Tropical Water Quality Hub

National Environmental Science Programme

Synthesis Report

Improving coral reef condition through better-informed resilience-based management:

A Synthesis of NESP Tropical Water Quality Hub research

The Tropical Water Quality Hub is funded by the Australian Government's National Environmental Science Program

Improving coral reef condition through better-informed resilience-based management

A Synthesis of NESP Tropical Water Quality Hub research

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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.

Cover photographs: (front) Reef landscape; Image: P. Mumby (back) Reef landscape; Image: R. Abom,

This report is available for download from the NESP Tropical Water Quality Hub website:
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ACRONYMS AND ABBREVIATIONS

ACCSP .... Australian Climate Change Science Programme
AIMS .... Australian Institute of Marine Science
bPAR .... Benthic Photosynthetic Active Radiation
BoM .... Bureau of Meteorology
COTS .... Crown-of-thorns starfish (*Acanthaster* cf. *solaris*)
CERF .... Commonwealth Environmental Research Facility
CRC Reef ..... Cooperative Research Centre for the GBRWHA
CSIRO .... Commonwealth Scientific and Industrial Research Organization
DAWE .... Department of Agriculture Water and the Environment
DST .... Decision Support Tool
GBR .... Great Barrier Reef
GBRMPA ..... Great Barrier Reef Marine Park Authority
GBRWHA ..... Great Barrier Reef World Heritage Area
IPM .... Integrated Pest Management
JCU .... James Cook University
LTMP .... Long Term Monitoring Program
ms-PAF .... Multistressor-Potentially Affected Fraction
MTSRF .... Marine and Tropical Science Research Facility
SeaSim .... National Sea Simulator (AIMS)
NERP .... National Environment Research Program
NESP .... National Environmental Science Program
NGO .... Non-governmental Organisation
NOAA .... National Oceanic and Atmospheric Administration
NRM .... Natural Resource Management
RIMReP .... Reef 2050 Integrated Monitoring and Reporting Program
RRRC .... Reef and Rainforest Research Centre
TWQ .... Tropical Water Quality
UQ .... University of Queensland

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EXECUTIVE SUMMARY

The Great Barrier Reef is the world's largest coral reef ecosystem and a globally important natural resource, increasingly subject to multiple pressures, both global and local. As climate change becomes the dominant driver of Great Barrier Reef (GBR) coral reef health, there is recognition that major disturbance events, such as coral bleaching and severe cyclones, will become more frequent, placing extra pressure upon the natural ability of coral reefs to recover. Reef managers cannot directly reduce the drivers of global climate change. Therefore, the emphasis is to maintain and enhance resilience through management efforts that support reefs and associated habitats to resist or recover from future shocks and cope with the uncertainty of future change. The acute influences of pressures such as crown-of-thorns starfish (COTS) outbreaks, flood events driven by extreme weather, coastal development and other anthropogenic threats are exacerbated by climate change. Previously, impacts on the GBR from these drivers have been documented individually but the potential for additive and synergistic effects will be more severe than indicated from studies of individual stressors.

Several projects across the National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub focused on delivering science that can quantify simultaneous and cumulative pressures to inform resilience-based management and decision-making to maintain and improve coral reef condition in the GBR. Many of the research projects were initiated as a direct response to the 2016 and 2017 mass bleaching events and have contributed to the goals outlined in the Reef Blueprint for Resilience (2017). Resilience-based management and integrated monitoring and reporting are key initiatives for managing the GBR ecosystem, identified in the Reef 2050 Long-Term Sustainability Plan, as they allow early detection of trends and changes and timely and adaptive management responses. This synthesis, therefore, brings together the learnings of multiple research projects and initiatives driven by the same goal of informing resilience-based management of the GBR to current and future disturbances.

NESP TWQ Hub investments investigated reef resilience and resilience-based decision-making through a variety of projects. These include: examining the relationship between water quality and bleaching risk, as well as other cumulative impacts; identifying the function of important species on the GBR and how values are connected and managed across jurisdictions; understanding spatial variability of thermal stress and bleaching; trialling methods for coral restoration; and identifying the traits of corals that have survived bleaching, among others. The NESP TWQ Hub has also invested in developing a resilience-based decision-making tool for marine park managers. Investments in water quality improvement, COTS control and enhanced monitoring and reporting in support of the Reef Integrated Monitoring and Reporting (RIMRep) program were also relevant to this synthesis. This synthesis report provides a summary of NESP TWQ funded projects as well as a review of how the information aligns with or builds on existing knowledge and management approaches from the literature.

NESP TWQ Hub research focused on the interactions between pressures and resilience-based indicators contributed towards an improved understanding of what pressures undermine reef resilience (e.g. poor water quality including nutrients, sediments and other pollutants; pest species such as COTS) and what management strategies can support resilience of vulnerable ecosystems (e.g. new water quality guidelines and targets, COTS control programs).

Numerous NESP projects contributed to the improvement of GBR monitoring through: a) identification of additional indicators for monitoring programs required to populate cumulative risk maps (such as reef state and reef performance), b) new cost-effective indicator based on benthic light (I_{bPAR}), c) detection of relevant observational gaps required for bleaching prediction tools, d) identification of reef recovery rates through a new Resilience-based Management system and using carbonate budgets, and e) identification of priority species for inclusion in monitoring and surveillance based on key ecological functions.

This synthesis includes the results of 5-years of research delivered by over 30 scientists with vast experience in catchment, coastal and GBR research and management. Where relevant, it summarises the previous work of many agencies who have actively engaged in research and management of the GBR and adjacent ecosystems, including GBRMPA and Queensland State government. NESP funding has supported access to state-of-the-art technologies and methods and research projects have benefited from the coordination of the TWQ Hub by the Reef and Rainforest Research Centre (RRRC), as well as previous research programs over the past 25 years.

The substantial NESP TWQ Hub investment in research activities across various topics related to improving coral reef resilience, and linkages across projects provides an opportunity to understand the current state of knowledge and a perspective on future resilience needs. This synthesis brings together the learnings from these various research projects to inform reef managers, scientists and other stakeholders on the efforts underway to ensure coral communities and reef ecosystems are resilient for the future in the face of global warming and ocean acidification. The report also outlines how the information can be applied to practical management of the GBR and other connected reef systems in Australia.

1.0 INTRODUCTION

1.1 NESP Tropical Water Quality Hub

The Australian Government, through the National Environmental Science Program (NESP), has funded $145 million of research effort on environmental and climate science from 2015 to 2021. All NESP-funded projects focused on generating practical and applied research to improve environmental management decision-making processes. The program builds on its predecessors (the National Environment Research Program (NERP), the Australian Climate Change Science Program (ACCSP), the Marine and Tropical Science Research Facility (MTSRF), and the Cooperative Research Centre for Ecologically Sustainable Development of the Great Barrier Reef (CRC Reef)) undertaken to support better understanding, management and conservation of Australia's environment (Department of Agriculture Water and the Environment (DAWE), 2020).

The Tropical Water Quality (TWQ) Hub[1] was one of six multi-disciplinary research hubs within NESP, investing AU$31.98 million on delivering innovative research to maintain and improve tropical water quality from catchment to reef (NESP, 2020), mainly on the Great Barrier Reef and adjacent tropical waters. It was structured into three main themes: Theme 1: Improved understanding of the impacts, including cumulative impacts, and pressures on priority freshwater, coastal and marine ecosystems and species; Theme 2: Maximize the resilience of vulnerable species to the impacts of climate change and climate variability by reducing other pressures, including poor water quality; and Theme 3: Natural resource management improvements based on sound understanding of the status and long-term trends of priority species and systems. Thus, research projects within the hub covered a wide spectrum of fields, from genes to ecosystems (e.g. reef water quality improvements and management in the Great Barrier Reef -GBR- catchment), including a better understanding of pest species such as the coral-eating crown-of-thorns starfish (COTS) and box jellyfish, species of conservation interest such as dugongs and marine turtles and habitats such as coral reefs and seagrasses. The TWQ Hub also had a strong focus on cumulative impacts and climate resilience, while building indigenous connections and capacity in management of Queensland sea country.

The NESP TWQ Hub was delivered through a collaborative, multi-disciplinary research network composed of six leading Australian universities and research institutions, including the Australian Institute of Marine Science (AIMS), James Cook University (JCU), Commonwealth Scientific and Industrial Research Organisation (CSIRO), Central Queensland University (CQU), University of Queensland (UQ) and Griffith University (GU), coordinated through the Reef and Rainforest Research Centre (RRRC). These partner institutions have collaborated for over 20 years and have established an extensive network of research end-users, including government, industry, NGOs, Indigenous groups and other community groups. The partners contributed to the Hub through co-funded research programs (e.g. in-kind contributions to specific projects through staff expertise or research facilities and resources), and contributed to the success of the TWQ Hub while fostering partnerships across the other Hubs and with a wide range of relevant stakeholders. This synthesis, therefore, collates the results of 5-years of research by over 30 scientists with vast experience in catchment, coastal and GBR research

[1] https://nesptropical.edu.au/

and management. NESP TWQ Hub research built on 40 years of targeted research on catchment, coastal and reef ecosystems by many agencies, universities and institutions.

This report is one in a series of technical reports designed to synthesise the findings of NESP TWQ Hub research on topical issues most relevant to policy and stakeholder groups. These include: Improving coral reef condition through better informed resilience-based management (this report; Pineda & Johnson, 2021), innovations in crown of thorns starfish control on the GBR (Erdmann et al., 2021), reducing end of catchment fine sediment loads and ecosystem impacts (Pineda & Waterhouse, 2021), overcoming barriers to reducing nitrogen losses to the GBR (Waterhouse & Pineda, 2021), restoring ecosystems from catchment to reef (Pineda et al., 2021), influencing agriculture practice behaviour change and trust frameworks (James, 2021), and learnings from applied environmental research programs (Long, 2021). The reports are supported by individual project research publications, in addition to several targeted case studies and fact sheets accessible through a dedicated website[2].

1.2 Current Reef resilience-based policy and management directions

The GBR World Heritage Area (GBRWHA) status was recently described as 'Critical' and following a 'deteriorating' trend by the IUCN World Heritage Outlook (Osipova et al., 2020). Within this context, resilience-based management and integrated monitoring and reporting through the Reef 2050 Integrated Monitoring and Reporting (RIMRep) Program are key initiatives for managing the GBR ecosystem and contribute to enhancing inherent resilience (GBRMPA, 2015). The RIMRep underpins the Reef 2050 Long-Term Sustainability Plan (Reef 2050 Plan) management approach, allowing early detection of trends and changes in Reef environments and enabling timely and adaptive management processes. Other key policy and management instruments that highlight the need to restore Reef resilience include the most recent Outlook report (GBRMPA, 2019) and the Reef 2050 Water Quality Improvement Plan (Commonwealth of Australia, 2018) underpinned by the 2017 Scientific Consensus Statement (Waterhouse et al., 2017). Numerous projects across the NESP TWQ Hub focused on resilience-based management and decision-making for maintaining and improving coral reef condition in the GBR. Most of the research underlying these projects was a direct response to the 2016-17 mass bleaching events and has contributed significantly to the goals outlined in the Great Barrier Reef Blueprint for Resilience (GBRMPA, 2017). This synthesis, therefore, brings together the learnings of multiple research projects and initiatives driven by the same goal of building the resilience of the GBR to current and future disturbances.

As climate change becomes the dominant driver of GBR coral reef health outcomes, there is recognition that major disturbance events (e.g. mass thermal bleaching and severe cyclones) will become more frequent, placing extra pressure on the ability of coral reefs to recover. As Reef managers cannot directly act upon the drivers of climate change, it is important to maintain and enhance reef resilience and to focus management efforts on priority reefs and habitats which best support the GBR's ecological, social, economic, cultural and heritage values. The Great Barrier Reef Blueprint for Resilience (GBRMPA, 2017) states that building resilience at local, regional and reef-wide scales is important for the long-term health of the GBR. In order to build this resilience, the Great Barrier Reef Marine Park Authority proposes to enhance the use of existing tools and trial new approaches and technologies such as the

[2] https://synthesis.nesptropical.edu.au/

implementation of an integrated COTS control program, strengthening compliance with regulations, enhancing protection of key species for reef recovery, and testing and deploying methods for reef restoration. For those changes to take place, policies need to be adapted and reliable evidence-based information is required to support new decision systems and inform future-focused adaptive, resilience-based management.

Research funded through the NESP TWQ Hub focused on enhancing resilience and resilience-based decision-making, included the study of the relationship between water quality and bleaching risk; the functionality and management of key species within the GBR; the spatial variability of thermal stress and bleaching; methods for coral restoration; the identification of traits of coral that have survived bleaching; and the development of a resilience-based decision-making tool for marine park managers. Additionally, as investments in research to support water quality improvements and projects related to enhanced monitoring and reporting (RIMRep) are relevant to this synthesis, they were also incorporated here along with related projects conducted through other research programs and published over the last five years. This synthesis report therefore provides a summary of NESP TWQ funded projects (and other relevant sources), and how the results align with or build on existing knowledge and management approaches from the peer-reviewed and grey literature.

There has been a lot of research activity across various topics related to improving coral reef resilience, with many linkages and synergies between projects. This synthesis brings together the learnings from these varied research projects to inform reef managers, scientists and stakeholders on the efforts being made to ensure coral communities and reef ecosystems are resilient for the future in the face of global warming and ocean acidification. It also outlines how the information can be applied to practical management of the GBR and other connected reef systems in Australia.

2.0 NESP TWQ HUB RESEARCH HIGHLIGHTS

2.1 State of the GBR and drivers of change

The Great Barrier Reef is a global natural wonder and asset, declared a Marine Park in 1975 and listed as a World Heritage Area in 1981 due to its outstanding universal value (UNESCO). Many values and the overall function still endure but signs of deterioration are increasingly observed. The latest AIMS long-term monitoring results show that while hard coral cover increased slightly in the Central and Southern GBR between 2019 and 2020, cover remained low to moderate in all regions and no increase was observed in the Northern GBR (AIMS LTMP)[3]. This continues a long-term trend of low coral cover, and shorter disturbance and recovery cycles on reefs as the GBR faces significant pressures from climate change, tropical cyclones, predation by COTS and other anthropogenic threats. The Great Barrier Reef Marine Park Authority stated in the most recent Outlook Report (GBRMPA, 2019) that 'Australia is caring for a changed and less resilient Reef', and reinforced the need to restore Reef resilience through mitigating climate change and the effective implementation of the Reef 2050 Long-Term Sustainability Plan (Commonwealth of Australia, 2015).

Threats to the GBR are multiple, cumulative and increasing (GBRMPA, 2019). The main drivers of change in the Region are climate change, severe cyclones, COTS predation, land-based run off and direct extractive uses (i.e. fishing). How these drivers interact to impact on GBR ecosystems is not well understood but emerging evidence shows that multiple stressors can have additive as well as synergistic impacts on coral reefs. Among them, climate change is the biggest long-term threat to coral reefs worldwide, due to the impacts of increasing sea temperatures, altered weather patterns, ocean acidification, more frequent severe storms and sea level rise. Global action would be required to slow deterioration of coral reef ecosystems and to support their resilience and recovery to future variability and change.

Increasing sea surface temperatures and marine heatwaves caused successive coral bleaching events on the GBR in 2016 and 2017, followed by widespread coral loss and flow-on effects to ecosystem structure and function (GBRMPA, 2019). The spatial footprint and duration of extreme accumulated heat stress and levels of severe bleaching and coral mortality were greater during the 2016 and 2017 bleaching events than previous events. This spatial variability was reflected in the location of the most severely impacted coral reefs along the GBR from north to south. After the back-to-back bleaching events of 2016 and 2017, 45% of total reef area had been exposed to extreme heat stress (degree heating weeks > 8), with 51% of reefs at this level of heat stress experiencing coral community impacts (Cantin, Klein-Salas, et al., 2021). The Region's key habitats have an inherent resilience to acute physical disturbances, such as tropical cyclones, however, climate-driven events are exacerbating both acute and chronic disturbances, reducing recovery periods and limiting resilience capability (GBRMPA, 2019). Therefore, while action at a national level and targets to mitigate and adapt to climate change are essential, a strong focus on the development of reef resilience in the face of a variable and changing climate is also required (Commonwealth of Australia, 2015).

Crown-of-thorns starfish (COTS) are predators of hard coral and are one of the most significant threats facing the GBR (for a complete synthesis on NESP TWQ hub research on COTS, see

[3] https://www.aims.gov.au/docs/research/monitoring/reef/latest-surveys.html

Erdmann et al., 2021). An outbreaking COTS population is estimated to be capable of consuming 0.18% of hard coral biomass per day on an average reef, with significant coral loss occurring when densities climb beyond 1000 individuals/km^2 (Westcott et al., 2016). COTS control is therefore considered an important local management action that can improve the health and resilience of coral reefs.

Poor water quality, mostly due to land-based run-off from adjacent catchments (i.e. nutrients, fine sediments and pesticides associated with agricultural industries), is another major driver of change within the GBR (see synthesis in Pineda & Waterhouse, 2021 and Waterhouse & Pineda, 2021). Despite modest improvements in water quality on a regional scale due to changing agricultural land management practices (e.g. such as the Smartcane and Grazing Best Management Practices), poor water quality continues to affect inshore areas of the GBR (GBRMPA, 2019). Poor water quality can directly impact reefs through smothering and enhanced competition between coral and macroalgae as well as inhibiting resistance to thermal stress and recovery from disturbances (Waterhouse et al., 2017). Indicators of water quality have been found to be predictive of changes in coral community resilience that are not explained by acute impacts of storms, coral bleaching events or COTS outbreaks (Thompson et al., 2020). Therefore, water quality improvements are essential to support ecosystem resilience.

The Reef 2050 Water Quality Improvement Plan 2017-2022 (Commonwealth of Australia, 2018), underpinned by the 2017 Scientific Consensus Statement (Waterhouse et al., 2017), was designed to establish the guidelines and policies required to improve the quality of water entering the GBR. In order to meet the recommended water quality targets (i.e. 60% reduction in nitrogen, 20% reduction in nutrients and 25% reduction in fine sediments loads by 2025), some measures including improvements to governance (i.e. more adaptive, participatory and transdisciplinary approaches), program design and delivery and evaluation systems were deemed as urgently needed (Waterhouse et al., 2017). However, the annual Reef water quality report cards, which detail progress against the Reef Water Quality Improvement Plan targets at an NRM scale, show that the overall condition of the inshore marine environment (water quality, seagrass and coral) remains moderate to poor[4].

Overall, most habitats within the GBR are considered to be in poor condition due to the habitat loss and degradation, substantially affecting populations of species that depend on these habitats (but see Pineda et al., (2021) for a synthesis in ecosystem restoration). For example, coral reef habitats have been impacted by coral bleaching, cyclones and COTS outbreaks, although the level of impact varies within the Region. Some species are also under significant threat and are considered to be in a *poor* to *very poor* condition, mostly as a result of historical commercial harvesting (e.g. dugongs and turtles) and other current impacts (e.g. rising sea temperatures, unsustainable fishing) (GBRMPA, 2019). The overall ecosystem condition has also been deteriorating in the past years. For instance, record high sea temperatures in 2016 and 2017 have resulted in significant negative effects in important ecological processes such as symbiosis and reef building. Outbreaks of disease (e.g. white syndrome disease), introduced species and pest species (e.g. COTS outbreaks, synthesized in Erdmann et al., 2021) have also increased recently. As a result of all the above cumulative impacts, the overall trend for coral reef habitats within the Region is one of long-term decline, as the natural

[4] https://reportcard.reefplan.qld.gov.au/

ecosystem resilience within the GBR might not be sufficient to bounce back from repeated and more frequent disturbances (GBRMPA, 2019).

Hence the urgency to support ecosystem resilience in the face of a variable and changing climate, which is the key principle of the Reef 2050 Long-Term Sustainability Plan (Commonwealth of Australia, 2015). By reducing the impacts of COTS, improving water quality, maintaining biodiversity, and ensuring port-development and shipping have minimal impacts on the GBR, the Plan is building the GBR's resilience. Additionally, increased investment in management of the GBR since 2014 has enabled the delivery of significant protections and tangible actions through the *Reef Blueprint for Resilience* (GBRMPA, 2017) and the *Reef 2050 Water Quality Improvement Plan* (Commonwealth of Australia, 2018), setting the framework for improved resilience-based management and protect values (GBRMPA, 2019). The research synthesised in this report will further facilitate the development and implementation of resilience-based management strategies to ensure a positive future for the GBR.

2.2 Science supporting resilience-based reef management as an emerging priority

The National Environmental Science Program (NESP, 2015-2021) built on predecessor national programs: National Environmental Research Program (NERP, 2011-2015), Commonwealth Environmental Research Facilities (CERF, 2005-2011), including the Marine and Tropical Sciences Research Facility (MTSRF) program administered by the Reef and Rainforest Research Centre (RRRC), and the Australian Climate Change Science Programme (ACCSP, 1989-2016). Additional collaborative research in the GBR funded by the Australian Government previous to 2006 was led by The Cooperative Research Centre for the Great Barrier Reef World Heritage Area (CRC Reef) (1999-2006) and contributed to creating the basis for topics such as water quality monitoring, COTS and box jellyfish research, impacts of ports and shipping, global warming and climate change effects and Torres Strait marine research. The knowledge regarding coral reef condition and resilience-based management previous to the NESP TWQ Hub is summarized in Appendix Table A1.1:.

Overall, the precursor programs contributed to a better understating of the general health and future trend of the Great Barrier Reef (De'ath et al., 2012; Miller & Sweatman, 2013), described the effects of protection measures such as zoning (Ryan, 2015) and made significant contributions towards establishing appropriate monitoring programs for both ecosystem health and water quality across the Region including the Torres Strait (Delean & De'ath, 2008; Waterhouse et al., 2013).

Numerous projects contributed to establishing the foundation for understanding the effects of cumulative impacts from climate change (i.e. high temperature, ocean acidification, low salinity; (Maynard et al., 2011; Mongin et al., 2016; Vogel et al., 2015) and poor water quality (i.e. high turbidity, sedimentation, high concentration of nutrients; (Devlin & Negri, 2015; Logan et al., 2014a; Waterhouse, 2010; Waterhouse & Brodie, 2011)) on the condition of coral reefs. Importantly, a link was established between poor water quality and ecosystem resilience to climate change and therefore initial thresholds and guidelines were provided in order to manage the GBR for resilience (Johnson & Martin, 2011; Wooldridge, 2009). Additional research investigated the potential of corals and their symbionts to adapt to warmer waters associated with future climate change scenarios (Hughes, 2010; Maynard et al., 2008). The concept of 'Adaptive Resilience-based management' is more recent (Anthony et al., 2015) and has become a key foundation for several management strategies and policies within the Region (Commonwealth of Australia, 2015; GBRMPA, 2015, 2017, 2019).

Despite the success of earlier programs, knowledge gaps were identified in key fields such as water quality and cumulative impacts, including: (i) fine sediment delivery from activities such as dredging and potential effects in light availability for GBR ecosystems, (ii) pesticide uses, pathways, thresholds and potential alternatives, (iii) better understanding of cumulative impacts to develop measurable climate and regionally adjusted water quality targets and cumulative impact guidelines, (iv) assessing the potential of acclimation and adaptation to cumulative impacts, (v) COTS ecology and movements to underpin integrated management programs (Devlin et al., 2015).

2.3 NESP research progressing reef resilience understanding

NESP TWQ Hub investments have investigated enhanced resilience and resilience-based decision-making through a variety of projects. These include examining the relationship between water quality and bleaching risk; identifying the function of important species on the GBR and how they are connected and managed; understanding spatial variability of thermal stress and bleaching; trialling methods for coral restoration; and identifying the traits of corals that have survived bleaching (Figure 1). The NESP TWQ Hub has also invested in developing a resilience-based decision-making tool for marine park managers. A summary of NESP-funded research on coral reef resilience is provided in Appendix Table A1.2:

2.3.1 Cumulative impacts affecting coral reef resilience in the GBR and adjacent waters

The GBR is affected by multiple local and global stressors, from tropical cyclones, point source pollution (i.e. nutrients, pesticides, turbidity) (Pineda & Waterhouse, 2021; Waterhouse & Pineda, 2021) to global climate change (i.e. increased water temperature) and associated bleaching events (Figure 2). Frequent outbreaks of pest species such as the COTS (Erdmann et al., 2021) or other direct uses such as tourism and fishing are an additional threat to reef condition. While considerable research through MTSRF and NERP investigated these impacts, there were still significant gaps in understanding regarding how multiple stressors interact in time and space, thus reducing the overall health and resilience of the reef (Anthony, 2016; Mellin et al., 2019).

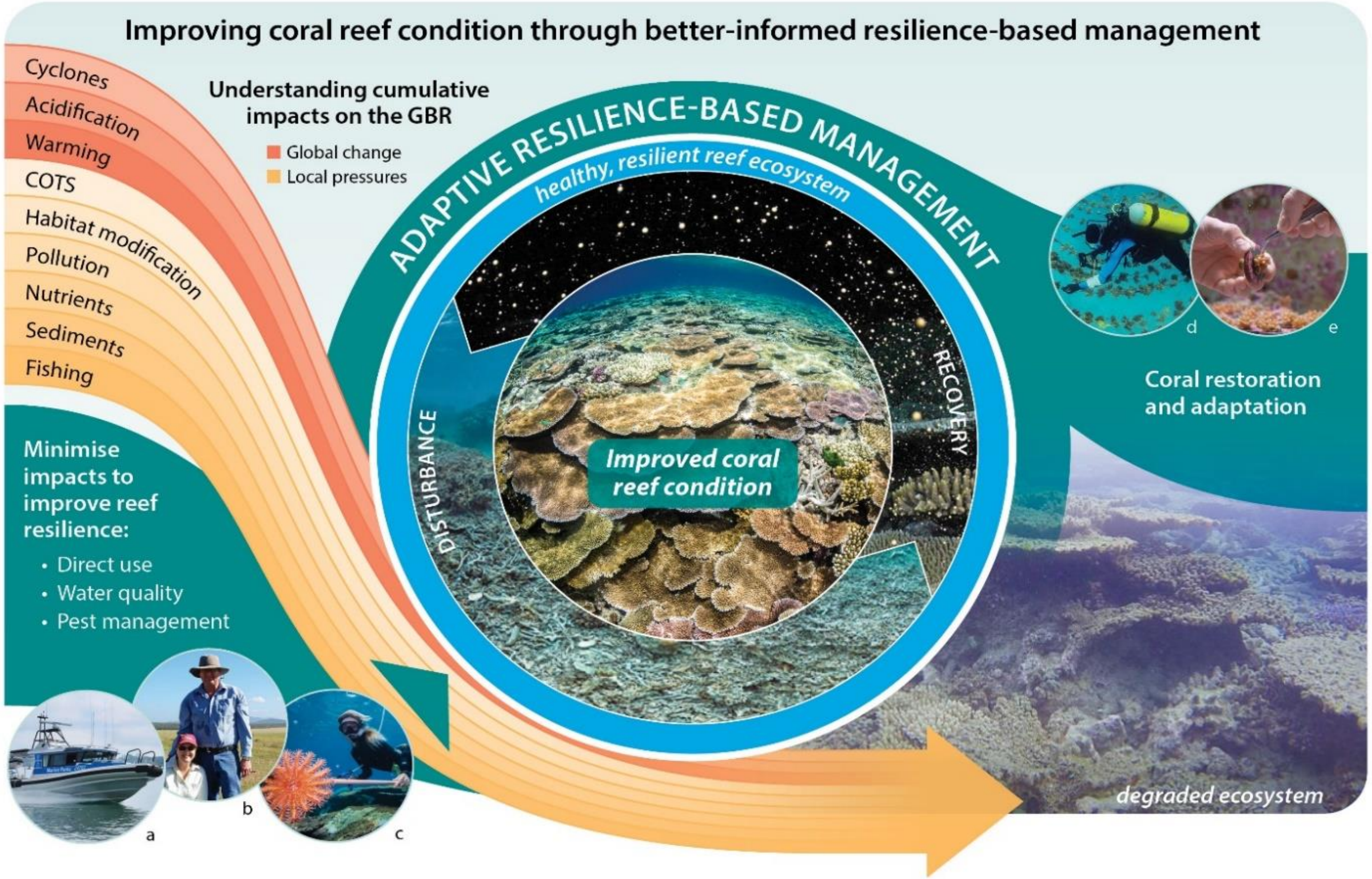


Figure 1: Summary diagram of processes impacting on coral reef condition and how adaptive resilience-based management can influence ecosystem outcomes. (a) GBRMPA's high speed patrol vessel, Reef Sentinel [Photo: GBRMPA]; (b) Landholders Catherine and Neil Simmonds, revegetating their land to help prevent, reduce and reverse erosion damage [Photo: Greening Australia]; (c) COTS control on the GBR [Photo: SMH]; (d) Corals growing in a rope nursery for restoration [Photo: Mia Tranthem/Science]; (e) Researcher at the AIMS National Sea Simulator preparing coral samples for experiments aimed at improving the resilience of reefs to warming seas [Photo: Cameron Laird]; [Disturbance Image, by Matt Curnock; Recovery Image, by Peter Harrison/SCU; Improved coral reef condition imagen, by Matt Curnock/Coral Reef Image Bank; Degraded ecosystem image, by Andreas Dietzel].

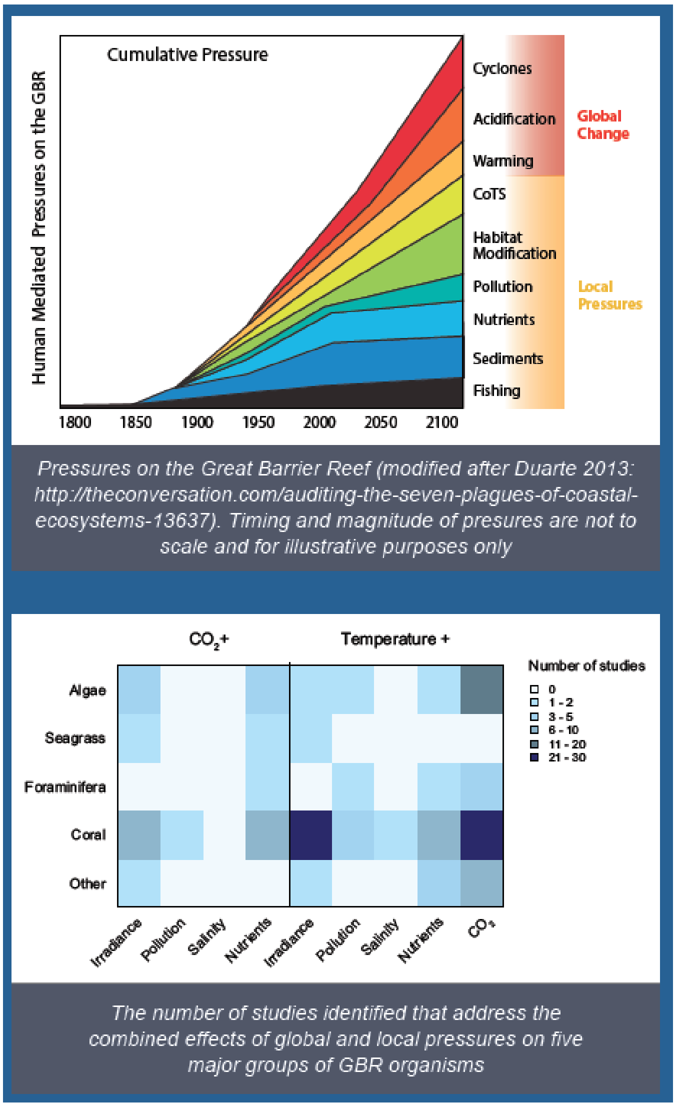


Figure 2: Cumulative pressures on the GBR (top) (modified from Duarte 2014 in The Conversation, https://theconversation.com/auditing-the-seven-plagues-of-coastal-ecosystems-13637) and number of studies identified for the combined global versus local pressures on five major groups of GBR organism (bottom). Source: Uthicke et al., (2020).

The findings of Wiedenmann et al., (2012) demonstrate how nutrient imbalances increase coral susceptibility to thermal stress and have implications for management as global warming begins to manifest. NESP research further examined these interactions, initially with a review of case studies that investigated cumulative impacts of global and local pressures on coral reef organisms (Uthicke et al., 2016). The review found that there are important interactions between some variables such as ocean acidification and salinity, and ocean acidification and pollution that remain relatively unstudied (Figure 2) (Uthicke et al., 2016). The review recommended greater focus on understanding the interactions between pressures that managers can influence, specifically light/turbidity and sediment-bound pollutants (including nutrients), and ‘global’ pressures such as ocean acidification and ocean warming that are outside the influence of local managers, and provided a list of research topics to prioritise and guide subsequent projects (Uthicke et al., 2016).

Laboratory experiments testing the interaction between water quality and climate change

In order to develop effective ecosystems models and management strategies, several NESP projects focused on developing pressure thresholds and levels of interactions for cumulative impacts affecting the GBR. With that purpose, experimental / laboratory studies are the best approach as they allow accurate control of most variables and appropriate experimental designs. Experimental assessments of concentration-response relationships for selected habitat-builder organisms (i.e. corals, seagrasses, macroalgae and foraminifera) under local stressors (sediments and/or herbicides) and different climate scenarios were performed at the AIMS National Sea Simulator (SeaSim) (Uthicke et al., 2020). While responses depended on the organism and stress variable, the combined stressors created an overall worse outcome for most organisms than single stressors. For example, the effects of nutrient enrichment and elevated water temperature on several life history stages of the coral *Acropora tenuis* showed an additive impact on fertilization, thus affecting the overall larval supply and recruitment success (e.g. <50 % survival at 30 °C and 'medium' nutrient enrichment) (Figure 3; Humanes et al., 2016).

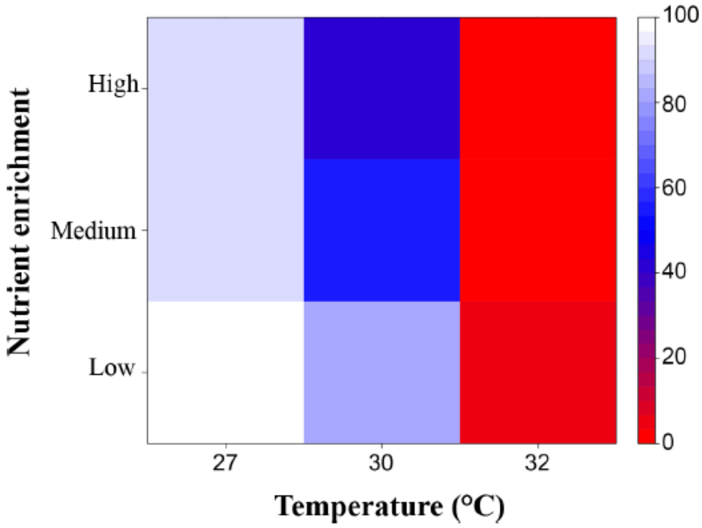


Figure 3: Combined effect of nutrient enrichment and water temperature on recruitment success of the coral *Acropora tenuis.* Scale represents the percentage of survivorship. Source: Humanes et al. (2016).

The results of this research highlighted the need to adjust water quality guidelines to take into account projected increasing ocean temperatures in the future (Figure 4). An adapted version of the 'multistressor-Potentially Affected Fraction' (ms-PAF) method to include non-chemical stressors (thermal stress) and develop 'climate adjusted thresholds' was applied for two reference toxicants, copper and the herbicide diuron, for tropical marine species. The combination of stressors predicted that more species would be affected by contaminants as ocean temperatures increase. For example, the concentration at which 95% of the species are protected (PC95) for diuron would need to be adjusted from 0.67 µg L^{-1} to 0.59 µg L^{-1}, while the PC95 for copper would require adjustment from 1.4 to 0.90 µg L^{-1} under a 1°C temperature increase (Figure 4). The approach could be extended further to other stressors such as sediment exposure, low salinity, light limitation, anoxia and ocean acidification to advance more comprehensive environmental guidelines, reporting and assessing the risk posed by multiple stressors (Negri et al., 2019; Negri, Smith, et al., 2020; Uthicke et al., 2020).

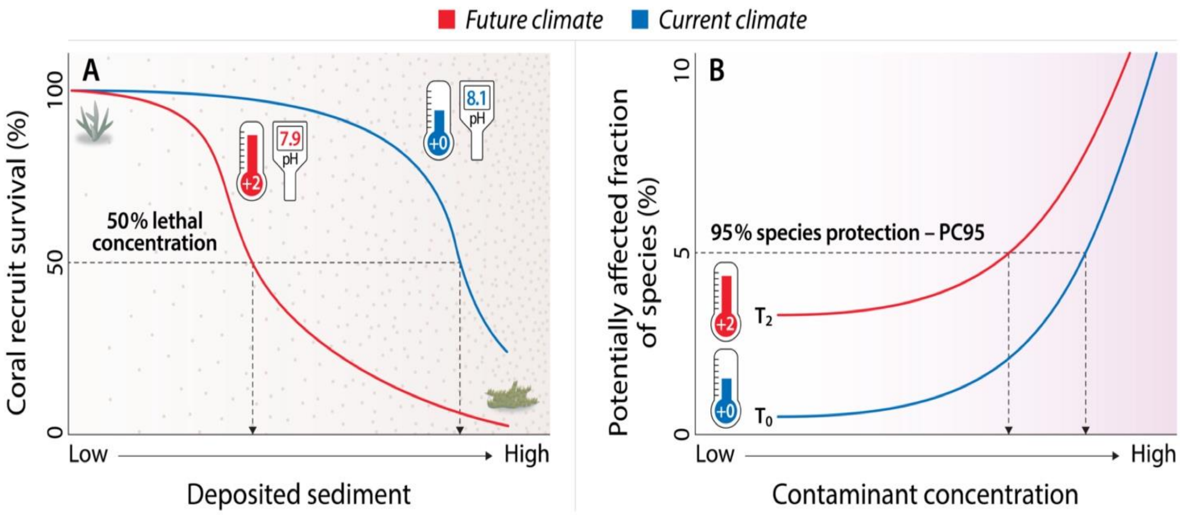


Figure 4: Cumulative impacts of local and global pressures, illustrating the influence of climate on thresholds for ecological processes. A) Sediment impacts on coral recruitment under present day and future climate (temperature and ocean pH). B) Effect of contaminants on species sensitivity using the multi-stressor Potentially Affected Fraction (ms-PAF) method, under current (blue line; ambient temperature) and future (red line; + 2 °C elevated temperature) climate conditions. Note that 50% lethal concentration (A) and PC95 guideline concentration values (the levels at which 95% of all species are protected) (B) reduce under future climate conditions. Source: Brunner et al., (2020); Negri, Templeman, et al., (2020); Uthicke et al., (2020).

Targeted research funded after the 2016 bleaching event quantified the linkages between water quality and the thermal tolerance of corals, specifically their ability to resist and recover from bleaching events, such as those experienced in the GBR in 2016 and 2017 (Cantin, Klein-Salas, et al., 2021; Cantin, Baird, et al., 2021). Aquaria experiments at the SeaSim facility identified the water quality parameters (i.e. nutrients, light, turbidity) that affect coral thermal tolerance and how water temperature and water quality exposure histories influence bleaching susceptibility and recovery. For instance, inshore corals had a lower bleaching response in experimental conditions, with less than a 50% decline in photosynthetic pigment content at high temperature, whereas the mid-shelf corals lost around 75% of pigments (Cantin, Baird, et al., 2021). A literature review identified that water quality is likely to influence coral health mostly through the cascade effects caused by excess nutrient availability (specifically increases in nitrogen:phosphorous ratios), which causes the shift of symbiont algae from a mutualistic to a parasitic relationship. The study concluded that stable metabolic compatibility between the coral host and algal symbiont could ameliorate bleaching and increase resistance to environmental stress. Furthermore, historical nutrient conditions may influence host-symbiont metabolic capability, and therefore bleaching susceptibility (Morris et al., 2019). However, additional field studies and experimental research, showed that temperature is the major driver of coral bleaching nowadays, and that the effect of different water quality regimes was only evident at lower heat exposures, below the temperature increases experienced during recent bleaching events in 2016 and 2017. It was concluded that if oceans continue to warm, corals will increasingly experience significant heat stress at an intensity that is currently masking acute water quality effects (Cantin, Baird, et al., 2021).

Field studies and naturally occurring cumulative impacts

Field studies can also contribute to a better understanding of cumulative impacts occurring in the environment and the inherent ability of the reef to recover (i.e. reef resilience). For example, Prof Jones' team focused on long-term monitoring (from 2004 to 2015) of coral and fish communities in the Keppel Islands (southern GBR) to assess reef resilience based on marine zoning and protection status (closed versus fished reefs) (Williamson et al., 2016). The study documented significant declines in live hard coral cover and fish abundances after experiencing cumulative pressures in preceding years (e.g. coral bleaching event, flood plume and a category 5 cyclone), despite the protection status. However, a small percentage of reefs (ca. 13%) remained relatively healthy by 2015 (i.e. with at least 45% cover of live hard coral) and were identified as 'key' refugia. These refugia reefs provide important genetic stores of biodiversity, and can contribute to the replenishment and recovery of degraded reefs through larval supply. Field data additionally supported risk analyses, exposure maps and the development of spatial resilience models along the GBR under cumulative disturbance impacts (Mellin et al., 2019; Uthicke et al., 2020).

Another project assessed the oceanographic drivers of bleaching in the GBR and Torres Strait, with the main goal of developing more accurate predictive tools in space and time, which can lead to better management outcomes for coral reefs. The project contributed to the identification of additional potential key refugia reefs, which were not as severely affected by bleaching, and linked those with regions of persistent cold-water upwelling and intrusions. Additionally, a seasonal prediction capability tool was developed to assist GBR managers identify marine heatwaves, hence prioritising intervention on those reefs at higher risk of bleaching (Steinberg et al. in review).

Contaminants of emerging concern

Most of the previous research and current policy and management strategies for GBR water quality focuses on suspended sediments, nutrients and PSII herbicides (synthesised in Pineda & Waterhouse, 2021; Waterhouse & Pineda, 2021). Although other contaminants are known to be present in the environment (such as alternate pesticides, antifouling paint components, coal particles, petroleum hydrocarbons, heavy/trace metals and metalloids, nanomaterials, marine debris including microplastics, pharmaceuticals and personal care products), little is known about their sources, role and fate in the GBR and Torres Strait regions. A project to assess the risks of emerging contaminants in the GBR and Torres Strait provided a list of priority emerging contaminants for future research investment (Kroon et al., 2015; Kroon, Berry, et al., 2020). The study determined that marine plastic pollution poses the highest risk to marine ecosystems, particularly in the Cape York and Torres Strait regions due to exposure to oceanic and shipping sources. Chronic contamination of water and sediments by antifouling paints and exposure to personal care products (such as the UV filter benzophenone-3) to marine ecosystems were other important risks which require further research. Additional proposed research included the effect of cumulative impacts of emerging contaminants with ocean acidification and increasing sea temperatures as the two highest risk pressures on the GBR (Kroon et al., 2015; Kroon, Berry, et al., 2020).

Effects of cumulative pressures on ecosystem connectivity

The GBR is part of a wider ecosystem, connected with adjacent systems that collectively form the northeast Australian seascape, which also includes the Torres Strait, Coral Sea and Great Sandy Strait (Johnson et al., 2018a). The shared natural values of this region support healthy ecosystems that include coral reefs, inter-reefal habitats, estuarine and tidal habitats, seagrass meadows, mangroves and pelagic open water habitats. Ocean currents are the major mechanism that connects values across these areas, for example, by facilitating larval dispersal and transporting water properties from one area to another. Therefore, connectivity within the northeast Australian seascape is important for maintaining larval connectivity with source reefs that are natural refugia from regional and global pressures, providing a mechanism for recovery in areas affected by marine heatwaves or other pressures (Hock et al., 2017). However, changes in ocean currents expected in the coming decades (e.g. projected weakening of the top 50 m of the East Australian current) may impact the connectivity within the region, potentially impacting larval supply, recovery and ultimately resilience (Johnson et al., 2018a).

Additional cumulative pressures affecting coral reefs across the northeast Australian seascape were identified and ranked as high priority for future cross-jurisdictional planning and management, including flood events (i.e. reduction in pollutants delivered via river discharges), chemical/oil spills (i.e. shipping accidents) and dredging (noting that the current regulatory regime for capital and maintenance dredging includes cross-jurisdictional planning and management) (Table 1; Johnson et al., 2018a). Some cumulative pressures that effect keystone species can influence multiple jurisdictions due to their connectivity, such as the potential impact of poor water quality or marine heatwaves on the pelagic stages of species or coral health in source reefs (Table 1). Therefore, understanding the attributes that are affected by different pressures and how these cumulative threats can influence multiple jurisdictions is an important consideration for cross-jurisdictional management in order to effectively minimise the threats and maintain reef resilience within the entire northeast Australian seascape (Johnson et al., 2018a).

Table 1: Summary of priority threats that would benefit from improved coordination of management and the attributes they influence. Source: Johnson et al., (2018a).

	Attributes								
Threat	Hard corals	Seabirds	Turtles & dugong	Ornate rock lobster	Beche de mer	Spanish mackerel	Yellowfin tuna	Sharks	*Pisonia grandis*
Flood events	Major	Major	Major		Major	Lesser			
Chemical/oil spills	Major	Major	Major	Major	Major				
Dredging	Major	Major	Major	Major	Major				
Fishing		Major		Major	Major	Major	Major	Major	
Pathogens/disease outbreak	Lesser	Major	Lesser	Lesser	Lesser			Lesser	Major
Loss of food source		Major	Lesser	Lesser	Lesser	Lesser			Lesser
Pest outbreaks	Lesser	Major		Lesser	Lesser				Major
Regulation change		Major				Major	Major	Major	Major
Recreational use		Major		Major		Major			
Agriculture	Major	Major			Major				
Loss of natural habitat	Lesser	Lesser			Major				Major
Traditional hunting				Major	Major	Major			
Wildfires		Major	Major						Major
Loss of Traditional & Cultural Knowledge			Major			Major			Major
Ship grounding	Major	Major	Major						
Drought		Lesser			Lesser	Major			Lesser
Economic stress			Lesser	Major		Lesser	Lesser		
Mining & mineral processes	Major	Major							

Legend

Highest priority for inter-jurisdictional coordination	
Medium priority for inter-jurisdictional coordination	
Major benefit from improved management of threat	
Lesser benefit from improved management of threat	

Effects of cumulative pressures on ecosystem function

Cumulative pressures such as those identified above also threaten key functions of the GBR, including for habitats (e.g. reef growth) and production (e.g. fisheries). While biodiversity conservation is a core management strategy, a subset of species might be critical to maintain and/or facilitate ecosystem functioning. Wolfe et al., (2019) focused on how to preserve key species' functions through: (i) identifying species that play critical roles in the GBR and assessing their vulnerability and manageability, and (ii) making recommendations for management which supplement current measures of broader-scale habitat protection, such as marine park areas. The study outlined a diversity of key species, including branching and tabular corals, microorganisms, crustose coralline algae, turf algae, COTS (and triton snails), and herbivorous parrotfishes, and recommended additional efforts on the conservation and monitoring of these key taxa (Figure 5) (Frade et al., 2020; Wolfe et al., 2019). Additional novel taxa which might benefit from specific consideration in management initiatives included chemoautotrophic microbes, cleaner wrasse, bivalves, coral-associated decapods, and detritivores fishes (Figure 5). A third group identified as potentially relevant associated with their roles in ecosystem functioning and vulnerability had lower scientific certainty and were recommended for further research (i.e. cryptic predators, deposit-feeding sea cucumbers, marine worms, cryptic sponges and crustaceans). The study concluded that although there is opportunity to increase monitoring and novel management and science approaches, the current initiatives seem to effectively capture key groups with overall benefits to reef function (Wolfe et al., 2019). The information provided on key reef species was used to inform the analyses of reef resilience and identification of ecologically valuable reefs in a related project (Wolfe et al., 2019).

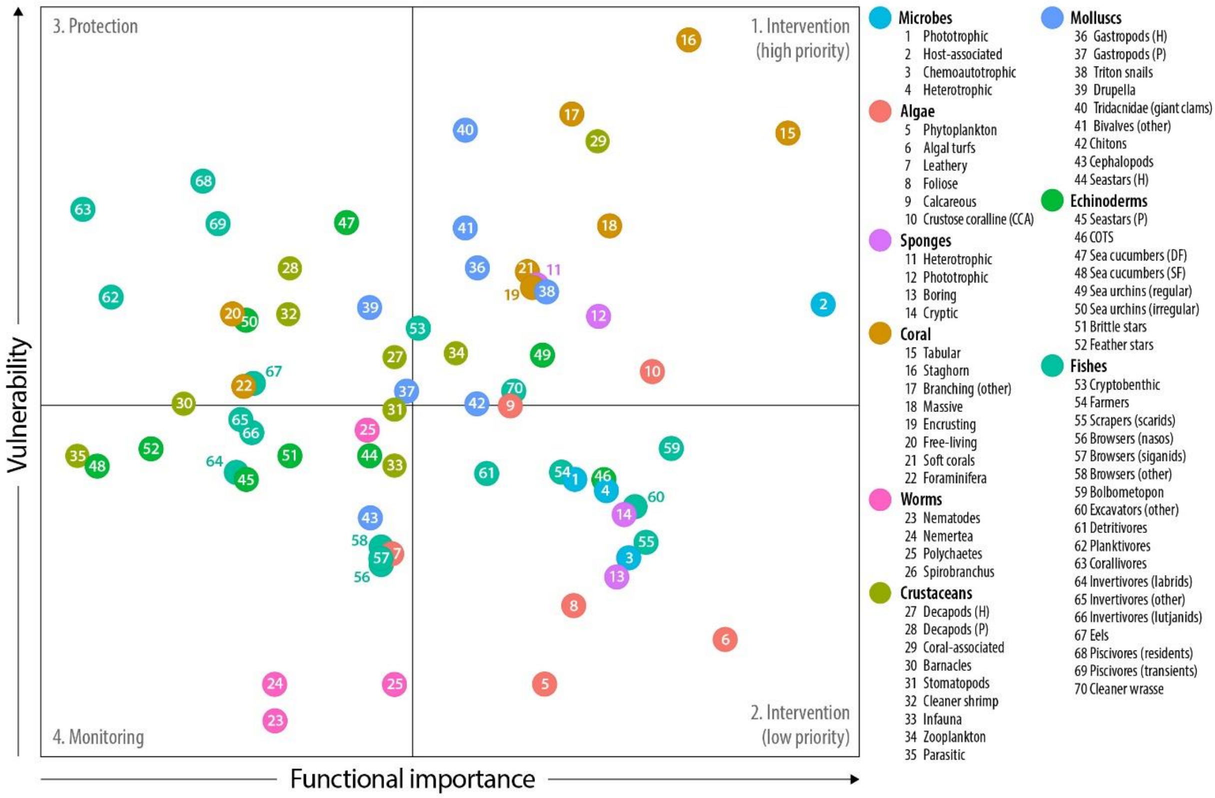


Figure 5: Functional importance and vulnerability of 70 functional groups common to the GBR coloured by phyla. Modified from: Wolfe et al., (2019).

2.3.2 Building reef resilience

As a complex ecosystem, the GBR has significant capacity to recover from cumulative pressures (Anthony, 2016; Williamson et al., 2016). However, given the projections for increasing frequency of extreme climate events and ocean acidification that reef managers cannot directly influence, effective management is essential to protect biodiversity and enhance reef resilience to cope with future changes. Some of the 'manageable' pressures that can be practically reduced by reef managers and therefore contribute to increasing reef resilience include poor water quality (e.g. turbidity, pollutants), effects of direct use (e.g. tourism, fishing) and pest species outbreaks (e.g. COTS) (Anthony, 2016).

Water Quality

Several experimental and field studies have demonstrated that the negative impacts on coral reefs caused by climate change could be exacerbated by poor water quality conditions (Cantin, Baird, et al, 2021; Uthicke et al., 2020), synthesised in Pineda & Waterhouse, 2021 and Waterhouse & Pineda, 2021, although intense heat stress events (over 5°C of accumulated heat stress on the NOAA Degree Heating Weeks Scale) could mask other potential water quality effects (Cantin, Baird, et al., 2021). Under more moderate scenarios, however, improvements in water quality are expected to enhance tolerance to other pressures such as increasing water temperatures of some life stages of corals as well as other key species (Humanes et al., 2016). A revision of water quality guidelines was proposed to apply 'climate adjusted thresholds' and thus minimise toxicity effects potentially exacerbated by climate change (Negri et al., 2019; Negri, Smith, et al., 2020; Uthicke et al., 2020). Toxicity levels for an array of emergent pesticides were also developed in order to further contribute to water quality guideline values and assessments of the potential risks to the GBR and its catchment (Negri, Smith, et al., 2020).

In order to estimate water quality trends and predict ecological consequences of human activities, such as run-off, dredging or on-ground management strategies, a new water quality indicator was developed, based on the amount of light that penetrates to the seafloor (Robson et al., 2019; Robson et al., 2020). A benthic irradiance product was derived from satellite data and validated against *in-situ* light loggers, and proposed as a cost-effective, responsive, ecologically-relevant water quality indicator that describes the light environment at local and GBR-wide scales. The new benthic light water quality index (I_{bPAR}) was made available for incorporation into the GBRMPA Report Cards (Robson et al., 2019).

Direct Use

The GBR is a multi-use marine park with commercial and recreational uses such as fishing, diving, boating and shipping that can impact reef ecosystems and therefore reef resilience. No-take (green) zones have a role in protecting reefs from some direct uses but are less effective at protecting coral reefs from acute regional-scale disturbances (such as oil spills). However, protection can support higher biomass of targeted fish and therefore population recovery and long-term persistence after acute disturbances, including climate-driven events such as cyclones (Emslie et al., 2015; Sweatman et al., 2015). This demonstrates the importance of zoning within the GBR Marine Park and associated protection measures, such as 'no anchoring' areas, to protect biodiversity and enhance reef resilience (Bainbridge et al., 2015; Williamson et al., 2014, 2016). Establishing highly connected networks of no-take marine reserves can contribute future resilience of coral reefs, but effective measures to mitigate regional and global pressures are still needed (Emslie et al., 2015).

Pest species (Crown of Thorns Starfish)

Successful COTS management aims to contribute to reversing the current long-term decline in coral cover on the GBR, increasing reef resilience to other global pressures. In fact, investment in COTS management is one of the few actions that can be taken on individual reefs that will contribute significantly to the reduction in the cumulative stresses experienced by the GBR (Westcott et al., 2016). Therefore, COTS control that minimises coral predation impacts is a priority for management supported by integrated pest management research.

Accordingly, the NESP TWQ hub supported research into developing an Integrated Pest Management (IPM) approach for COTS control (i.e. including all aspects of COTS management) and improving the deployment of in-water resources to manage COTS impacts on coral reefs (i.e. manual control) (summarized in Erdmann et al. 2021). More specifically, NESP-funded management strategies for COTS control included: (i) Control at priority sites and areas, (ii) Protection of key ecological and tourism assets, (iii) Culling frequencies that minimise outbreak spread, (iv) Prevention of primary outbreaks, (iv) Addressing drivers of outbreaks, and (vi) Implementation of non-manual controls (Westcott et al., 2016).

For instance, the IPM approach developed by Dr. Westcott's team (Fletcher et al., 2020; Fletcher & Westcott, 2016) provided an intelligent, field-deployable decision support tool to guide strategic selection of control activities based on site condition and management constraints. A series of parallel studies were additionally undertaken in order to inform the decision support tools, such as (i) the detection of environmental DNA (eDNA) of COTS in water samples using molecular techniques (i.e. digital droplet PCR or dipsticks/lateral flow assays) (Doyle & Uthicke, 2020; Uthicke et al., 2018), (ii) the study of movement patterns of COTS in order to optimise spatial and temporal aspects of localised culling and removal activities (Pratchett et al., 2020), and (iii) the identification of a low risk of adult COTS outbreaks in deep-water habitats, and subsequent recommendation for all COTS control effort to still continue in the shallow waters of emergent reefs (Beaman, 2018).

Despite the ongoing discussion regarding the main causes of COTS outbreaks, it has been suggested so far that both excess nutrient levels from terrestrial runoff and the removal of potential predators may have a role to play (Anthony, 2016; Kroon, Lefèvre, et al., 2020; Wilmes et al., 2019). Hence, additional potential COTS management strategies could also include improvements in water quality and protection/manipulation of predator populations to prevent COTS outbreaks (Pratchett & Cumming, 2019; Westcott et al., 2016, 2020) (Figure 6, as synthesized in Anthony, 2016). For example, consumption of pelagic and settled COTS by coral reef fish species may well be more common than is currently appreciated, as evidenced by the detection of COTS DNA in faecal and gut content samples of 18 different coral reef fish species, nine of which had not been reported to consume COTS before (Kroon, Lefèvre, et al., 2020). This adds the total number of coral reef fish species reported to have consumed COTS to 80, including important fisheries species such as Lethrinidae (Emperors) and Lutjanidae (Tropical Snappers) (Cowan et al., 2017; Kroon, Lefèvre, et al., 2020). Moreover, the giant triton snail *Charonia tritonis* could be deployed at specific reefs to control population outbreaks of COTS either through direct predation or thorough the dispersion effect created by chemicals released by the snail which could prevent aggregations of COTS during the spawning season (Hall et al., 2017). Additional biologically-based control technologies for COTS population outbreaks for enhancing the IMP Approach were also reviewed, including molecular and genetic approaches (Hoj et al., 2020). Therefore, in order to address the threat to coral resilience posed by COTS, multiple and diverse approaches are required (e.g. water quality improvements, increased fishery regulations, zoning, manual control) to prevent future outbreaks (Pratchett & Cumming, 2019; Westcott et al., 2020).

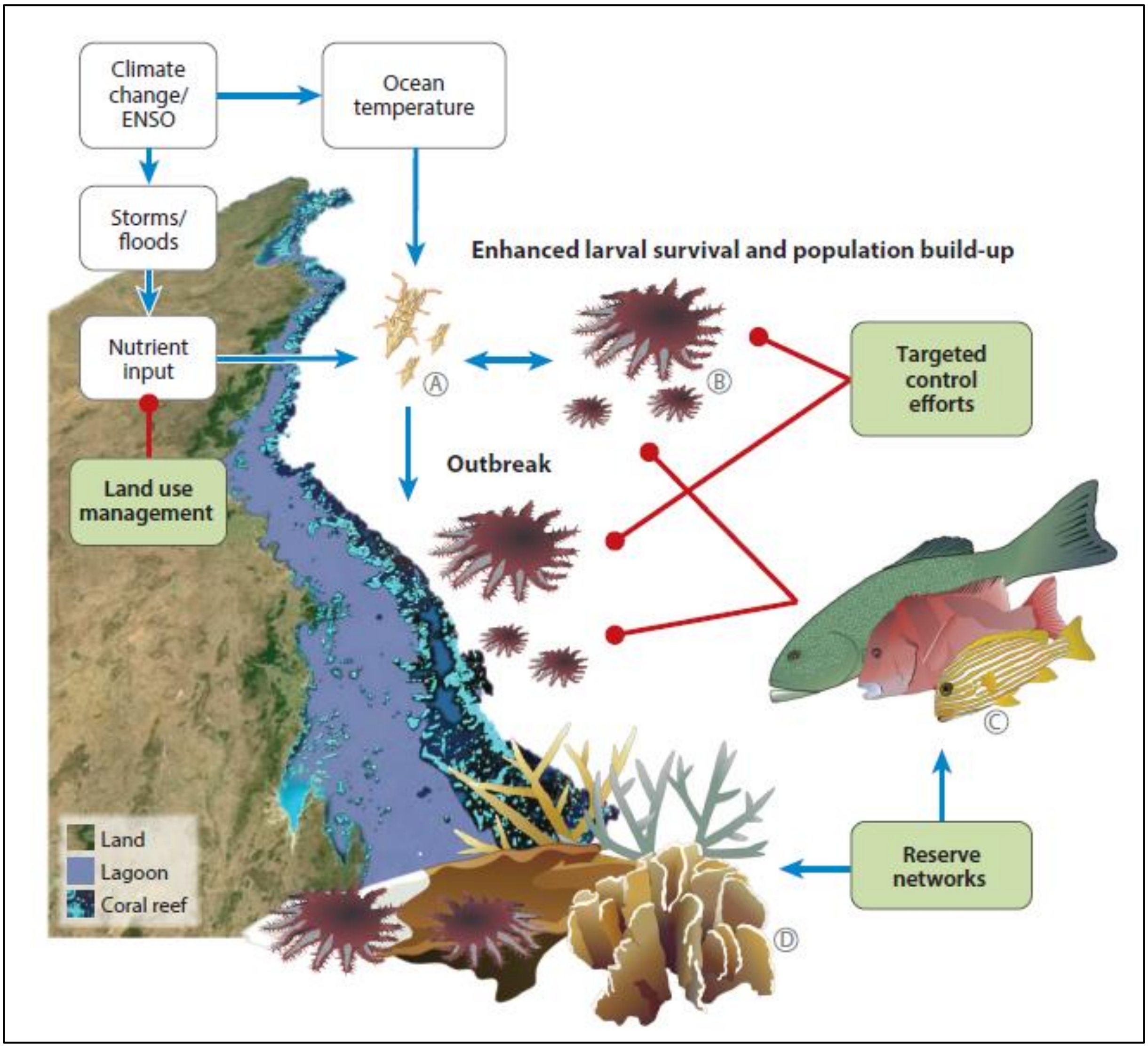


Figure 6: Schematic representation of the drivers (white boxes) influencing outbreaks of crown-of-thorns starfish on the GBR and three potential management strategies (green boxes). Sharp (blue) and blunt (red) arrows indicate positive and negative influences, respectively. Source: Anthony, (2016).

2.3.3 Coral reef restoration and adaptation

In the face of current and future climate changes that will impact the GBR ecosystem, coral reef restoration and adaptation practices are increasingly gaining interest among researchers and reef managers. A summary is provided below, and for a complete synthesis on the topic of ecosystem restoration from catchment to reef within NESP-funded research, see Pineda et al., (2021).

Coral reef restoration

Coral reef restoration and assisted recovery techniques have been trialled overseas and in Australia, however, until recently there was no evaluation of the most suitable methods for GBR conditions. A summary and evaluation of success of coral restoration and assisted recovery techniques worldwide led by Dr McLeod identified the techniques that could be applied to the GBR (Boström-Einarsson et al., 2020; McLeod et al., 2020). Several coral restoration intervention types were identified, including coral gardening (transplantation and/or nursery), direct transplantation, artificial reefs, substrate enhancement by electricity, substrate stabilisation, algae removal, larval enhancement and microfragmentation, with most methods documenting successful growth and survival (Figure 7). Most of the coral restoration case studies assessed were short-term (<18 months) and at relatively small spatial scales (ca. 500 m^2 in average). Therefore, substantial scaling-up would be required for restoration to be a useful tool to support the recovery and persistence of reefs on the GBR. Challenges identified included lack of clear restoration objectives, lack of appropriate monitoring and reporting, and poorly designed projects. These challenges need to be overcome in order to successfully scale-up and retain public trust in restoration as a tool for resilience-based management (Boström-Einarsson et al., 2018, 2020).

While there is an urgent need to support degraded reefs at a GBR-wide scale, there is still value in small scale interventions that can increase the amenity value of tourism sites and engender greater community stewardship of the GBR. This can be delivered through hands-on participatory projects, such as those undertaken by tourism operators between 2017 and 2019, with growing interest and participation of more operators since. For example, COTS control, macroalgae removal and coral restoration at small scales were deemed appropriate to improve the health of local reefs, while educating the general public and providing stewardship opportunities (McLeod et al., 2020).

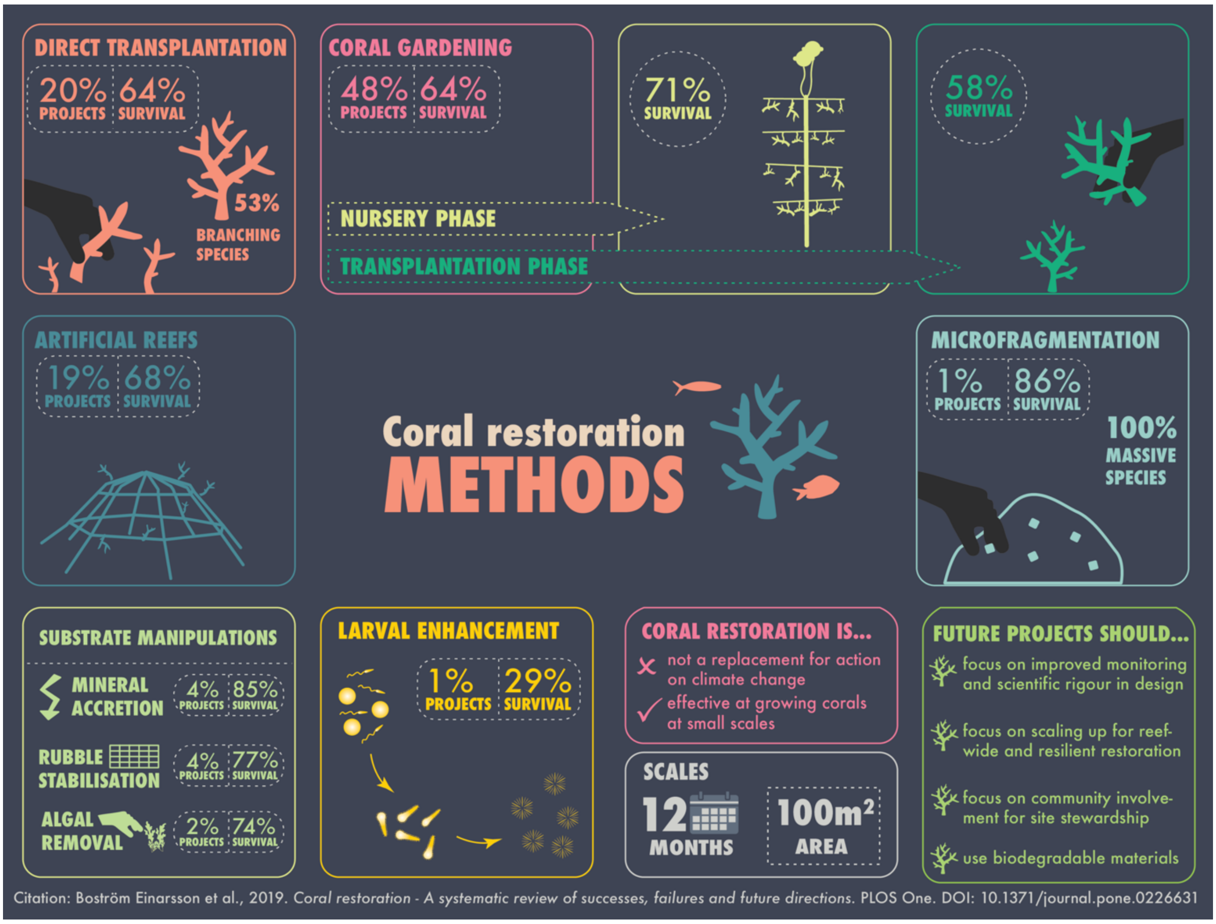


Figure 7: Summary of the different coral restoration intervention types that are available for use on the GBR. Source: Boström-Einarsson et al., (2020)

Further to this preliminary NESP research, a multi-disciplinary initiative to investigate the best science and technology to support the GBR to resist, repair, and recover – the [Reef Restoration and Adaptation Program](#) (RRAP) – was initiated in 2018. The RRAP is a partnership of leading Australian experts including scientists, engineers, modellers and mathematicians. An initial feasibility study found successful intervention was possible and could double the likelihood of sustaining the GBR in good condition by 2050. RRAP has since embarked on a long-term research and development program to develop, test, and risk-assess novel interventions to support a resilient GBR and sustain critical ecosystem functions and values. Additionally, intervention strategies discussed by global experts at the GBR Restoration Symposium in 2018 (Burrows et al., 2019) are being trialled through numerous coral restoration projects in the GBR.

Some examples of coral restoration projects in the GBR included the installation of the first coral nursery (on Fitzroy Island, offshore Cairns), led by the Reef Restoration Foundation in 2017 (Cook et al., 2018). The nursery started with 240 fragments from four *Acropora* species, collected from donor coral colonies that had survived the 2016 and 2017 mass bleaching events in the region, and was expanded to over 1500 coral fragments, and outplanting commenced in 2019. Since then, coral nursery and gardening projects have been established in other locations along the GBR, such as the Whitsunday Islands and Opal Reef (offshore Daintree), including the development of new technology for coral deployment (i.e. Coralclip®). Other projects within the GBR are trialling substrate stabilisation (e.g. rehabilitation project at Agincourt Reef by Reef Ecologic and Quicksilver, 2018), coral repositioning (e.g. relocation of over 400 tons of *Porites* spp. in the Whitsunday Islands to allow for a pipeline (McLeod et al., 2019)), macroalgae removal (e.g. Magnetic Island, Ceccarelli et al., 2018) and larval enhancement (McLeod et al., 2020). If successful, these techniques could help support reef recovery and resilience in many locations across the GBR and other tropical reef systems around the world (McLeod et al., 2020).

There are thousands of square kilometers of coral reefs in the GBR and Australia, and no existing restoration techniques can currently be scaled-up to a sufficient degree. Ultimately however, coral restoration techniques are likely to be integrated into the coral reef management toolbox along with stress reduction, zonation and predator control as a range of tools to support reef recovery and resilience. Using existing methods, coral restoration and adaptation in Australia can at best restore local-scale sites, and buy time while urgent global action on climate change increases (McLeod et al., 2020).

Coral reef adaptation

Human-assisted evolution is being considered as a tool to increase coral reef adaptation by testing explanting manipulated (i.e. more climate resistant) coral and or symbiont stock onto reefs. These methods generally include four approaches: (i) stress exposure and acclimatization of natural stock within and between generations, (ii) modification of the microbial community associated with corals to afford increased stress resistance and decrease risk of disease, (iii) selective breeding for stress resistance, and (iv) manipulation of the strains of algal symbionts (Symbiodiniaceae). NESP TWQ Hub research focused on understanding the traits of corals that survived recent bleaching events, documenting: (i) genetic variants that underpin bleaching resistance and resilience through genomic comparison of corals sampled pre- and post-bleaching events in the GBR in 2017, (ii) the dynamics of the coral symbiont

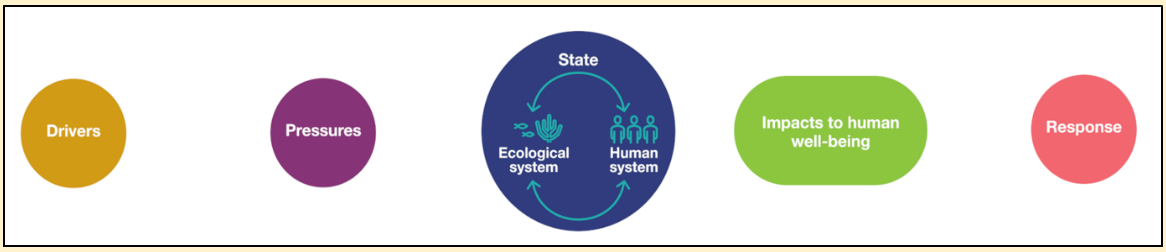
Symbiodiniaceae during and after mass bleaching, and (iii) environmental drivers of total and adaptive coral host genetic diversity and Symbiodiniaceae community structure across the GBR. Importantly, key hard coral populations were identified that support resilience and may provide potential breeding stock for future coral reef restoration activities (Quigley et al., 2021), and the genes that enable some coral species to withstand bleaching were identified (Fuller et al., 2020). The potential enhanced physiological capacity for bleaching resistance and improved performance of selected species of corals could help inform managers on how to maintain ecosystem function, thus supporting coral reef managers to improve reef resilience.

2.3.4 Facilitating resilience-based management in the GBR

Resilience-based management seeks to identify and preserve the aspects of ecosystem function that are important for maintaining key ecological and social benefits. In practice, for a large ecosystem such as the GBR that is at risk from multiple natural and anthropogenic impacts, resilience-based management seeks to minimise damage and maximise recovery potential (Lam et al., 2020; Mason et al., 2020). The 2019 Outlook Report (GBRMPA, 2019) identified the pressures of greatest concern for the GBR as altered weather patterns (storms, floods), sea temperature increases (and associated marine heatwaves and coral bleaching events), ocean acidification, sea-level rise, nutrients run-off, sediment run-off, outbreaks of COTS, and illegal fishing. Many of these pressures occur simultaneously, thus causing cumulative impacts on the reef ecosystem. As reefs vary in their sensitivity to pressures, ability to recover from multiple pressures and their response to management, resilience-based management helps identify where and when the most effective management actions can be deployed to maximise overall ecosystem resilience. The development of resilience-based management guidance requires good science-based quantitative information for ecosystem models, as well as accurate maps of current state of the reef, ecological values and ecosystem trajectories (Mason et al., 2020).

Although minimising cumulative impacts is a priority issue for resilience-based management in the GBR, most of the tools available before NESP were qualitative. A NESP TWQ Hub-funded project developed a structured approach based in quantitative analytical tools in order to provide a more objective and reliable system for decision-making (Uthicke et al., 2016). The model was built on the Drivers-Pressures-State-Impacts-Responses (DPSIR) framework (see Box 1), to identify the sources of stress (drivers), the environmental scenarios that might play out to produce a complex set of pressures and identify potential management levers for intervention or risk prevention. The new mechanistic model enables predictions of cumulative risk in space and time under complex environmental scenarios. The model was applied to a cumulative impacts problem for corals on inshore reefs and cumulative impact risk maps were developed for a set of environmental scenarios driven by land-based run-off and climate change. Using coral bleaching and mortality, it was demonstrated that when used as a risk assessment tool, the model can inform management decisions about what actions are needed to mitigate or prevent stressor combinations that lead to cumulative impacts and/or the exceedance of thresholds. Briefly, the Spatial Cumulative Impacts Risk Analysis (SCIRA) model uses dynamic environmental layers as input variables, using data sources including eReefs and eAtlas, and produces estimates of bleaching and mortality risk (Uthicke et al., 2020). The outputs of the model (risk maps) can be analysed statistically allowing direct comparisons among scenarios that represent alternative management options, in order to inform transparent decision-making. For example, by presenting the results of different scenarios with varying combinations of stressors in a consequence table, the results can inform decision analysis that compares risks against costs of intervention or prevention (Uthicke et al., 2020). Pressure maps were also produced to show drivers of changes in coral cover and potential to recover from disturbance from a combined dataset (Long-Term Monitoring Program and Inshore Marine Monitoring Program). This e-Atlas interactive tool provides a resource that can be queried by managers and stakeholders to show issues and cumulative impacts (Uthicke et al., 2020).

BOX 1: Drivers Pressure State Impact Response (DPSIR) Framework



1. DRIVERS

Overarching causes that can drive change in the environment and have also been referred to as underlying causes of change in the environment. Drivers can operate across a range of scales, both in time and space, and are interlinked (i.e. each one influences the others). For example, technological developments can play a role in economic growth, population growth and societal attitudes. Similarly, population growth can affect economic growth and societal attitudes. In addition, community benefits can illicit change in Drivers as income and employment directly links to economic and population growth.

Six drivers of change for the Great Barrier Reef system have been identified:

1. Climate change
2. Population growth
3. Economic growth
4. Technological developments
5. Societal attitudes
6. Governance systems

2. PRESSURES

Mechanisms that exert a change force (either positive or negative) on a value. Pressures are the change mechanisms (e.g. processes or activities) that result from drivers. Pressures are referred to as 'threats' in the GBR Outlook Report (2014) and as 'impacts' in the Strategic Assessment Report (2014). A pressure exerts a change force on a value, which is measured as a change in the state of the value. Pressures may come from difference sources, both global and local and include: coastal development, land-based pollutants, greater competition (and conflict) between resource users, and extractive practices, e.g. dredging.

3. STATE

Values are those aspects or attributes of an environment that make it of significance (Strategic Assessment Report, 2014). Values include attributes of both environmental and human systems. The State is the way of describing the condition of the value, either quantitatively or qualitatively, thus enabling a measurement of change in the health or quality of that value. While values are not part of the DPSIR framework, they nonetheless link Pressures, State and Impacts.

Three sets of values have been adopted for the GBR:

1. Biophysical values
2. Socioeconomic values
3. Heritage values (including Indigenous, historic and world heritage).

4. IMPACTS

The change in human wellbeing that results from a change in the State of a value (biophysical, socioeconomic or heritage). Impacts to human wellbeing can be assessed using multiple lines of evidence to understand the relationship between the state of the values in the system and the impacts on people who use or depend on the system.

5. RESPONSES

Actions (generally management actions) that people take which are related to changes in the ecosystem. Responses represent a feedback mechanism through which human activities can alter Drivers, Pressures, values (measured as State), or Impacts. Responses reflect decisions based on what people perceive about ecosystem services, the state of the environment, or the changes occurring within an ecosystem. The intent of responses differs depending on the part of the system that they are directed at. For example, responses can be directed at drivers or pressures for the purpose of avoiding, offsetting or mitigating the effects.

Source: GBRMPA DPISR Framework, https://reefiq.gbrmpa.gov.au/ReefKnowledgeSystem/DPSIR

Another NESP TWQ Hub-funded project quantified the links between bleaching thresholds and water quality and adapted the eReefs modelling framework to predict mass bleaching events on the GBR. The model takes into account a comprehensive set of processes over different spatial scales from the photochemistry and oxidative stress within individual corals to the GBR shelf, including spectrally resolved benthic light, the hydrodynamics of temperature, flood plume sediment transport and dissolved and particulate nutrient concentrations (Cantin, Baird, et al., 2021). The model was used to determine the effects of anthropogenic nutrients and sediment loads entering the GBR lagoon on the likelihood of coral bleaching in 2017. Simulations suggested low impacts from nutrient and sediment loads on the predicted levels of heat stress at the modelled reefs in 2017, most likely explained by the absence of high rainfall events in the preceding years (2013-2017), particularly in the Dry Tropics region (Cantin, Baird, et al., 2021). However, while accumulated heat was the main driver of bleaching severity across inshore and mid-shelf reefs, a suite of water quality parameters also significantly contributed to exacerbate the prevalence and severity of coral bleaching and mortality. Total nitrogen, chlorophyll *a* concentration and nitrogen sourced from detritus were positively correlated with bleaching severity, particularly at inshore reefs. Hence, the modified eReefs model improves forecasting of bleaching risk and allows the comparison of scenarios of different water quality management actions and river load reductions required to maximise the thermal tolerance of corals to keep pace with projected sea temperature increases (Cantin, Baird, et al., 2021).

Furthermore, investigation of coral genetic variation (including across a diversity of Symbiodiniaceae taxa found within corals) associated with bleaching tolerance revealed the vulnerability and resilience of three coral species. In particular, the *sacsin* gene (the co-chaperone for the heat-shock protein Hsp70) found within *Acropora millepora* was identified as playing an important role in variability in bleaching tolerance (Fuller et al., 2020). While a more dynamic symbiotic community consisting of a higher proportion of thermally-tolerant symbionts (*Durusdinium* spp.; formerly called “clade D” of Symbiodiniaceae) were found in corals of the same species that survived mass bleaching compared to other *Acroporid* species such as *Acropora hyacinthus* and *Acropora tenuis* (Figure 8) (Quigley et al., 2021). These results could contribute to identifying reef locations for targeted management actions, such as locations for spatial protection (e.g. refuges) or sites for future restoration activities. This research could also inform GBR monitoring programs by identifying coral species that are more likely to be heat-stress sensitive with fixed symbiont communities (e.g. *Acropora hyacinthus*), and spatially identifying GBR reefs at risk from future thermal stress (Figure 8) (Quigley et al., 2021).

The spatial patterns of ecosystem values and connectivity, and how pressures influence them were delivered through an interactive tool to inform management and prioritisation of interventions (Johnson et al., 2018a, 2018b). This project assessed the broader northeast Australian seascape that includes the GBR, Coral Sea, Torres Strait and Great Sandy Strait, and identified values and attributes that would benefit from improved cross-jurisdictional management due to their strong connectivity and current effectiveness of collaborative management (Johnson et al., 2018a, 2018b). For example, twelve attributes that included four species of shark, coral reefs, dogtooth tuna, cultural resources, seabirds and recreational use were identified as being targets for cross-jurisdictional management between the GBR and Torres Strait (Figure 9). These management priorities provide detail on which jurisdictions need to consult on managing specific attributes. Ultimately, the information can be used to develop aligned and collaborative agreements and for future cross-jurisdictional planning, including with oversea territories, such a New Caledonia that shares the values and attributes of the Coral Sea with Australia, and Papua New Guinea that shares the values and attributes of the Torres Strait with Australia.

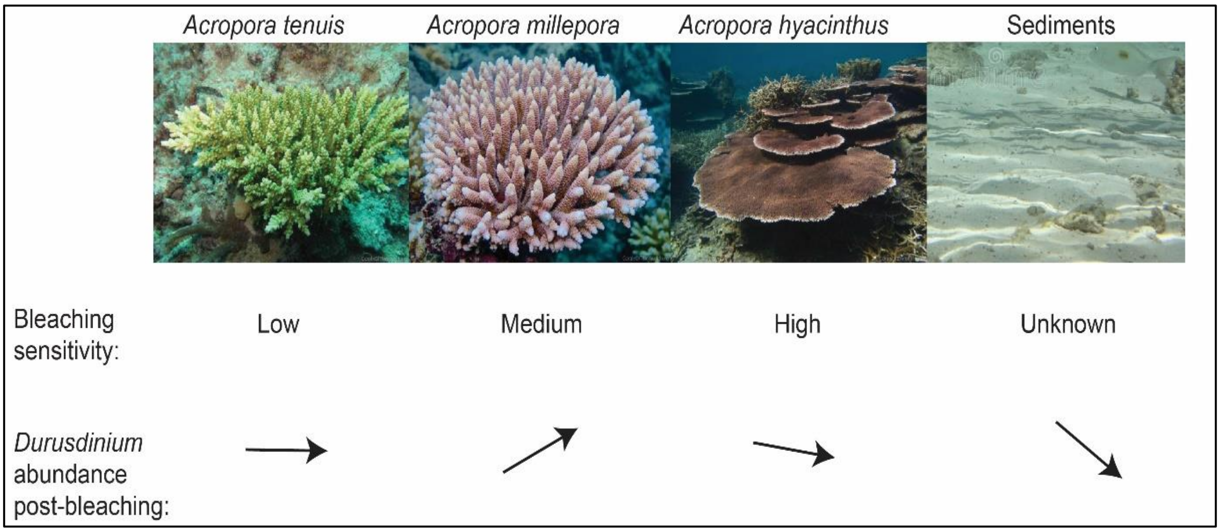


Figure 8: Summary of the changes in prevalence of stress tolerant photosymbionts (genus Durusdinium) within surviving corals sampled after bleaching and in the environmental pool. Arrows indicate direction and magnitude in changes in the relative abundance of *Durusdinium* within the four sample types (increase, no change, decrease; more drastic arrow angle signifies a larger change). Source: Quigley et al., (2021).

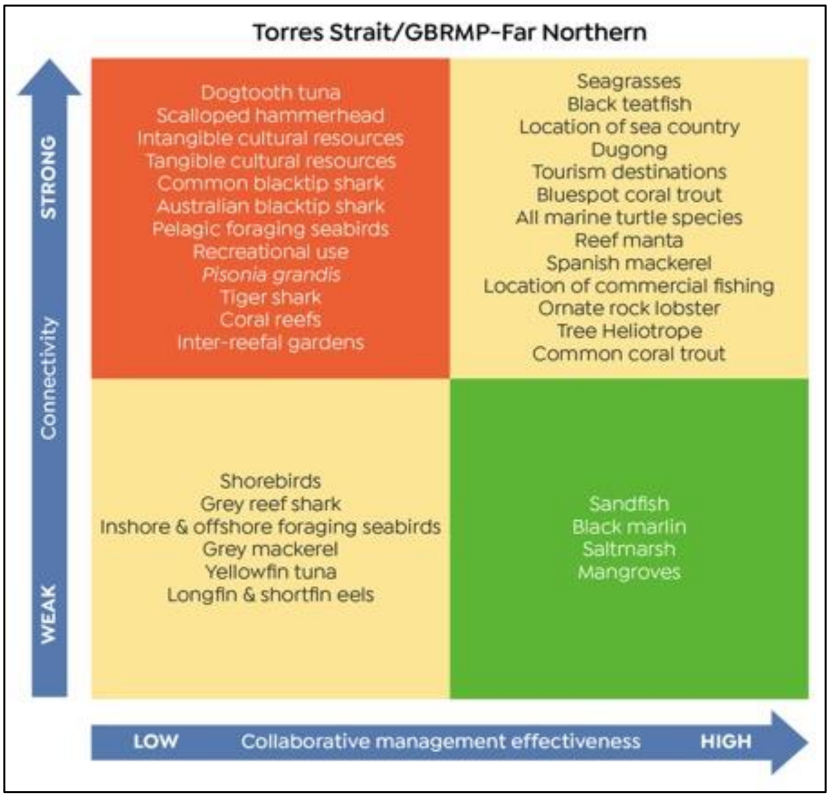


Figure 9: Management prioritisation for attributes connected between the GBR and Torres Strait jurisdictions. Red = attributes that are highest priority due to strong connectivity and low collaborative management effectiveness; Yellow = attributes that are moderate priority due to either weak connectivity and low collaborative management effectiveness or strong connectivity and high management effectiveness; Green = attributes that are lowest priority due to weak connectivity and high management effectiveness. Source: Johnson et al. (2018a).

The results from these studies are important for informing resilience-based management in the GBR and connected systems, as they are filling knowledge gaps and provide relevant thresholds and risk maps to identify potential threats. Thus, management actions can be modified accordingly to promote recovery and limit further disturbances or impacts. This new knowledge has informed the development of a comprehensive guide for resilience-based management of the GBR (the ‘RBM tool’) that is currently being tested, with the resulting reef resilience maps being used by GBRMPA to explore strategic options for restoring and protecting reefs (Mason et al., 2020). The ‘adaptive resilience-based management cycle’ (Figure 10), shows the important role of monitoring in assessing the effectiveness of resilience-based management actions, which can inform adjustments and further research and monitoring in order to improve ecosystem resilience. Novel monitoring indicators based on the erosion and accretion of calcium carbonate on reefs were identified and tested as part of NESP TWQ Hub-funded research (see Box 2). These indicators may ultimately prove useful in moving beyond simply monitoring state and being able to monitor ecosystem function.

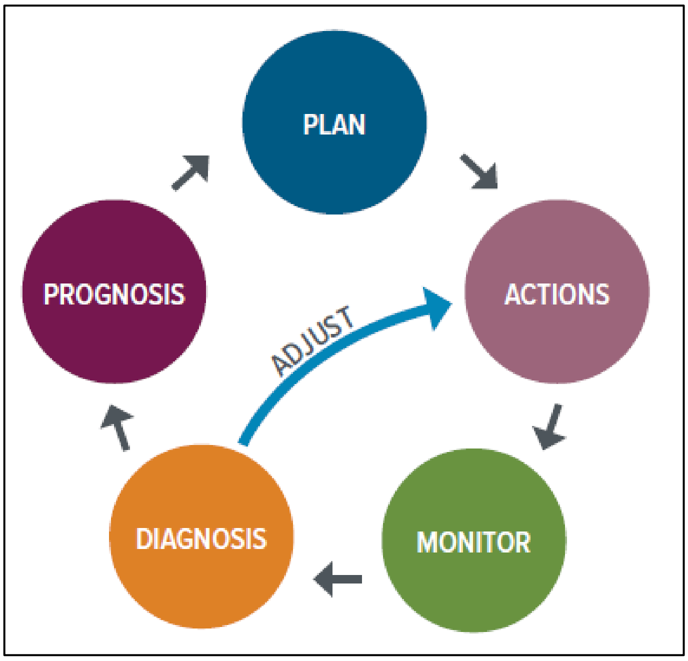


Figure 10: Adaptive resilience-based management cycle. Source: GBRMPA, 2017.

Properly designed management strategies can contribute to increased reef resilience where multiple stressors from local, regional and global stressors combine to impact on the processes that underpin resilience (e.g. recruitment, recovery, resistance to disturbances such as bleaching and disease). However, some scientists suggest that there is a 'ceiling' imposed by ocean warming and acidification that will limit the efficiency of resilience-based management as global atmospheric carbon continues to increase (Anthony, 2016). Reduced coral calcification, recruitment and competitive strength of corals over macroalgae caused by acidification will hinder resilience and can only be addressed by halting and reversing ocean acidification through global emissions reductions. Therefore, despite management opportunities to maintain and increase reef resilience in the face of global change, this presents only short- to medium-term protection and is unlikely to be a long-term solution to a global problem. Focusing management in this case will be important, as interventions are expensive, so a clear understanding of the scope and effectiveness of different actions can facilitate more targeted decision-making and better returns on investments in management and policy. Nevertheless, solutions that offer the best long-term prospects for coral reefs will be those that build on an integrated strategy of rapid reductions in global carbon emissions, climate adaptation and targeted local and regional management actions (Anthony, 2016).

BOX 2: Integrative carbonate budget model of the Great Barrier Reef (Desbiens et al., 2020)

This case study synthesizes and refines the carbonate budget produced for the GBR in Wolfe et al. (2019). Using AIMS LTMP data on coral cover and fish biomass between 2016-2020 to parametrize the R package '*caRbs*', the authors quantified spatial and temporal patterns in carbonate production and bioerosion and identified thresholds in coral cover required to maintain a positive carbonate budget for the GBR (Figure 11).

Results highlighted the importance of *Acropora sp.* as the primary contributor to the carbonate budget, although massive *Porites sp.* were identified as key framework builders to maintain carbonate production. Carbonate production varied latitudinally, with higher calcification rates at low latitudes, while there were no clear spatial or temporal trends in primary bioerosion on the GBR. Parrotfish (*Chlororus microrhinus*) was the primary driver of bioerosion on fore-reef habitats. The study concluded that overall estimates of the carbonate budget on the GBR ranged between -4.9 and 28.4 kg m^{-2} yr^{-1}, and the threshold of coral cover to maintain a positive carbonate budget on the GBR were estimated at ~17%.

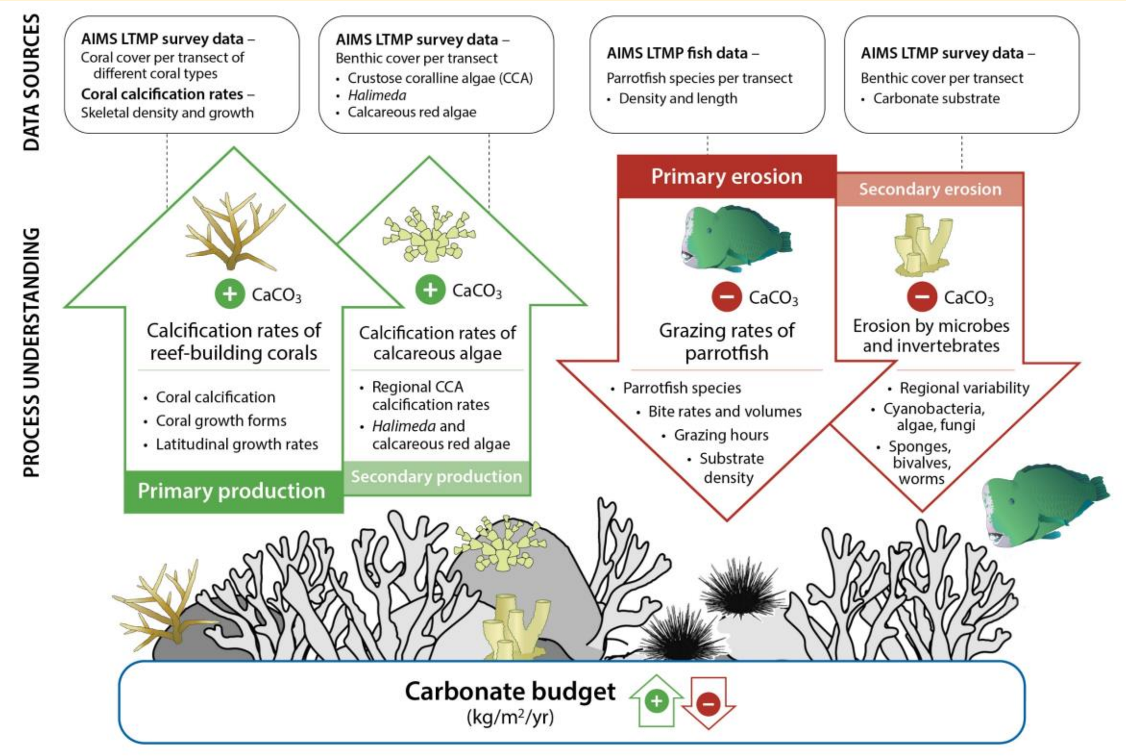


Figure 11: Main model functions (primary production, secondary production, primary erosion and secondary erosion) underlying the caRbs model. Modified from: Desbiens et al., (2020)

Key **take home messages** from a management perspective are:

1) Overall coral cover needs to exceed 17% in order for reefs to have a positive carbonate budget.
2) We do not yet have a corresponding threshold for inshore reefs where a number of processes, including bioerosion and biogeochemistry, can be quite different.
3) The fact that an individual reef may sit below the 17% threshold does not necessarily indicate that there is a problem; it may just be in an early stage of recovery.
4) The *caRbs* package presents an important tool to evaluate trends of reef state over time, asking how the proportion of reefs sitting below and above the 17% threshold is changing, and to ask whether one region has a higher proportion of 'positive reefs' than another.
5) A positive carbonate budget is a pre-requisite for many reef services but does not necessarily imply that all services, including accretion with sea-level rise and provision of high-quality habitat for fish and coastal protection, will occur at historical rates. Further work is needed to link carbonate budget trends explicitly to ecosystem functions.

2.4 Innovations in methods and delivery of resilience-based science

One of the most significant innovations of the NESP TWQ Hub program was the development of **quantitative analytical tools and interactive online platforms** for data delivery, which allowed more objective and reliable systems for decision-making, as well as open access information to stakeholders. Specifically, the new quantitative models and dynamic maps, delivered through online platforms such as eAtlas and eReefs, allow open access and easy interaction by end-users with data, including the use of statistical analyses, comparisons of complex environmental scenarios and risk assessments. Regular and meaningful communication between researchers and relevant stakeholders has also enabled the integration of some of those analytical tools within monitoring programs and reporting processes, such as the GBRMPA Outlook Report and RIMReP. Some examples of innovative methods and delivery tools are summarised below (further details provided in Appendix Table A1.2:):

- New dynamic mechanistic model developed that enables predictions of cumulative risks in space and time for complex environmental scenarios (Uthicke et al., 2016).
- New spatial representation of the sources of emerging contaminants that can contribute to future ecological risk assessments (Kroon et al., 2015; Kroon, Berry, et al., 2020).
- Exposure maps combining 25 important environmental pressures accessible through eAtlas (Uthicke et al., 2020).
- Refined eReefs model to derive water quality management scenarios expected to maximise coral survival in a warming climate (Cantin, Baird, et al., 2021).
- Interactive maps representing the direction and magnitude of connections of different values across the northeast Australian marine ecosystem and potential future pressures delivered through eAtlas (Johnson et al., 2018a, 2018b).
- 3D versions of remotely sense bleaching products by NOAA and BoM, and a seasonal prediction capability for marine heatwaves, delivered through eReefs, to enable a better spatial prediction of reefs that are more heat tolerant and therefore more likely to remain healthy in the future (Steinberg et al., in review).
- Optimisation of the Integrated Pest Management (IPM) strategy for COTS and associated local/regional decision support tools to achieve efficient and effective management of COTS outbreaks (Fletcher et al., 2020; Fletcher & Westcott, 2016; Westcott et al., 2016).
- Novel Resilience-based Management guidance system delivered through desktop software, which enables users to prioritise reefs to manage and potentially restore to maximise ecological and socio-economic outcomes (Mason et al., 2020).

NESP TWQ Hub research has also enabled the development of **new technologies** to contribute to increased reef resilience, such as the use of environmental DNA (eDNA) for COTS detection *per se* (Uthicke et al., 2018) and detection of COTS DNA in fish faecal and gut content samples to infer COTS predation by coral reef fish including fisheries species (Kroon, Lefèvre, et al., 2020), or a review on natural control technologies for COTS such as the potential use of chemicals from the giant triton snail (*Charonia tritonis*) to create 'landscapes of fear' among COTS and hence contribute to control of population outbreaks (Hall et al., 2017; Hoj et al., 2020).

NESP TWQ Hub research also filled key knowledge gaps in well-studied fields, such as the link between water quality and reef condition, with several projects proposing improvements in catchment management to minimise soil erosion and reduce chronic effects of sedimentation and poor water quality in coastal waters of the GBR (Williamson et al., 2014, 2016). For example, nutrient availability (i.e. increases in nitrogen:phosphorous ratios) and impacts on carbon metabolism were identified to likely affect negatively the stability of coral-Symbiodiniaceae symbiosis and resistance to environmental stress (Morris et al., 2019). Although temperature still seems to be the major diver of coral bleaching under severe heat stress (marine heatwave) events such as those experienced in the GBR in 2016 and 2017 (Cantin, Baird, et al., 2021).

Several projects also contributed to the development or improvement of **new guidelines in water quality**, including:

- Contaminants of emerging concern and new pesticide water quality guidelines (Kroon et al., 2015; Kroon, Berry, et al., 2020).
- Climate adjusted thresholds for water quality guidelines -*work in progress*- (Negri et al., 2019; Negri, Smith, et al., 2020).
- A new water quality indicator (I_{bPAR}) based on the amount of light that penetrates to the bottom of the water column, using satellite ocean colour data validated by *in-situ* data loggers (DiPerna et al., 2018; Magno-Canto et al., 2019; Robson et al., 2019; Robson et al., 2020).
- The identification of toxicity thresholds of 21 land-source pesticides for 16 tropical aquatic species to develop: (i) National and GBR ecosystem protection guidelines, (ii) toxic equivalency values, (iii) toxic loads and multisubstance-potentially affected fraction (ms-PAF) values (Negri, Smith, et al., 2020; Negri, Templeman, et al., 2020; Thomas et al., 2020).

Finally, another field of innovation within coral reef science includes the shift from traditional passive habitat protection of the GBR towards the acceptance of active **restoration and assisted coral adaptation** as a complementary tool for resilience-based management. New methodologies and approaches for reef restoration and adaptation science developed during NESP TWQ Hub include:

- Assessment of global restoration and rehabilitation techniques and identification of best practice coral restoration for the GBR (Boström-Einarsson et al., 2018, 2020; McLeod et al., 2020).
- Identification of traits of corals that survived bleaching events to assist in reef restoration and adaptation programs (Fuller et al., 2020; Quigley et al., 2021).

3.0 RESEARCH INFORMING POLICY & MANAGEMENT

3.1 Application of NESP resilience research for policy & management

NESP TWQ Hub research that focused on coral reef health and resilience-based management contributed towards an increased understanding of what cumulative pressures undermine resilience and what management strategies can support resilience of vulnerable ecosystems. Importantly, research results demonstrated that the impacts of climate variability and change act together with other pressures, including poor water quality and predation by COTS, and addressing local pressures can improve the outlook for coral reefs. Resilience-based management is a relatively new approach, and measuring ecological benefits that are a direct result of such a strategy will take years and possibly decades, exacerbated by the fact that global and regional disturbances are becoming more severe and more frequent. For example, 2020 experienced another thermal stress event in the GBR, before the results from research on the 2016 and 2017 bleaching events were available. Additional time is also required to apply research results to management actions and then observe ecological benefits, and it will therefore be some years before the full value of NESP research can be seen in GBR condition or resilience.

However, resilience-based management in the GBR is currently being implemented and NESP TWQ Hub research has contributed towards its operationalisation, through the inclusion of results and recommendations in policy documents such as the Blueprint for Resilience (GBRMPA, 2017), the GBR Outlook Report 2019 (GBRMPA, 2019) and the current review of the Reef 2050 Long Term Sustainability Plan (Commonwealth of Australia, 2020). NESP TWQ Hub research has provided for numerous improvements in management plans, strategies, monitoring programs and reporting processes, as well as policy (outlined below).

3.2 Policy applications

The most recent policy application of NESP TWQ science includes the current review of the Reef 2050 Long Term Sustainability Plan (Commonwealth of Australia, 2020). The review of the Reef 2050 Plan incorporated NESP TWQ Hub research related to improvements in water quality (e.g. nutrients, pesticides and sediments run-off, marine debris), control of COTS outbreaks, reduction in cumulative impacts, increased biodiversity protection, and restoration and adaptation initiatives. It is anticipated that NESP research results will also contribute to the development of the next Scientific Consensus Statement, which is the scientific evidence base that will inform the review of the Reef 2050 Water Quality Improvement Plan. NESP TWQ Hub research results also provided reviewed water quality guideline values (e.g. Kroon et al., 2015) including based on emerging ecotoxicology data in order to reduce the potential impacts of pesticides on GBR species and habitats (Negri, Templeman, et al., 2020).

Finally, numerous NESP TWQ Hub projects contributed to the improvement of the Reef 2050 Integrated Monitoring and Reporting Program Strategy (RIMRep) (GBRMPA, 2015) through: a) identification of additional indicators for monitoring programs required to populate cumulative risk maps (such as reef state and reef performance) (Castro-Sanguino et al., 2021, Uthicke et al., 2016), b) a proposed new cost-effective indicator based on benthic light (I_{bPAR}) (Robson et al., 2019; Robson et al., 2020), c) detection of relevant observational gaps required for bleaching prediction tools (Steinberg et al., in review), d) identification of reef recovery rates through the new Resilience-based Management system (Mason et al., 2020), and e) identification of priority species for inclusion in monitoring and surveillance based on key ecological functions (Wol fe et al., 2019).

3.3 Management applications

Most of the management applications resulting from NESP TWQ Hub research can be classified into three groups: 1) Objective and reliable systems for decision-making (through new information and quantitative tools), 2) Improved monitoring programs (through the development of new water quality indicators, thresholds or guidelines), and 3) Facilitated reporting (through access to new information, risk maps and ecosystem models).

3.3.1 Objective and reliable systems for decision-making

The development of cumulative impact risk maps, as well as the spatial and temporal assessment of ecological risks has application to guide management decisions about a range of activities in the coastal zone and inshore GBR waters (Uthicke et al., 2016, 2020). Furthermore, a better appreciation (through 3D bleaching maps) of which parts of the reef are more heat tolerant and therefore more likely to remain healthy into the future can inform spatial management decisions (Steinberg et al., in review). The new modelling framework proposed by Cantin, Baird, et al., (2021) could be used to identify management options that can mitigate the effects of warming on reefs exposed to water quality pressures. More specifically, the eReefs model was refined to assess bleaching risks and to derive water quality management scenarios expected to maximize coral survival under a warming climate (Cantin, Baird, et al., 2021; Morris et al., 2019).

NESP TWQ Hub funded research also confirmed the importance of protecting reefs from extractive activities (i.e. using no-take zones) by enhancing population recovery and long-term persistence of targeted fish and their ecological functions. However, it was demonstrated that zoning is more effective if complemented by additional protection measures (such as no anchoring areas), particularly in ‘key’ refugia reefs and areas of special value (Emslie et al., 2015; Sweatman et al., 2015; Williamson et al., 2014, 2016).

The COTS Integrated Pest Management Strategy and associated local/regional decision support tools provided managers with a robust system for planning COTS control activities and for assessing and refining the strategies and objectives of their approaches. Managers and policy makers were provided with guidelines on how to progress the development of a successful COTS control program for the GBR. Additional specific recommendations were also provided, such as to perform surveillance (manta-tows surveys) to assess each area before starting manual removal and to adopt the level of 0.12 COTS per tow as an ‘outbreak’ threshold for reporting. Detection of COTS eDNA was also proposed as a complementary tool to traditional monitoring (Fletcher et al., 2020; Fletcher & Westcott, 2016; Westcott et al., 2016) (see Erdmann et al., (2021) for full synthesis of COTS research).

Spatial information to inform resilience-based management was a key deliverable by several NESP TWQ Hub projects, including to inform management of connectivity of values across jurisdictions and support cross-jurisdictional policy and planning (Johnson et al., 2018a).

Results suggest that in order to manage connectivity, managers should identify priority values and attributes, and then (using online interactive maps), consider the location, direction and strength of connections that are important to sustaining those attributes. With this knowledge, managers can identify jurisdictions with features or processes that are important to sustaining priority values, and collaborate with those jurisdictions to develop shared management plans for values that span boundaries (Johnson et al., 2018a).

Reef restoration and adaptation is an emerging research field that NESP TWQ Hub research progressed, with best practice guidelines developed in order to maximise the chances of success and lower the risks in the GBR (Boström-Einarsson et al., 2018, 2020; McLeod et al., 2020). The identification of genetic markers for thermal resistance in corals can support restoration efforts by locating key coral populations for protection, reefs to focus resilience-based management and potential breeding stock for reef restoration activities (Quigley et al., 2021).

Finally, the new guidance system to implement Resilience-based Management in the GBR is helping GBRMPA make tactical and dynamic decisions regarding the effects of cumulative pressures for reef resilience (Mason et al., 2020).

3.3.2 Improved monitoring programs

In order to improve monitoring data for most contaminants of emerging concern, NESP TWQ Hub researchers proposed the inclusion of all relevant environmental data into integrated databases for building marine baselines for the GBR and Torres Strait regions, and the implementation of local, targeted monitoring programs informed by predictive methods for risk prioritisation (Kroon et al., 2015; Kroon, Berry, et al., 2020).

GBR monitoring was also bolstered through a proposed new water quality indicator (I_{bPAR}), which allows estimation of trends and prediction of ecological consequences of human activities (e.g. run-off) while being a cost-effective way to directly inform Reef Integrated Monitoring Plans and Report Cards (Robson et al., 2019; Robson et al., 2020).

Furthermore, new research on toxicity levels of some common pesticides on tropical marine and freshwater species contributed to the revision of metrics for evaluation of pesticide risk assessment and reporting for: (i) Queensland Regional Report Cards (Wet Tropics, Dry Tropics and Mackay Whitsunday regions), (ii) the Paddock to Reef Integrated, Monitoring, Modelling and Reporting program, (iii) Reef Water Quality Report Cards, (iv) regional Water Quality Improvement Plans (WQIP), (v) risk assessments for alternate pesticides, and (vi) spatial management prioritisation for the review of the Reef 2050 Water Quality Improvement Plan (Negri, Smith, et al., 2020).

Finally, the Reef Functioning Management Framework developed provided a stepwise method to assess coral reef species based on functional importance, vulnerability and manageability. This outcome aligned closely with RIMRep as it advised on priority species for inclusion in monitoring and surveillance activities (Wolfe et al., 2019).

3.3.3 Facilitated reporting

Reporting by a range of government agencies and regional bodies responsible for GBR management, such as GBRMPA, now has a range of tools available to access spatial and resilience data, including eAtlas, eReefs, and the newly developed RBM guidance system. These online tools offer open-access data, ecosystem models and predictions that enable the integration of information to provide potential future scenarios for the reef, which will be valuable for future GBRMPA Outlook Reports.

4.0 FUTURE DIRECTIONS FOR RESILIENCE-BASED MANAGEMENT

4.1 Investment priorities to support on-ground activities

The main pressures affecting the health of the GBR and its resilience are climate change (e.g. marine heatwaves causing bleaching events, ocean acidification, sea-level rise), severe cyclones, outbreaks of pest species such as COTS and other cumulative impacts caused by poor water quality and coastal development. As climate change requires global mitigation efforts, NESP TWQ Hub research highlighted the need to continue to invest in local and regional pressures amendable to management, such as water quality and COTS control in order to 'buy the reef time'.

While the NESP TWQ Hub contributed new information to improve management of single pressures, such as COTS outbreaks (see Erdmann et al., 2021) and poor water quality (see Pineda & Waterhouse, 2021; and Waterhouse & Pineda, 2021), understanding and addressing the synergistic and additive impacts of multiple pressures remains key for supporting reef resilience, particularly in a warming climate (Morris et al., 2019; Williamson et al., 2016). Investments in research to understand how multiple pressures interact, which pressures are priorities for management, and especially where management should focus effort are needed to maintain a healthy GBR. Addressing local-scale impacts on tropical marine ecosystems is critical for maintaining healthy ecosystems in order to build resilience to drivers of change, and secure future adaptation options for marine systems (Anthony et al., 2011; Bell et al., 2013; Hoegh-Guldberg et al., 2009; Wilkinson & Brodie, 2011). For example, management of nutrient enrichment can reduce the effects of low-moderate thermal stress on corals and thus support reef condition and resilience.

Monitoring on the GBR remains another on-ground activity that is essential to increase understanding of cumulative pressures, ecological responses, contaminants of emerging concern (i.e. microplastics, antifouling paints, UV filters, heavy/trace metals, hydrocarbons, pharmaceuticals and microplastics), bleaching risks, COTS outbreaks, the state of refuge reefs, and key species in order to inform management. New field data collected can contribute to improve ecosystem models and reduce uncertainty, enabling online platforms such as eAtlas and eReefs to make more accurate predictions and provide scenarios to inform reef managers (Cantin, Baird, et al., 2021; Fletcher et al., 2020; Kroon et al., 2015; Kroon, Berry, et al., 2020; Robson et al., 2019; Robson et al., 2020; Steinberg et al., in review; Uthicke et al., 2016, 2020; Wolfe et al., 2019). Additional water quality monitoring data from mid-shelf area of the GBR is also required to attribute spatial and temporal changes in reef and seagrass communities to episodic and chronic changes in water quality. Improved water quality monitoring and development of new proxies for water quality should also be a priority for future monitoring projects (Uthicke et al., 2020).

Finally, protection of live coral and reef habitat structural complexity, as well as other species or taxa with key environmental functions, must remain a high priority in order to maximise the natural resilience of the GBR and adjacent waters (Sweatman et al., 2015; Williamson et al., 2016; Wolfe et al., 2019).

4.2 Investment priorities for research to address knowledge gaps

Similarly, additional research has been suggested in the following fields in order to inform management and policy decisions that will maintain and improve the condition of marine environments in the GBR and adjacent regions as disturbances accelerate:

- Access to environmental data in the public domain through integrated databases for building marine baselines and community understanding of issues (Kroon et al., 2015; Kroon, Berry, et al., 2020).
- Increasing access of research data for the public and key stakeholders through appropriate online tools that inform local decision-making. Future investment could focus on canvasing end-user needs and developing a tailored online resource.
- Water Quality: Additional development of a benthic light indicator (I_{bPAR}) in order to automate and incorporate into Reef Report Cards and relevant monitoring programs (Robson et al., 2019) and further assess drivers and ecological consequences of changing light (Robson et al., 2020).
- Cumulative pressures:
    - Additional concentration-response experiments for key tropical species under different conditions (sediments, turbidity, nutrients, light, salinity and temperature) are still required to obtain critical exposure thresholds and further optimise exposure maps and guideline values for interacting pressures (Uthicke et al., 2020).
    - In order to understand the real risks posed by emerging pesticides in combination with other pressures (e.g. climate change), further targeted multiple stressor toxicity testing is recommended (Negri, Templeman, et al., 2020).
    - Climate adjusted thresholds for water quality guidelines (e.g. how trigger values for pesticides will have to be reduced as species sensitivity increases with temperature rises) (Negri et al., 2019; Negri, Smith, et al., 2020)
    - Further explore and quantify the linkages between water quality and the thermal tolerance of GBR coral reefs, particularly functionally important and foundational taxa. However, future research needs to take into account compositional differences between inshore and mid-shelf reefs when predicting bleaching risk and include the influence of substrate composition on recruitment and recovery along water quality gradients and across different reef locations (Cantin, Baird, et al., 2021).
    - Additional field-based studies to determine how coral reef communities assimilate available particulate nutrients will assist in resolving the overall contribution of terrestrial inputs to the GBR lagoon and the responses of inshore reef ecosystems under different climate scenarios (Cantin, Baird, et al., 2021).
    - Further examine the ecological impacts of marine plastic pollution, chronic contamination of antifouling paints, and certain pharmaceuticals on GBR and Torres Strait marine organisms and ecosystems, including the cumulative impacts with ocean acidification and sea temperature increase (Kroon et al., 2015; Kroon, Berry, et al., 2020).

4.3 Integrated research and on-ground actions

Finally, additional integrated research and on-ground actions are proposed in the following topics:

- Connectivity: A strategic assessment of how changing pressures (i.e. climate change, coastal development and population growth) are expected to influence connectivity of key values would supplement the documented connectivity maps and inform cross-jurisdictional management priorities (Johnson et al., 2018a).
- Reef restoration and adaptation: Coral restoration is increasingly being presented as one of many strategies to strengthen the resilience of coral reefs in the face of rising anthropogenic and climate change pressures. However, coral restoration and adaptation research requires partnerships that span beyond research and include engineers, social scientists, modellers, economists, infrastructure development experts and potentially tourism and other sectors. It is also important to continue collaborations with researchers internationally and with other sectors not currently involved in reef management, through coordination organisations and networks such as the Coral Restoration Consortium, the International Coral Reef Initiative, RRAP, The United Nations, and the International Coral Reef Society. Despite the ongoing refinement of techniques in reef restoration and adaptation, and the growing focus on scaling up both spatially and temporally, it is important to consider that coral restoration methods could be an important component of resilience-based management, provided the causes of coral damage are addressed (e.g. climate change) (Boström-Einarsson et al., 2018, 2020; McLeod et al., 2020).
- Future outlook for coral reefs: Finally, national and global greenhouse gas emission reduction strategies are required to rapidly reduce the global warming rate in the next 5-10 years in order to reduce the frequency and severity of ocean heat waves leading to widespread coral bleaching on the GBR (Cantin, Baird, et al., 2021).

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APPENDIX 1: SUMMARY OF RELEVANT PROJECTS

Table A1.1: Summary of projects and relevant information relevant to the synthesis topic (*Improving coral reef condition through better-informed resilience-based management*), previous to the NESP TWQ Hub (2015-2022).

Project Title	Ref.	Summary of knowledge relevant to the synthesis topic (6.5 ***Improving coral reef condition through better-informed resilience-based management***)
National Environmental Research Program (NERP, 2011-2015) (Tropical Ecosystems Hub)		
Monitoring status and trends of coral reefs of the GBR *(Project 1.1)*	(Miller & Sweatman, 2013)	• Storm damage from several tropical cyclones led to a strong overall decline in coral cover in the GBR in recent years. • Outbreaks densities of crown-of-thorns starfish (COTS) were recorded on 30% of reefs surveyed in 2012-13.
Monitoring the health of Torres Strait coral reefs *(Project 2.3)*	(Bainbridge et al., 2015; Johnson et al., 2015)	• Surveys showed that in general Torres Strait reefs were in good to excellent condition (i.e. in 2013) with high coral cover, presence of the major taxonomic and functional groups and minimal incidence of coral disease. • However, small scale outbreaks of COTS and some temperature-sensitive coral decline were observed.
Tracking coastal turbidity over time and demonstrating the effects of river discharge events on regional turbidity in the GBR *(Project 4.1)*	(Fabricius et al., 2014; Logan et al., 2014b)	• Photic depth was strongly negatively related to the freshwater discharge of the main rivers, starting with river floods and taking up to 150-260 days until complete recovery. • River runoff not only affects the inshore of the GBR as previously thought, but it can also reach most of the main reef matrix in central and norther areas, possibly due to the narrowness of the continental shelf on these areas combined with relatively high anthropogenic contributions to river nutrient loads. • Reductions in river loads all along the GBR coastline should lead to improvements in the GBR water clarity.
Chronic effect of pesticides and their persistence in tropical waters *(Project 4.2)*	(Devlin & Negri, 2015; Flores et al., 2013; Wilkinson et al., 2017)	• Pesticides, and particularly herbicides from agricultural sources, have been detected in nearshore sites of the GBR all year round. • Phytotoxicity data was obtained for 5 species of seagrasses under the effects of 8 PSII herbicides. • Cumulative impacts of other pressures such as extreme temperatures and light levels increased the sensitivity response of seagrasses to herbicide exposures.

Project Title	**Ref.**	**Summary of knowledge relevant to the synthesis topic (6.5 *Improving coral reef condition through better-informed resilience-based management*)**
Hazard assessment for water quality threats to Torres Strait marine waters, ecosystems and public health *(Project 4.4)*	(Johnson et al., 2015; Waterhouse et al., 2013)	• The main pollutant sources identified in Torres Strait were: i. Local island waste management; ii. Shipping, commercial vessels and marine infrastructure; and iii. Large-scale developments in adjacent areas (i.e. PNG) • The major risk to the ecological values of the Torres Strait region is associated with the transit of large ships.
Understanding diversity of the GBR: spatial and temporal dynamics and environmental drivers *(Project 5.1)*	(De'ath et al., 2012; RRRC, 2015)	• An overall decline in coral cover from 28 to 13.8% was reported based on time series data on reef condition from 1985-2012 (i.e. a 50.7% loss of initial coral cover). • Tropical cyclones, coral predation by COTS and bleaching accounted for the 42%, 48 and 10% mortality, respectively. • At the reported rate of decline, coral cover was estimated to fall to 5.2% (CI=2.9%, 8.7%) by 2025.
Combined water quality and climate effects on corals and other reef organisms *(Project 5.2)*	(RRRC, 2015; Schmidt et al., 2014; Vogel et al., 2015)	• Individual and cumulative impacts of water quality (nutrients, turbidity, light, sedimentation), ocean warming (elevated temperature, salinity) and ocean acidification were assessed on corals, algae, seagrasses, foraminifera and echinoderms. • The combination of stressors showed additive effects in many cases, suggesting that land management can ameliorate impacts of climate change
Assessing the long term effects of management zoning on inshore reefs of the GBR *(Project 8.2)*	(Ryan, 2015)	• Abundances of fishery-targeted species have increased significantly on most green zone reefs. • Coral diseases were 2-7 times more prevalent on non-reserve reefs than within green zones, • However, green zones cannot prevent degradation from a range of acute and chronic disturbances such as cyclones, floods, coral bleaching events, declining water quality and increasing sedimentation. These stressors must be addressed through effective coastal catchment and water quality management, as well as decisive global action on climate change.

Project Title	Ref.	Summary of knowledge relevant to the synthesis topic (6.5 *Improving coral reef condition through better-informed resilience-based management*)
Dynamic vulnerability maps and decision support tool for the GBR *(Project 9.1)*	(Anthony et al., 2015)	• Coral reefs are currently threatened by cumulative pressures from global climate change and multiple regional and local-scale stressors. • Increased press-type stressors (e.g. pollution, sedimentation, overfishing, ocean acidification) can reduce resilience to pulse-type disturbances (e.g. cyclones, coral bleaching events, destructive fishing, COTS outbreaks, flood events). • Strategic management for increased ecological resilience can reduce coral reef vulnerability. • The Adaptive Resilience-Based management (ARBM) framework can contribute to enhance resilience via management interventions. • Priority levers for ARBM in the GBR: influence national emissions policies, improve land-use management to reduce pollution, fisheries management, network of no-take areas, COTS management at local scales, build resilience for fishers and tourism operators.
Commonwealth Environmental Research Facilities (CERF, 2005-2011) (Marine and Tropical Sciences Research Facility)		
Identification of indicators and thresholds of concern for ecosystem health on a bioregional scale for the GBR *(Project 1.1.1)*	(Delean & De'ath, 2008)	• Analyses showed that reefs in the central inner-shelf regions of the GBR were in poor health. • Poor health indicators were linked with low levels of water quality (low clarity and high chlorophyll). • Results showed consistent declines in benthic health of the inner and mid-shelf regions of the GBR over the last decade, but improvements in the relative health of fish communities, in particular on the outer shelf.

Project Title	Ref.	Summary of knowledge relevant to the synthesis topic (6.5 *Improving coral reef condition through better-informed resilience-based management*)
Early warning and assessment system for thermal stress on the GBR *(Project 2.5i.2)*	(Anthony et al., 2008; Anthony et al., 2009; Császár et al., 2010; Diaz-Pulido et al., 2009; Maynard et al., 2008)	• A new model was developed for predicting coral mortality during and following bleaching events. • Ocean acidification was predicted to lead to increased bleaching overtaking the importance of ocean warming by 2050. • Bleaching events can potentially increase the thermal tolerance of the remining coral population to subsequent thermal stress events. • Coral can potentially recover from large scale bleaching within an annual cycle through coral tissue regeneration and seasonal algal dynamics. • The heritability of key genetic traits within corals and their symbionts was studied to determine if corals could respond to selection for increased thermal tolerance.
Resilience to climate change *(Project 2.5i.3)*	(Hughes, 2010; Maynard et al., 2011)	• High rates of self-recruitment and population inbreeding in a brooding coral (*Seriatopora hystrix*) in sheltered habitats within protected bays, suggest that those populations are particularly vulnerable to disturbance and extinction. • Environmental drivers of coral disease (e.g. white syndrome) were identified and linked to thermal anomalies associated with climate change, enabling the development of disease outbreak response plans for the GBR.
Tools to support resilience-based management in the face of climate change *(Project 2.5i.4)*	(Waterhouse & Devlin, 2011; Wooldridge, 2009)	• The benefit of 20%, 40%, 60% and 80% reductions in end-river dissolved inorganic nitrogen (DIN) concentrations in raising the thermal tolerance (i.e. bleaching 'resistance') of the GBR was modelled under different climate change scenarios. • Considerable improvements in the future survival prospects of corals were found under simulated reductions in DIN loads. • Results demonstrated that both local and global strategies are needed to prevent mortality risk and loss of resilience in the GBR.
Marine and estuarine indicators and thresholds of concern *(Project 3.7.1)*	(Cooper et al., 2009; Waterhouse & Devlin, 2011)	• Decreases in water quality cause shifts from phototrophic to heterotrophic communities and from reef-building coral dominated communities to sites dominated by macroalgae and abiotic substrata, on the inshore GBR. • Turbidity was by far the best predictor of biota and should be the first priority for monitoring water quality on the inshore GBR. • The project delivered a final list of 11 bioindicators useful for water quality monitoring on the GBR.
Connectivity and risk: tracing materials from the upper catchment to the reef *(Project 3.7.2)*	(Waterhouse & Brodie, 2011)	• The priority pollutants derived from anthropogenic land uses considered most likely to pose a threat to the quality of runoff water entering the GBR ecosystem are suspended sediment, dissolved inorganic nitrogen (DIN) and photosystem II (PS-II) herbicides. • Regarding management prioritisation, the Wet Tropics and Mackay Whitsunday regions have the highest priority ranking (High), the Burdekin and Fitzroy catchments a relatively high priority (Medium-high) and the Burnett Mary catchments a moderate priority in terms of the contribution and influence of land-based pollutants.

Project Title	**Ref.**	**Summary of knowledge relevant to the synthesis topic (6.5 *Improving coral reef condition through better-informed resilience-based management*)**
Theme 5. Thresholds of major pollutants with regard to impacts on instream and marine ecosystems	(Waterhouse, 2010)	• High levels of dissolved inorganic nitrogen can cause physiological changes in corals, including decalcification. • Macroalgae and heterotrophic filter-feeders benefit more from dissolved inorganic and particulate organic nutrients, out-competing corals. • Light limitation, from increased turbidity, reduces photosynthesis leading to slower coral growth. • Sedimentation reduces coral recruitment and coral biodiversity. • Outbreaks of COTS have been linked to high nutrient levels, with larvae being transported then by currents to remote regions. • Herbicides found in GBR waters have biological effects on coral Symbiodiniaceae at concentrations below 1 ug/L. • Resilience of the GBR inshore system is affected by loads of pesticides delivered from catchments in the wet season, together with sediments and low-salinity conditions when corals and seagrasses may already be suffering from high temperatures. Runoff of pesticides and herbicides is therefore likely to be contributing to degradation of ecosystem resilience of the inshore reefs in the GBR.
Theme 5. Water quality and climate change: Managing for resilience	(Johnson & Martin, 2011)	• Effective management and strategic investment in enhancing reef resilience (such as improvements to water quality), will help mitigate some of the risks associated with climate change in the GBR, giving natural communities time to adapt or acclimatise to a changing environment. • Quantifying the link between water quality and bleaching risk, together with a model exploring patterns of land use and changes in land management, will enable management to target areas to focus effort and cost-effective solutions to achieve water quality targets. • There is an emerging consensus that water quality is one of the high-priority management issues for the GBR, particularly in the face of climate change.
Australian Climate Change Science Programme (ACCSP, 1989-2016)		
Ocean Acidification *(Project 3.4)*	(ACCSP, 2016; Mongin et al., 2016)	• Corals need aragonite (a form of calcium carbonate) to build their exoskeleton, but ocean acidification is lowering the aragonite saturation state of seawater. • Results showed that future decline in the aragonite saturation state of seawater is likely to be steeper on the GBR than currently projected by the IPCC assessment report.

Table A1.2: List of NESP TWQ Hub projects and relevant information relevant to the synthesis topic (*Improving coral reef condition through better-informed resilience-based management*). Summary of research outcomes, innovations in methodology and delivery and implications for policy and management.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Cumulative Impacts Affecting Coral Reef Resilience in the GBR				
Dr L Bay (AIMS) - Quantifying the linkages between water quality and the thermal tolerance of GBR coral reefs *(Project 3.3.1)*	(Cantin, Baird, et al., 2021; Morris et al., 2019)	• The ability of corals to resist and recover from bleaching was assessed under different water quality parameters (nutrients/light/turbidity). • Nutrient availability and metabolism affect the stability of coral-Symbiodiniaceae symbiosis. • Historical nutrient conditions mediate host-symbiont compatibility and bleaching tolerance over proximate and evolutionary timescales.	New modelling framework to identify management options that would mitigate the effects of warming on reefs exposed to WQ pressures	The eReefs model was refined to derive WQ management scenarios expected to maximize coral survival in a warming climate.
Dr N Cantin (AIMS) - Assessment and communication of the spatial variability in bleaching severity throughout the GBR following back-to-back bleaching events in 2016 & 2017 *(Project 5.7)*	(Cantin, Klein-Salas, et al., 2021)	• The project assessed all available bleaching observations to provide an assessment of the spatial extent and severity of the 2016 and 2017 thermal bleaching events and an interpretation of the spatial variability in coral mortality. • The spatial footprint and duration of extreme accumulated heat stress and levels of severe bleaching and coral mortality were greater during the 2016 and 2017 bleaching events than previous events. • After the back-to-back bleaching events of 2016 and 2017, 45% of total reef area had been exposed to extreme heat stress (DHW > 8), with 51% of reefs at this level of heat stress experiencing coral community impacts.	All model analysis, spatial maps, images of coral bleaching and mortality and survey data were made publicly available through the eAtlas platform.	It is important to use available data to support the accurate communication of bleaching impacts and the threat of ocean warming for industries reliant upon the GBR and for the future of management strategies.

Project Title	**Refs.**	**Summary of research outcomes**	**Innovations**	**Implications for Management**
Prof G Jones (JCU) - Assessing the cumulative impacts of climatic disturbances in inshore GBR coral reefs, identifying key refuges and testing the viability of manipulative reef restoration *(Project 2.1)*	(Williamson et al., 2014, 2016)	• The project identified and mapped key local refuge reefs that are critical to the replenishment of degraded reefs, within the Keppel Islands (south GBR). • Marine Park Zoning had an overall positive effect in fish, but frequent and severe climatic disturbance events seem to progressively undermine many of the accrued benefits of green zones.	Active restoration through removal of macroalgae and transplantation of live coral could assist in recovery of degraded reefs, but it requires a previous analysis of costs and benefits.	Effective management is required to enhance reef resilience, such as: -Additional protection in key refuge reefs (e.g. no anchoring). -Improvements in river catchment management to minimise soil erosion and reduce chronic effects of sedimentation and poor water quality in coastal waters of the GBRMP.
Dr F Kroon (AIMS) - Identification, impacts and prioritization of emerging contaminants present in the GBR and Torres Strait marine environments *(Project 1.10)*	(Kroon et al., 2015; Kroon, Berry, et al., 2020)	• The presence and locations of emerging contaminants (i.e. alternate pesticides, endocrine disrupting chemicals, coal dust, hydrocarbons, metals, microplastics, pharmaceuticals and personal care products) was determined based on monitoring data and the types of human activities present. • Some emerging contaminants (personal care products i.e. such as the UV filter Benzophenone 3, chronic antifouling contamination and marine plastic debris i.e. macro- and microplastics) were identified as priorities based on their potential risk to the marine environment.	The new spatial representation of the sources of emerging contaminants will contribute to future ecological risk assessment. New pesticide water quality guidelines were developed.	The study highlights the lack of available monitoring data for most emerging contaminants and recommends (i) the inclusion of all relevant environmental data into integrated databases for building marine baselines for the GBR and TS regions, and (ii) the implementation of local, targeted monitoring programs informed by predictive methods for risk prioritization.
Prof P Mumby (UQ) - Recommendations for maintaining functioning of the Great Barrier Reef *(Project 4.6)*	(Wolfe et al., 2019)	• Identification of key species (or functional groups) that drive functioning coral reefs. • Description of threats facing these key species and ranking their vulnerabilities. • Proposed management actions to reduce those threats. • Scenarios were generated based on different outcomes regarding the protection of those key species.	Reef Functioning Management Framework (recommendations on what can be done to strengthen and protect key supportive species)	The Reef Functioning Management Framework provides a stepwise method to assess coral reef species based on functional importance, vulnerability and manageability. The project is closely aligned with RIMReP as it advises on priority species for inclusion in monitoring and reconnaissance activities.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr C Steinberg (AIMS) - Oceanographic drivers of bleaching in the GBR: from observations to prediction *(Project 4.2)*	(Steinberg et al., in review)	• The project aimed at understanding how local, regional and global oceanographic and meteorological processes influence the severity and spatial variability of thermally driven coral bleaching for the GBR and Torres Strait. • Oceanographic conditions during the 2015-17 bleaching events were summarized, with cold-water intrusions being linked to areas where bleaching was not observed. • Regional bleaching patterns were identified and prediction tools developed (i.e. bleaching hazard or susceptibility map of the GBR). • Seasonal prediction tools of marine heatwaves in the GBR were improved.	The project produced: 3D versions of remotely sensed bleaching products by NOAA and BoM; and a seasonal prediction capability for marine heatwaves.	A better appreciation of which parts of the reef are more tolerant and therefore more likely to retain their health into the future, could be used to better manage the GBR. Relevant observational gaps were detected and informed the RIMRep. Potential refugia within the GBR were identified and informed risk assessments such as the Reef Havens initiative and other activities.
Dr S Uthicke (AIMS) - Multiple and cumulative impacts on the GBR: assessment of current status and development of improved approaches for management *(Project 1.6)*	(Uthicke et al., 2016)	• Provided a review and synthesis of existing tools and qualitative and quantitative studies that describe cumulative impacts on reef ecosystems. • Road map to develop a practical framework to support assessment and management of cumulative impacts on the GBR.	New dynamic mechanistic model that enables predictions of cumulative risk in space and time for complex environmental scenarios.	A structured approach was developed to show how cumulative impact assessments can inform decision-making, building on the Drivers-Pressures-State-Impacts-Responses (DPSIR) framework. The new cumulative impact risk maps could guide management decisions around development proposals.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr S Uthicke (AIMS) - From exposure to risk: novel experimental approaches to analyse cumulative impacts and determine thresholds in the GBRWHA *(Project 2.1.6/5.2)*	(Brunner et al., 2020; Castro-Sanguino et al. 2021, Humanes et al., 2016; Marques et al., 2020; Negri et al., 2019; Negri, Smith, et al., 2020; Uthicke et al., 2020)	• Concentration-response experiments were performed for selected species under different conditions (sediments, turbidity, nutrients, light, salinity and temperature) to determine critical exposure thresholds. • Exposure maps were produced for individual stressors and cumulative pressures. • Guideline Values for pollutants were adjusted to account for thermal stress events. • Cumulative effect of nutrient enrichment and high temperatures had a negative impact on the overall larval supply and recruitment of *Acropora tenuis* in experimental conditions.	Climate adjusted thresholds for water quality guidelines. A set of 25 important environmental pressures were combined into exposure maps available through the eAtlas. Online interactive tool.	Results will inform spatial and temporal assessments of ecological risks, and management opportunities for a range of activities in the coastal zone and inshore GBR waters.
Building Reef Resilience				
Dr K Fabricius & B Robson (AIMS) - Benthic light as ecologically-validated GBR-wide indicator for water quality: drivers, thresholds and cumulative risks *(Project 2.3.1 / 5.3)*	(DiPerna et al., 2018; Magno-Canto et al., 2019; Robson et al., 2019; Robson et al., 2020)	• Water Quality indicators were developed based on the amount of light that penetrates to the seafloor, using satellite data validated through in-situ light loggers. • Minimum light requirements and thresholds for healthy corals were also determined using experimental and field data.	The new water quality indicator will allow estimating trends and predicting ecological consequences of human activities (e.g. run-off, dredging).	The new indicator could become a cost-effective means to directly inform Reef Integrated Monitoring Plans and Report Cards.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr A Negri (AIMS) - Ecotoxicology of pesticides on the Great Barrier reef for guideline development and risk assessments *(Project 3.1.5)*	(Flores et al., 2020; Negri, Templeman, et al., 2020; Thomas et al., 2020)	• The toxicity of 21 land-source pesticides (herbicides, insecticides and fungicides) to 16 tropical aquatic species was assessed in order to improve water quality guidelines and assessments of their potential risks to the GBR. • Most herbicides tested were less toxic than the reference Photosystem II herbicide diuron. • Most non-PSII herbicides had far less effect on the growth of both marine and freshwater microalgae. • Some insecticides/fungicides were moderately toxic to coral larvae.	Toxicity levels found will be used for development of (i) National and GBR ecosystem protection guidelines, (ii) toxic equivalency values, (iii) toxic loads and multisubstance-potentially affected fraction (ms-PAF) values.	The data contributed to the revision of metrics for pesticide monitoring and reporting for: (i) QLD Regional Report Cards, (ii) Reef Plan 2013, (iii) GBR Report Cards, (iv) Reef 2050 Long Term Sustainability Plan, (v) regional Water Quality Improvement Plans (WQIP), (vi) chemical risk assessments for pesticide registration and review, (vii) risk assessments for alternate pesticides, and (viii) ecological risk assessments (Scientific Consensus Statement).
Dr H Sweatman (AIMS) - Monitoring the effects of zoning on coral reefs and their associated fish communities in the GBR Marine Park *(Project 3.7)*	(Emslie et al., 2015; H. Sweatman et al., 2015)	• Protection from fishing (no-take zones) has a clear effect on target species (e.g. coral trout), but few indirect effects on other components of the reef community, such as herbivorous fishes and hard coral. • Major disturbances caused by cyclones may have swamped some more subtle indirect effects of zoning.		No-take zones cannot protect coral reefs directly from acute regional-scale disturbances, but after a strong tropical cyclone, protected reefs supported higher biomass of targeted fishes and could enhance population recovery and long-term persistence.
Dr D Westcott (CSIRO) - Establishing the future NESP COTS research framework including an ecologically-based approach to the management of COTS at multiple scales *(Project 1.1)*	(Westcott et al., 2016)	• A research strategy (Integrated Pest Management approach) was developed, based on how COTS outbreaks arise and how they spread in order to achieve efficient and effective management solutions on COTS control. • Suggested areas of research investment included the optimisation of control at both local and regional scales, addressing ultimate causes to prevent future outbreaks and developing new control technologies.	Introduction to the Integrated Pest Management (IPM) of COTS.	Suggested management strategies included: (i) Control at sites and local areas, (ii) protection of assets, (iii) minimize outbreak's spread, (iv) prevention of primary outbreaks, (v) managing ultimate causes and (vi) implementation of non-manual controls.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr D Westcott (CSIRO)- Integrated Pest Management of Crown-of-Thorns Starfish *(Project 2.1.1)*	(Fletcher & Westcott, 2016; Hall et al., 2017; Sweatman & Cappo, 2018; Uthicke et al., 2018)	• Development of an Integrated Pest Management (IPM) approach based on detailed understanding of COTS ecology and management operations. • Recommendations for managers were provided regarding surveillance and control. • The giant triton snail (*Charonia tritonis*) could mitigate populations of COTS through direct predation or the creation of 'landscapes of fear' (deterrent effect through chemicals released). • eDNA of COTS was detected using digital droplet PCR. The method could be optimised to supplement or replace traditional monitoring in the field.	Improvement of surveillance (e.g. eDNA) and natural control technologies (i.e. predation/deterrent effect by giant triton snail).	Recommendation to perform surveillance (manta-tows surveys) at each area before starting removal and specifics to improve the efficiency of the COTS control program. The level of 0.12 COTS per tow should be adopted as an 'outbreak' threshold for reporting. Detection of COTS eDNA could e traditional monitoring.
Dr D Westcott (CSIRO) - Implementation of the Crown-of-thorns research strategy: regional strategies *(Project 3.1.1)*	(Beaman, 2018; Fletcher et al., 2020; Pratchett et al., 2020; Westcott et al., 2020; Wilmes et al., 2019)	• A decision support framework was developed to assist in prioritizing reefs for COTS control (regional scale) and for assessing alternative strategies by integrating the full range of ecological and management information available. • Assessment of deep-water habitat: Results showed a low risk of adult COTS outbreaks in deep-water habitats and a low probability of deep-water recruitment. • COTS movement on longer timescales: Most COTS remained within 50-100m for up to 6 months, despite having the capacity to move at 20-35 cm min^{-1} when required. • Predation during/immediately after settlement was found to likely have a major influence on population dynamics.	Three decision trees were described to ensure that key decision-making processes in the Expanded COTS Program are informed by the appropriate ecological principles (i.e. Intensive Control at Priority Reefs to achieve the Ecological Threshold).	Together with the local-area decision support tool (Project 2.1.1), the regional decision support tool will provide managers with a robust system for planning COTS control activities and for assessing and refining the strategies and objectives of their approaches.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr D Westcott (CSIRO) - Crown-of thorns starfish: surveillance and life history *(Project 4.1)*	(Westcott et al. 2020)	• The project supported the implementation of the NESP COTS Integrated Pest Management strategy. • Analysed existing datasets to address knowledge gaps (e.g. interaction between COTS, bleaching and management). • Obtained information on the key life history stages (e.g. age specific recruitment rates) and on predation (using faecal DNA sampling methods). • New tools were developed to detect and control new outbreaks (e.g. COTS detection using eDNA technologies.	eDNA technologies to assist in the monitoring of COTS outbreaks.	Guidelines were provided for managers and policy makers on how to progress the development of a successful COTS Control Program for the GBR.
Coral Reef Restoration and Adaptation				
Dr K Quigley (AIMS) - The traits of corals that survived recent bleaching events *(Project 4.4)*	(Fuller et al., 2020, Quigley et al., 2021)	• High throughput genomic sequence variant analysis identified genes in corals associated with bleaching tolerance (i.e. *sacsin* gene in *Acropora millepora*). • Amplicon sequencing identified Symbiodiniaceae shifts in three coral species associated with bleaching susceptibility and tolerance: higher proportion of the thermally-tolerant *Durusdinium* spp in *Acropora millepora* versus other Acroporid species. • The project developed a spatially explicit understanding of the distribution and abundance of bleaching tolerant symbionts across multiple coral species. • *Symbiodiniaceae* dynamics within corals and the environment were also described before, during and following bleaching.	Genetic markers and symbionts that enabled survivouring corals to withstand high temperatures were identified.	Using genetic analysis, the project identified key coral species and populations for protection, key reefs for resilience management and potential breeding stock for use in reef restoration activities.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr I McLeod (JCU) - Best practice coral restoration for the Great Barrier Reef *(Project 4.3)*	(Boström-Einarsson et al., 2018, 2020; McLeod et al., 2020)	• The success of coral reef restoration and assisted recovery worldwide was summarized and evaluated, including the identification of most suitable techniques for the GBR. • The most promising reef restoration techniques were experimentally tested. • The best practices for post-impact coral reattachment and reorientation were identified. • The project additionally explored options for training courses, offset models and Indigenous employment.	Global coral restoration and rehabilitation techniques assessed, through literature (including unpublished) and stakeholder engagement.	Best practice guidelines in reef restoration will contribute to increased chances of success and lower risk of these activities.
Facilitation resilience-based management in the GBR				
Dr J Johnson (JCU) - Defining the values of the ecological systems that influence the GBR and lie outside the marine park and world heritage area boundaries *(Project 3.3.3)*	(Johnson et al., 2018a, 2018b)	• The project filled in the knowledge gaps about values and connectivity across the different marine areas in the NE Australia marine ecosystem (GBRWHA, Coral Sea, Torres Strait and Great Sandy Marine Park) to inform effective and coordinated management. • The project delivered a resource that can inform cross-jurisdictional planning and management of the region.	Project outputs were driven by stakeholder needs and delivered using the eAtlas online platform (through interactive value maps as well as the direction and magnitude of connections).	The project delivered a product which can inform protected area management policy and planning in the GBRWHA as well as the Coral Sea, Torres Strait and Great Sandy Marine Park, and help Australia to more effectively meet its obligations as World Heritage Area managers in the region.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Prof P Mumby (UQ) - Guidance system for resilience-based management of the Great Barrier Reef *(Project 4.5)*	(Lam et al., 2020, Mason et al., 2020)	• The project developed a desktop software that enables users to prioritise which reefs to manage, and potentially restore, in order to maximise ecological and socio-economic outcomes. • The development of a Resilience-based Management (RBM) guidance system required (i) mapping current state of the reef, (ii) mapping social, cultural and economic values, (iii) mapping ecological values and ecosystem trajectories, (iv) matching management interventions to reef characteristics, and (v) the creation, testing, and refining of the RBM guidance system.	New guidance system to implement Resilience-based Management (RBM).	Outputs of this project will help GBRMPA (i) make tactical and dynamic decisions; (ii) provide scenarios of reef futures to support the Outlook reporting; (iii) support Reef 2050 RIMRep by identifying target reef recovery rates; and (iv) contribute to the IPM system to control COTS.

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