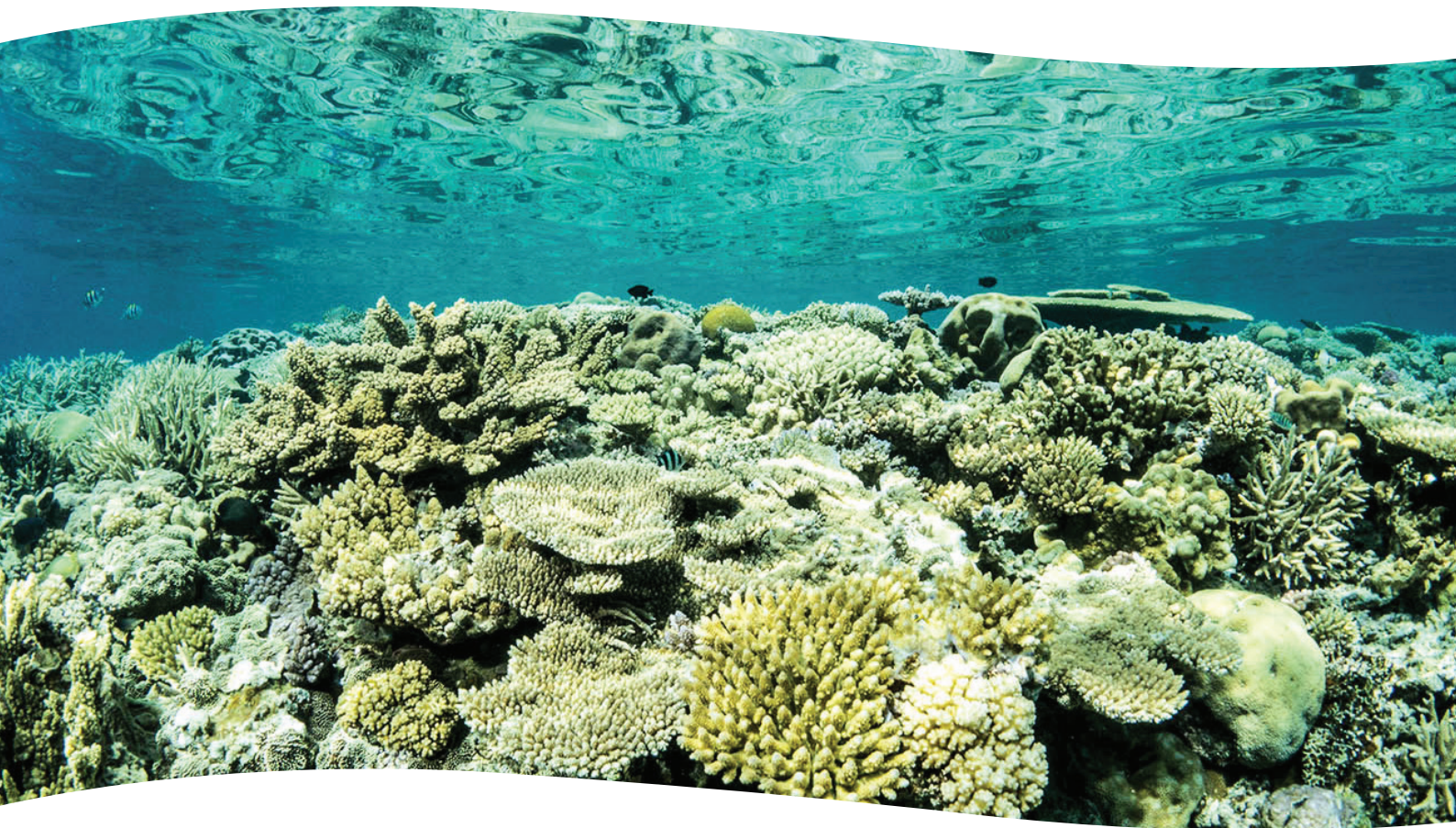


Identification of Important Source Reefs for Great Barrier Reef Recovery following the 2016-17 Thermal Stress Events

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Supported by the Australian Government's
National Environmental Science Program
Project 4.5 Guidance system for resilience-based management of the Great Barrier Reef

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This report should be cited as:

Mason, R. A. B., Hock, K. and Mumby, P. J. (2018) *Identification of Important Source Reefs for Great Barrier Reef Recovery following the 2016-17 Thermal Stress Events*. Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns (11pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub.

The Tropical Water Quality Hub is part of the Australian Government's National Environmental Science Program and is administered by the Reef and Rainforest Research Centre Limited (RRRC). The NESP TWQ Hub addresses water quality and coastal management in the World Heritage listed Great Barrier Reef, its catchments and other tropical waters, through the generation and transfer of world-class research and shared knowledge.

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Cover photographs: Peter Mumby

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CONTENTS

Contents.....	i
List of Tables.....	ii
List of Figures.....	ii
Acronyms	iii
Abbreviations	iii
Acknowledgements	iv
Executive Summary	1
1.0 Introduction	2
2.0 Methodology.....	3
2.1 Computational modelling.....	3
2.1.1 Prediction of damaged and undamaged reefs	3
2.1.2 Connectivity analysis	4
3.0 Discussion.....	5
3.1 Important source reefs	5
3.1.1 Source reefs for overall coral community recovery	5
3.1.2 Source reefs for recovery of highly temperature-sensitive coral.....	7
4.0 Recommendations and Conclusion	9
References.....	10
Appendix 1: Accompanying GIS Shapefile	11

LIST OF TABLES

Table 1:	Numerical categories in DHW6 and DHW3 columns of the attribute table of the “Key_Source_Reefs_2016-17” Shapefile.....	11
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LIST OF FIGURES

Figure 1:	Important source reefs for the subset of reefs that exceeded 6 DHW (the temperature-dose threshold for overall coral community damage) during 2016-2017.	5
Figure 2:	Important source reefs for the subset of reefs that exceeded 3 DHW (the temperature-dose threshold for highly temperature-sensitive coral species damage) during 2016-2017.....	7

ACRONYMS

DHW Degree Heating Weeks
GBR Great Barrier Reef
GBRMPA Great Barrier Reef Marine Park Authority
GIS geographic information system
NOAA United States National Oceanic and Atmospheric Administration
RBM resilience-based management
SST sea-surface temperature

ABBREVIATIONS

2016/2017 the years 2016 and 2017
in prep. manuscript in preparation
v3 version 3

ACKNOWLEDGEMENTS

The Great Barrier Reef Marine Park Authority is thanked for their map of reef outlines which was used to build Figures 1 and 2.

EXECUTIVE SUMMARY

- The analysis of reef positions in relation to water movement patterns enables the likelihood of larvae movement (connectivity) between reefs to be identified.
- Larval connectivities between reefs that exceeded, and did not exceed, thermal thresholds for damage during the 2016/2017 Great Barrier Reef bleaching events were analysed.
- In the northern and central GBR, most reefs that exceeded thresholds for damage were located a great distance from reefs that were both a good disperser of larvae and did not exceed the thermal damage threshold (source reefs). In contrast, in the southern GBR, most reefs that exceeded thermal damage were located proximate to source reefs.
- Reanalysis of larval connectivity between reefs based upon a higher-resolution sea-surface temperature product than the one used here may enable refugia for larval dispersal to be identified in the northern and central GBR.

1.0 INTRODUCTION

Coral bleaching is a key threatening process on coral reefs globally, with major bleaching events on the Great Barrier Reef (GBR) in 1998, 2002, and 2006. For the first time ever documented on the GBR, back-to-back bleaching events were seen in 2016 and 2017, with major changes to ecosystem structure and function resulting from mass coral cover loss in many areas (Hughes et al., 2018).

On the worst-damaged reefs, the loss of reproductive adult colonies has the implication that coral cover recovery will require the supply of coral larvae from external sources (other reefs). Coral larvae dispersal between reefs depends on the positioning of the reefs in relation to significant ocean currents or movements of seawater. For the GBR, currents and water movement patterns have been well characterised using in-field measurements and physical modelling. These models enable the likelihood of larvae movement between any two reefs on the GBR to be quantified, allowing the identification of larval supply to and from reefs. Performing the analysis on a GBR-wide scale provides a connectivity network that can be further analysed to identify specific connectivity patterns (Hock, Wolff, Condie, Anthony, & Mumby, 2014; Hock et al., 2017). This analysis allows for identification of important source reefs – reefs that have the potential to provide a substantial portion of larval supply to other reefs.

As a result of bleaching, many reefs that are potentially good sources of coral larvae under normal conditions have experienced high coral cover loss. Whilst these reefs may be in good positions in relation to ocean currents to supply many other reefs with larvae, their ability to produce larvae has been compromised by the loss of adult colonies. In addition, some of the remaining source reefs may have increased in importance due to their connectivity to and ability to supply larvae to other reefs that have been severely damaged by bleaching.

Resilience-based management (RBM) seeks to identify and preserve the aspects of ecosystem functioning that are important for maintaining the key ecological and social benefits of that ecosystem (Chapin III, Kofinas, & Folke, 2009). In practice, for an ecosystem such as the GBR that is at risk of multiple natural and anthropogenic impacts, RBM seeks to minimise damage to and maximise the recovery potential of the ecosystem. For the GBR, connectivity analyses will be a key component of the RBM, as they identify reefs that are the most important for facilitating coral recruitment through external larval supply under normal circumstances, as well as those that can supply larvae following acute events that cause damage to the GBR.

This report describes an application of connectivity analysis to identify important sources that may support recovery from the recent 2016/2017 bleaching events on the GBR. Through doing so, we identified reefs that avoided the worst bleaching impacts and could function as key suppliers of larvae to the reefs damaged by bleaching. This information could have application to initiatives for the monitoring or enhanced protection of these source reefs until the surrounding damaged reefs have achieved recovery.

2.0 METHODOLOGY

2.1 Computational modelling

2.1.1 Prediction of damaged and undamaged reefs

Due to the geographic size and quantity of reefs on the GBR, the ascertainment of bleaching and coral mortality on all GBR reefs through in-field surveys is currently unfeasible. However, an effort by a consortium of researchers led to aerial surveys of 1,156 reefs during the 2016 bleaching event and follow-up diving surveys at 63 of these reefs that quantified coral mortality in November 2016. By matching up the surveyed bleaching and mortality data with satellite measurements of sea-surface temperature over the bleaching period, Hughes et al. (2018) were able to establish a threshold dose of heat exposure that caused a major loss of coral cover and a subsequent shift in coral community structure. This threshold was 6 Degree Heating Weeks (DHW), where DHW is the scale of underwater heat-wave severity that is measured by NOAA Coral Reef Watch and in common use globally. The cumulative intensity of thermal stress is expressed as DHW in units of °C-weeks, which accumulates any thermal anomalies > 1°C above the maximum monthly mean at a location over a 12-week window. As coral response to heat exposure is a physiological response that is only likely to change over evolutionary timescales (Hoegh-Guldberg et al., 2007), we applied this threshold, determined in 2016, to analysis of both the 2016 and 2017 bleaching events.

Further analysis by Hughes et al. (2018) identified an additional ecologically important threshold value, 3 DHW, the heat exposure at which the most heat-sensitive coral species experienced mortality. This includes the species within the tabular *Acropora* and staghorn *Acropora* species groups.

We performed two heat-exposure analyses using the two DHW thresholds. The first was an analysis to identify important source reefs for overall coral community recovery. For this analysis, all reefs on the GBR with exposure that was above 6 DHW for ≥25% of their surface area were considered to have been sufficiently damaged by bleaching to require external larval supply for recovery (calculated from indicative reef boundaries as defined in GBRMPA zoning plan (GBRMPA, 2004)). Any reefs in this group were immediately ruled out as being a potential source reef.

The second analysis identified source reefs important for recovery of the most heat-sensitive coral species. For this analysis, all reefs on the GBR with exposure that was above 3 DHW for ≥25% of their surface area were considered to have been sufficiently damaged by bleaching to require external larval supply for recovery, and any reefs in this group were immediately ruled out as being a potential source reef.

For both heat-exposure analyses, we used DHW measurements derived from satellite-measured daily sea-surface temperature layers at 5 x 5 km resolution for the years 2016 and 2017, provided by NOAA Coral Reef Watch v3. Though sea-surface temperature layers are available from other data vendors (e.g. the Bureau of Meteorology, Australia), the NOAA Coral Reef Watch sea-surface temperature data was used for this analysis as the heat exposure thresholds that we used had been established using this data (Hughes et al., 2018).

2.1.2 Connectivity analysis

Connectivity patterns over seven years for which the oceanographic patterns were available (summers of 2008-09, 2010-11, 2011-12, 2012-13, 2014-15, 2015-16, 2016-17) were used to estimate the connectivity relationships among the reefs. The larval dispersal simulations used Connie2 dispersal tool (Condie, Hepburn, & Mansbridge, 2012), which uses eReefs hydrodynamics to displace simulated larval particles. In general, the simulations followed protocols previously published by Hock et al. (2017). In the current batch of simulations, key components of larval dispersal such as spawning times and pelagic larval duration were designed so as to match dispersal of broadcast spawning *Acropora* (Hock et al. in prep., life history parameters based on Connolly and Baird (2010)). The resulting connectivity matrices were added to obtain a single matrix representing the cumulative supply potential over the modelled spawning seasons. The reefs have then been divided into two sets, the first set consisting of those reefs that exceeded the respective thermal stress threshold in 2016 and/or 2017, and the second set consisting of those that did not exceed the threshold. The resulting connectivity matrices were then used to identify reefs that both had the largest potential to supply larvae to each reef that exceeded the thermal stress threshold (i.e., they were important sources to damaged reefs) and at the same time also did not exceed the thermal stress threshold (i.e., their breeding stocks avoided bleaching damage caused by heat exposure above the threshold).

3.0 DISCUSSION

3.1 Important source reefs

3.1.1 Source reefs for overall coral community recovery

The analysis of SST data identified that over the entire GBR, 2247 reefs exceeded 6 DHW and 418 important source reefs were present at this threshold (Figure 1).

■ Reef that exceeded 6 DHW ■ Important source reef ■ Other reef ■ Reef not assessed

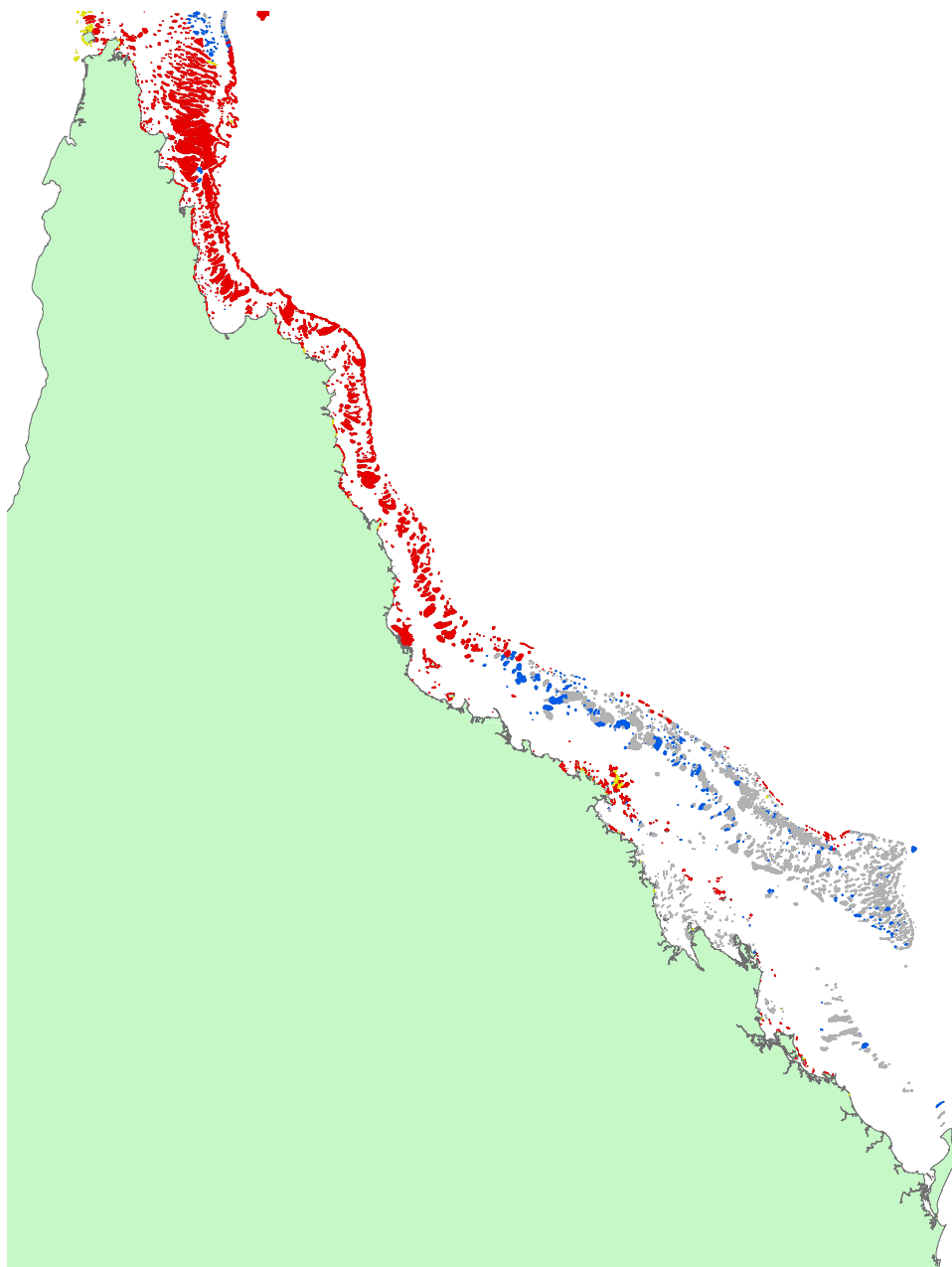


Figure 1: Important source reefs for the subset of reefs that exceeded 6 DHW (the temperature-dose threshold for overall coral community damage) during 2016-2017.

Nearly all of the GBR reefs between Townsville and the Torres Strait exceeded a DHW threshold value of 6 and were therefore in need of larval supply to aid recovery after the 2016 and/or 2017 bleaching events. This reflects in-field observations of bleaching over both years. In 2016, high levels of bleaching and mortality were recorded in the northern section of the GBR, north from Cooktown to the Torres Strait (Hughes et al., 2018). In 2017, widespread and severe bleaching was seen in large portions of the central section of the GBR from Townsville north to Cooktown. In the GBR regions south of Townsville, a small proportion of reefs exceeded the 6 DHW threshold.

With SST data indicating that nearly all reefs exceeded the thermal stress threshold in the northern and central sections, source reefs that could aid in recovery following bleaching were found to be clustered at the southern edge of the area affected by bleaching. Several potentially important source reefs were also located in the far northern section of the GBR in the Torres Strait, clustered at the edge of the continental shelf. A number of source reefs were also identified in the southern GBR, due to the occurrence of a limited number of reefs damaged by bleaching in this region. While the reefs in the southern GBR were able to provide larval supply to adjacent damaged reefs that were also in the south, most of the reefs in the northern parts did not have unaffected sources that could directly supply them.

3.1.2 Source reefs for recovery of highly temperature-sensitive coral

Under 3 DHW threshold (the threshold for damage to the most thermally-sensitive coral species), the bleaching footprint was even more extensive (Figure 2). Over the entire GBR, 3625 reefs exceeded 3 DHW during 2016-2017 and 552 important source reefs were present at this threshold.

■ Reef that exceeded 3 DHW ■ Important source reef ■ Other reef ■ Reef not assessed

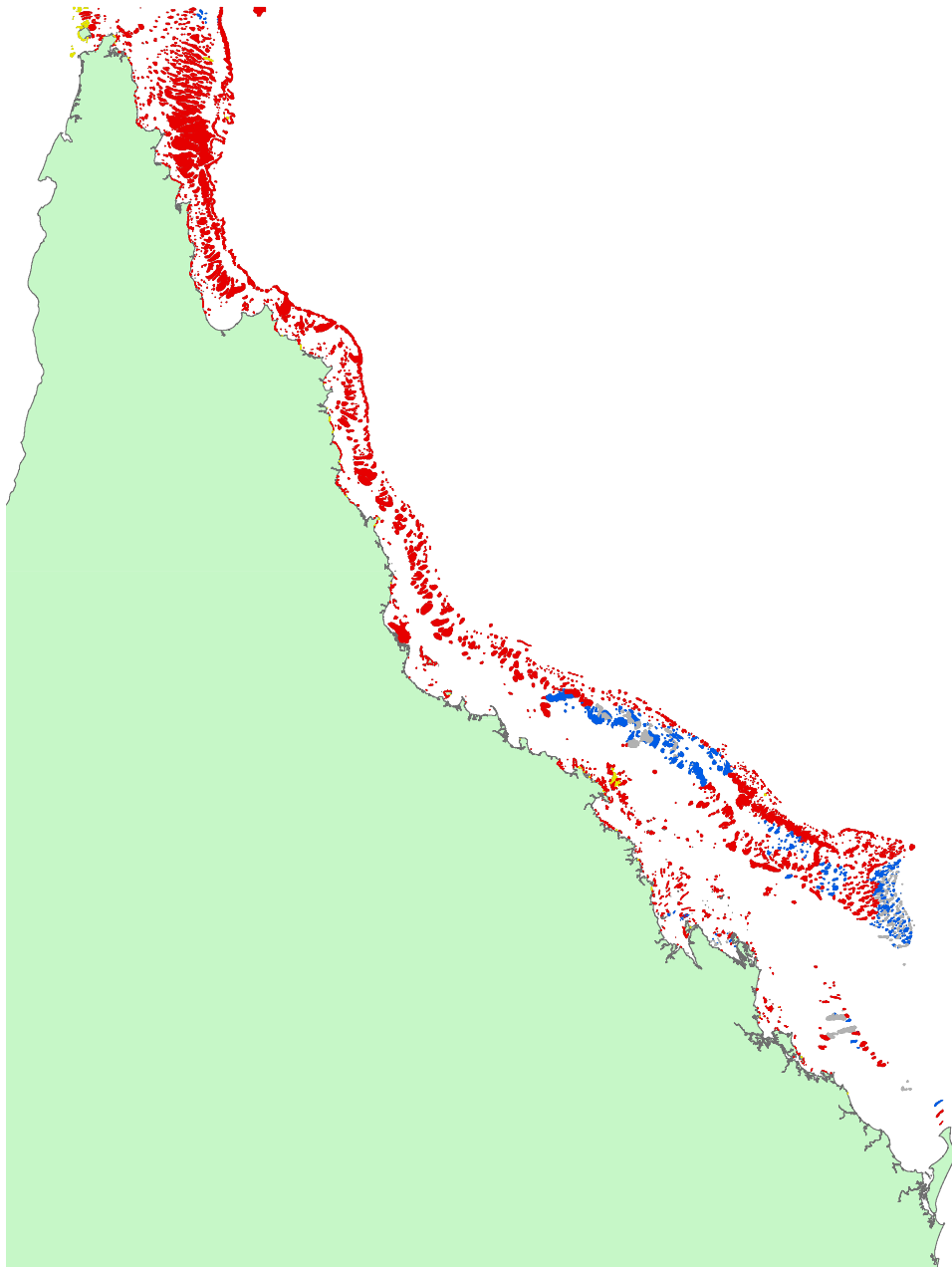


Figure 2: Important source reefs for the subset of reefs that exceeded 3 DHW (the temperature-dose threshold for highly temperature-sensitive coral species damage) during 2016-2017.

Most of the spatial patterns seen at the 6 DHW threshold were repeated, with bleaching damage extending to large areas of the southern GBR as well. There were still some clusters of unaffected reefs, most notably in mid-shelf in the Mackay region and in the Swains, as well as a small cluster in the Torres Strait. However, any direct recovery that these reefs could provide has been limited to their local region, with large swathes of the central and northern GBR having no reefs below the DHW 3 threshold.

4.0 RECOMMENDATIONS AND CONCLUSION

This analysis has revealed that a large swath of bleaching-affected reefs in the northern and central GBR appear to be located a long way from source reefs that managed to avoid the thermal stress. This leaves few options for finding and possibly protecting potential sources of recovery in these regions of the GBR. This in turn suggests that local resistance, e.g. by having thermally tolerant coral colonies in a heat-affect reef that can then help repopulate that reef or adjacent reefs, may be a more likely mechanism for recovery than the external supply of larvae from unaffected areas. Still, in areas where the thermal stress was less comprehensive, such as the southern GBR, reefs affected by bleaching would appear to be better supplied by larvae from reefs that suffered lower exposure. Local protection of specific sources could be more effective in these regions.

However, there are some important caveats in the current analysis methodology. Most importantly, the Coral Reef Watch SST data layer has a resolution of 5 km², which is larger than many reefs on the GBR. Higher-resolution products, such as ReefTemp Next Generation, a high resolution (approximately 2 km²) daily product developed by the Australian Government's Bureau of Meteorology and used in Hock et al. (2017), could be better suited to reveal locations of potential thermal stress refugia. Moreover, field observations have shown that the relationship between thermal stress and subsequent mortality tends to be imperfect, as some reefs exhibited low mortality even in conditions of high thermal stress (Hughes et al., 2018). Such reefs may therefore serve as important larval sources, but cannot be identified by only taking into account SST anomalies, as was the case here. Such reefs may harbour thermally resistant corals, and/or may have had environmental cues such as pulses of warm water early in the season that prepared them to better cope with subsequent levels of thermal stress (Ainsworth et al., 2016).

Previous connectivity analyses have identified source reefs that generally (that is, during non-stressful years) are important to larval supply to many other reefs on the GBR (Hock et al., 2017). It is natural to ask how many of the important source reefs identified in Hock et al. (2017) are also important source reefs following bleaching. However, such a comparison could lead to spurious conclusions because the methods of identifying source reefs are technically different between the two analyses - in the former case, all linkages between reefs are considered, whilst in the latter, only linkages between non-bleached reefs and bleached reefs are considered. For instance, a source reef (denoted here as reef 1) that is important source overall may be identified as such because it has strong connectivity (and therefore larval supply) to reefs A, B, C and D. If only reef A bleaches, then the strong links of reef 1 to reefs B, C and D are not important to the analysis of key source reefs for recovery from bleaching, which will likely affect whether reef 1 is identified as an important source. In addition, if a reef has high connectivity to bleached reefs, but experienced bleaching itself, then it will be eliminated from contention as a key source reef for recovery from bleaching.

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APPENDIX 1: ACCOMPANYING GIS SHAPEFILE

File name: *Key_Source_Reefs_2016-17.shp*

Description: Shapefile of important source reefs and thermally damaged reefs at 3 DHW and 6 DHW, openable in the GIS program ArcMap (Esri) or other GIS software. This is the current file of GBR reef outlines (publicly available through GBMRPA), with each reef annotated with the following categories (in the columns named DHW6 and DHW3 of the attribute table).

Table 1: Numerical categories in DHW6 and DHW3 columns of the attribute table of the “Key_Source_Reefs_2016-17” Shapefile.

Category	Description
2	Reef did not experience DHW above threshold (3 or 6) in 2016 and/or 2017, and is the best source to at least one of the reefs that experienced DHW over that same threshold
1	Reef experienced DHW above threshold (3 or 6) in 2016 and/or 2017
0	Reef did not experience DHW above threshold (3 or 6) in 2016 and/or 2017, but is not the best source to any of the reefs that did
-1	Reef not represented in connectivity models (usually small reefs close to the shore)
-2	Feature not relevant to connectivity models (cay, rock, island or mainland)

