $40m^2$.

Disease prevalence: Recording the number of cases of disease and the total number of healthy corals per unit area gives a measure of disease prevalence. This is a better, but more time consuming way of quantifying disease.

1. Select an appropriate area (e.g. 20m x 2m belt transect);
2. Select appropriate replication (e.g. 3 belt transects per site);
3. Record all corals showing signs of disease or compromised health and all healthy corals on the following data sheets;
4. Calculate mean (± SE) percent of corals that are diseased per $40m^2$.

Disease incidence: Tagging and monitoring the number of diseased corals in a given area through time identifies the number of new cases of disease per unit time and gives a measure of disease incidence or spread throughout the population.

1. Select an appropriate area (e.g. 10m x 10m quadrat) ;
2. Select appropriate replication (e.g. 3 quadrats per site);
3. Tag all diseased colonies within quadrats;
4. Monitor quadrats regularly (e.g. monthly), tagging all new cases of disease;
5. Calculate mean (± SE) # of new disease cases per unit time.

Disease progression: Tagging and photographing corals through time enables rates of disease progression across corals to be calculated.

1. Tag replicate diseased corals at study site;
2. Photograph each diseased coral with a scale bar and at a standard angle;
3. Re-photograph tagged corals at regular intervals (e.g. weekly or monthly) ;
4. Measure linear spread of disease front or progressive area of tissue loss from images;
5. Calculate mean (± SE) rate of disease progression.

We are grateful to the following people for images reproduced in these Cards: David Abrego, Greta Aeby, Shelley Anthony, Roger Beeden, Doug Fenner, Mike Flavell, Great Barrier Marine Park Authority, Mohammed Mohammed, Cathie Page, Laurie Raymundo, Maria Rodrigues, Kathryn Rosell, Emily Smart (Fantasea Cruises), Yui Sato, David Stewart, Meir Sussman and Bette Willis. We thank Greta Aeby, Andy Bruckner, Drew Harvell and Thierry Work for invaluable discussions during the genesis of these Cards. We thank the CRTR Program for its support and for funding this publication, and the ARC Centre of Excellence for Coral Reef Studies for funding the majority of research underpinning these cards.

Product code: CRTR 002/2008

Name:

Date:

Reef:

			Tissue Loss										Tissue Discolouration			
			Known Predator/ Grazer				Non-Predation (i.e. Disease)						2. Bleaching			
			Fish Grazer	Drupella	Coralli-ophila	COTS	Coloured Band Diseases			No Distinct Band			Whole/ partial colony	Focal	Non-Focal (unusual patterns)	
Family	Genus	Colony Shape	FISH	DRU	COR	COTS	SEB	BBD	BrB	UWS	WS	AtN	%	Spots	Patches	Stripes
Acroporidae	*Acropora*	tabular (plates)														
		corymbose (pillows)														
		digitate (finger like)														
		bottlebrush														
		clumping														
		bushy														
		staghorn														
	Montipora	encrusting														
Pocilloporidae	*Pocillopora*	clumps – branches														
	Stylophora	blunt branches														
	Seriatopora	spiky branches														
Poritidae	*Porites*	massive														
		branching														
	Alveopora	(12 tentacles)														
	Goniopora	(24 tentacles)														
Faviidae	*Favia*															
	Montastrea															
	Favites															
	Echinopora															
	Platygyra															
	Goniastrea															
	Cyphastrea															
	Diploastrea															
(record other favids)	1															
	2															
Other (record genus if known & describe)																
Photo number(s)																
(Take 3 photos: colony, branch & close up)																

GPS coordinates:	Depth (m) Ave: m	Depth (m) Max: m	Timed Swim/Dive: mins

Name:

Date:

Reef:

			Non-White		Growth Anomalies			Compromised Health						
					Exp	Unexplained		Overgrowth						
			Pigment Response	Trematodiasis	Invert Galls	Enlarged structures	Irreg. white plaques	Cyanobacteria	Sponges	Red Filament Algee	Sediment damage	Flatworm Infestation		
Family	Genus	Colony Shape	PR	TR	IG	ES	IWP	CY	SP	RA	SD	RW	Healthy Coral	Unknown Scars
Acroporidae	*Acropora*	tabular (plates)												
		corymbose (pillows)												
		digitate (finger like)												
		bottlebrush												
		clumping												
		bushy												
		staghorn												
	Montipora	encrusting												
Pocilloporidae	*Pocillopora*	clumps – branches												
	Stylophora	blunt branches												
	Seriatopora	spiky branches												
Poritidae	*Porites*	massive												
		branching												
	Alveopora	(12 tentacles)												
	Goniopora	(24 tentacles)												
Faviidae	*Favia*													
	Montastrea													
	Favites													
	Echinopora													
	Platygyra													
	Goniastrea													
	Cyphastrea													
	Diploastrea													
(record other favids)	1													
	2													
Other (record genus if known & describe)														
Photo number(s)														
(Take 3 photos: colony, branch & close up)														

GPS coordinates:

Water temp: °C

APPENDIX 2

Visual aid used to support Reef Health and Impact Surveys

Appendix 2 contains the double-sided visual aid (size A4) that was developed based upon the content of the *Underwater Cards for assessing coral health in the Indo-Pacific* (Chapter 2). The visual aid is laminated to make it waterproof, and attached to the slate that holds the Reef Health and Impact Survey form (Chapter 4).

The top of first side of the visual aid shows a graphical representation of the RHIS method including memory prompts for how to complete the site and benthos components of the form. The bottom half contains representative images of the benthos, macroalgae and coral life-forms assessed using the RHIS protocol. The reverse side of the visual aid includes an adapted version of the decision tree from the *Underwater Cards* (Chapter 2). The decision tree was adjusted to only include the categories of impacts that are assessed using RHIS, with the addition of a section on mechanical damage. The bottom half of the page provides illustrative examples of each class of impact, with a colour-coded border that matches the colours used in the decision tree.

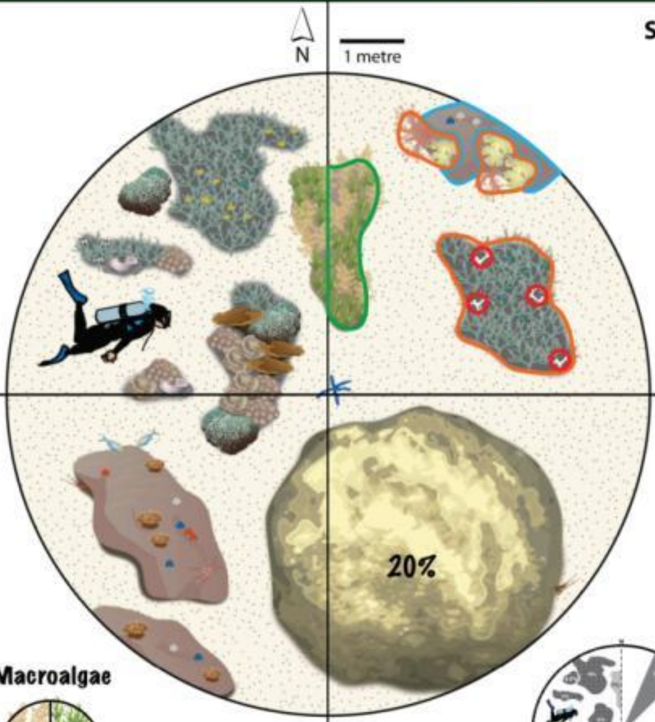
The graphics used throughout the visual aid are the same as those in the integrated Eye on the Reef online training system. The visual aid was designed in consultation with rangers, tourism staff and community volunteers. The visual aid graphics will be integrated into version 2 of the Underwater Cards, due to be completed by the end of 2014.

Eye on the Reef – Reef Health and Impact Survey Visual Aid

Step 1: Select your site

- Randomly select RHIS site
- Select a memorable centre point
- Swim 5 metres to the north, south, east and west of the centre and select perimeter reference points
- Swim the perimeter between these points, looking towards the centre
- Consider which benthic categories are most and least common

See EotR RHIS Training: Module 4

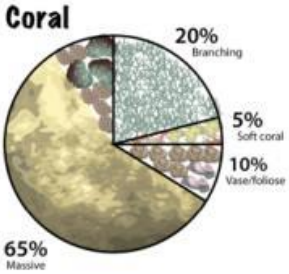


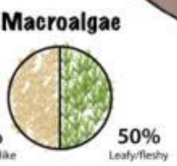
Step 2: Classify the benthos

- Macroalgae
- Live coral
- Recently dead coral
- Live coral rock
- Coral rubble
- Sand

See EotR RHIS Training: Modules 3

Step 4: Estimate lifeforms





Tip: see below

See EotR RHIS Training: Modules 4&5

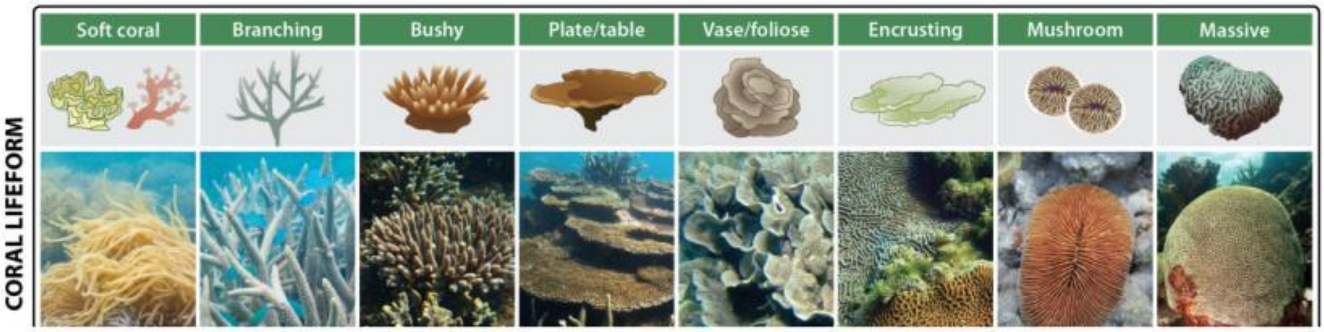
Step 3: Estimate % cover

- Start with most and least common
- In this example:
  - **Sand = 50%**
  - **Live coral = 35%** (20% coral bommie + 15% other coral)
  - **Coral rubble = 0%**
- Remember total benthos must equal 100%

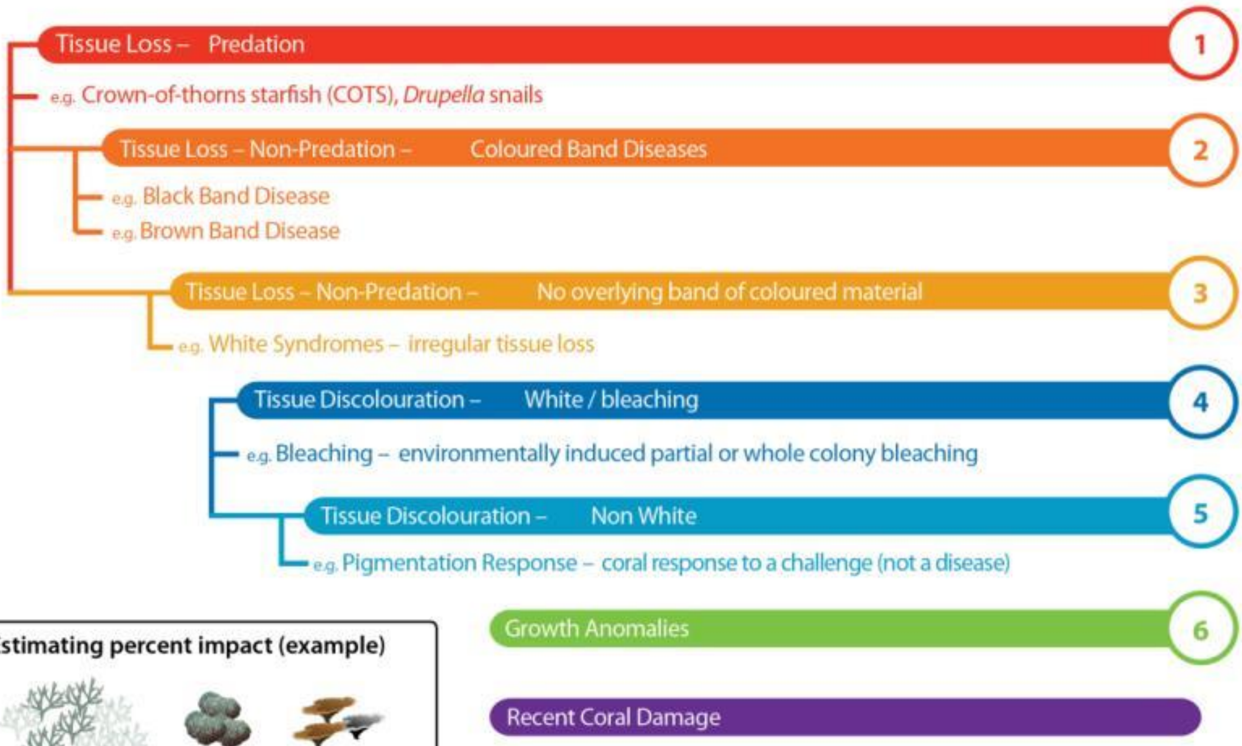
Tip: Use the RHIS % cover tool, see www.gbrmpa.gov.au

BENTHOS:	
Macroalgae:	5 %
Live coral:	35 %
Recently dead coral:	1 %
Live coral rock:	9 %
Coral rubble:	0 %
Sand:	50 %
TOTAL:	100 %

See EotR RHIS Training: Modules 4



Indo-Pacific Coral Health Decision Tree



Estimating percent impact (example)

1) Proportion of coral cover (live and recently dead)
branching = 50% massive = 25% plate = 25% = **100%**

2) Proportion of the corals that are bleached
branching = 50% massive = 0% plate = 33%

For more information including how to use the above decision tree please refer to R. Beeden et al (2008). *Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs* <http://gefcoral.org/>

APPENDIX 3

Statement of Contribution of Others

Chapter	Details of publications on which the chapter is based.	Nature and extent of the intellectual input of each author	I confirm the candidate's contribution to this paper and consent to the inclusion of the paper in this thesis
2: Development of a decision tree and field guide for assessing coral health impacts on Indo-Pacific reefs.	**Beeden RJ**, Willis BL, Raymundo LJ, Page CA, Weil E 2008, *Underwater Cards for Assessing Coral Health on Indo-Pacific Reefs*. Coral Reef Targeted Research & Capacity Building for Management Program, St Lucia, QLD AUSTRALIA.	Willis and Raymundo developed the field-based morphological descriptions of coral diseases and other indicators of compromised health and advised on key disease identification signs described in the guide. Beeden designed, developed and tested the field version of the decision tree and the final product appropriate for reef managers, reef tourism operators and for the purposes of citizen science. All co-authors contributed photographs and reviewed and commented on drafts of the text and layout of the field guide.	Name: Professor Bette Willis Signature: Name: Dr Laurie Raymundo Signature: Name: Dr Cathie Page Signature: Name: Professor Ernesto Weil Signature: Eweil (signed via email 10th September 2014)
3: A framework for responding to coral disease outbreaks that facilitates adaptive management.	**Beeden RJ**, Maynard JA, Marshall P, Heron S, Willis B 2012, 'A framework for responding to coral disease outbreaks that facilitates adaptive management', *Environmental Management*, vol. 49, no. 1, pp 1-13. doi: 10.1007/s00267-011-9770-9 Authority, Great Barrier Reef Marine Park 2013b, *Coral Disease Risk and Impact Assessment Plan,* eds **RJ, Beeden**, JA, Maynard, J, Dryden & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2809 Authority, Great Barrier Reef Marine Park 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2808	Beeden led the development of the coral disease response plan, and subsequent risk and impact assessment plans and the manuscript published in *Environmental Management*. Maynard, Willis, Marshall and Heron all reviewed and provided editorial comments to the *Environmental Management manuscript.* Willis, Maynard, Marshall and Dryden also provided comments the draft Coral Disease Response Plan (later Coral Disease Risk and Impact Assessment Plan) technical report. The approach to responding to incidents contained in the technical report is based upon work by Marshall and Maynard to respond to coral bleaching events presented within Maynard et al. (2009). Heron and Maynard developed the remote sensing tools and White Syndromes forecasting models described in the Framework and the Risk and Impact Assessment Plan (Heron et al. 2010; Maynard et al. 2011).	Name: Professor Bette Willis Signature: Name: Dr Paul Marshall Signature: Name: Dr. Scott Heron Signature: Name: Dr Jeff Maynard Signature: Name: Ms Jen Dryden Signature:
4: Rapid survey protocol that provides dynamic reef health and condition information to managers of the Great Barrier Reef.	**Beeden, RJ**, Turner, MA, Dryden, J, Merida, F, Goudkamp, K, Malone, C, Marshall, PA, Birtles, A & Maynard, JA 2014a, 'Rapid survey protocol that provides dynamic reef health condition information to managers of the Great Barrier Reef', *Environmental Monitoring and Assessment,* vol. 186, no. 12, pp. 8527-8540. doi: 10.1007/s10661-014-4022-0 Authority, Great Barrier Reef Marine Park 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2808	Beeden led the integration of the Eye on the Reef system to address the full suite of coral health impacts, and the writing of the manuscript. The 'circular belt transect' method was developed in close collaboration with Turner and Marshall. All co-authors provided input into the selection of site, benthos and reef health indicators included in the Reef Health and Impact Survey form and supporting database. Merida, Goudkamp and Turner made recommendations on the useability of the survey method and datasheet. All co-authors and other GBRMPA, QPWS and tourism operator staff contributed to the 2 years of RHIS form and survey methodology evolution. Turner, Goudkamp, Malone, Merida and Dryden contributed to the design, development and implementation of the integrated Eye on the Reef information system (those authors and I formed a technical working group). Turner, Goudkamp and I co-managed the work program to deliver the operational supporting database. Goudkamp led the testing and quality control of the database. Malone helped with the development of visualisation algorithms and the Google EarthTM Keyhole Markup Language (KML) layer design. Dryden helped project manage the development, testing and deployment of the e-learning system. The RHIS visual aid (Chapter 4, Figure 4.4) and educational support materials (Chapter 4, Appendix 2) were developed in collaboration with R. Kelley, D. Tracey and D. Schultz based upon training content developed in collaboration with Turner, Merida, Marshall and Maynard. Data collection described in this chapter and the submitted manuscript included some staff from the Great Barrier Reef Marine Park Authority (referred to throughout the thesis as 'GBRMPA'), QPWS and Great Barrier Reef tourism industry staff. Maynard and Marshall assisted with parts of the data analysis related to visualising impact extent and severity.	Name: Mr Malcolm Turner Signature: Name: Ms Jen Dryden Signature: Name: Ms Fiona Merida Signature: Name: Ms Katrina Goudkamp Signature: Katrina Goudkamp (signed via email 25th September 2014) Name: Ms Cherie Malone Signature: Name: Dr P. Marshall Signature: Name: Dr A. Birtles Signature: Name: Dr Jeff Maynard Signature:

5: Impacts of severe tropical cyclone Yasi on the Great Barrier Reef	**Beeden RJ**, Puotinen M, Marshall P, Goldberg J, Dryden J, Williams, G & Maynard, JA (in review) Impacts of severe tropical cyclone Yasi on the Great Barrier Reef. Submitted to PLoS ONE Authority, Great Barrier Reef Marine Park 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2808 Authority, Great Barrier Reef Marine Park 2013d, *Tropical Cyclone Risk and Impact Assessment Plan*, eds **RJ, Beeden**, JA, Maynard, J, Goldberg, J. Dryden & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2813 Authority, Great Barrier Reef Marine Park, 2011, *Impacts of tropical cyclone Yasi on the Great Barrier Reef: a report on the findings of a rapid ecological impact assessment,* Great Barrier Reef Marine Park Authority, Townsville.	Beeden led the ecological impact assessment following severe tropical cyclone Yasi, including site identification, sampling design and data analysis. Beeden also designed and led the recovery surveys conducted between 2011 and 2014. Beeden and Marshall jointly led the writing of the initial Impact Assessment technical report in partnership with Dryden and Goldberg. Beeden led the analysis of the recovery survey data and subsequent manuscipt submitted to PLoS ONE. All co-authors contributed to the development and editing of the manuscript. Marshall, Goldberg, Maynard and Dryden helped collect data on impact severity following TC Yasi after our working group implemented an impact assessment plan developed in collaboration with Marshall and Maynard. Many staff from the GBRMPA and QPWS helped assisted with data collection following TC Yasi. Dryden and Goldberg led the data entry and quality control following the surveys. Williams completed the PERMANOVA statistical analysis in collaboration with Beeden, Puotinen and Maynard. Puotinen developed the wave modelling tools, analysis and graphic shown in Figure 5.5 comparing Yasi to all other cyclones that produced gale force winds in the GBR Marine Park since 1985 in collaboration with Beeden and Maynard.	Name: Dr P. Marshall Signature: Name: Ms Jen Dryden Signature: Name: Mr J. Goldberg Signature: Name: Dr Marji Puotinen Signature: Name: Dr G. Williams Signature: Name: Dr Jeff Maynard Signature:
6: No-anchoring areas reduce coral damage in an effort to build resilience in Keppel Bay, southern Great Barrier Reef.	**Beeden, RJ**, Maynard, J, Johnson J, Dryden, J, Kininmonth, S & Marshall, P 2014b, 'No-anchoring areas reduce coral damage in an effort to build resilience in Keppel Bay, southern Great Barrier Reef', Australasian Journal of Environmental Management, vol. 21, no. 3, pp. 311-319, http://dx.doi.org/10.1080/14486563.2014.881307 Authority, Great Barrier Reef Marine Park 2013c, *Reef Health Incident Response System*, eds **RJ, Beeden**, JA, Maynard & PA, Marshall, Great Barrier Reef Marine Park Authority, Townsville. <http://elibrary.gbrmpa.gov.au/jspui/handle/11017/2808>	All authors contributed to the development and editing of the manuscript. Beeden designed and led the no-anchoring area management action evaluation surveys. The surveys in 2010, 2011 and 2012 were conducted in collaboration with Dryden. Kininmonth and other GBRMPA and QPWS staff also collected survey data. Kininmonth and Maynard assisted with the data analysis and figures were developed in collaboration with Maynard and Tracey. Maynard, Johnson and Marshall conducted the baseline Keppel Bay resilience assessment and established the no anchoring areas in 2008 in partnership with the local community.	Name: Dr J. Maynard Signature: Name: Ms Jo Johnson Signature: Name: Ms Jen Dryden Signature: Name: Dr Stuart Kininmonth Signature: Name: Dr P. Marshall Signature: