Tropical Water Quality Hub

National **Environmental Science** Programme

Synthesis Report

Restoring ecosystems from catchment to reef

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

Restoring ecosystems from catchment to reef

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Cover photographs: (front) Sugarcane drain. Image Nathan waltham. (back) Researcher assessing an alluvial gully in the Bowen catchment. Image Justin Stout.

This report is available for download from the NESP Tropical Water Quality Hub website:
http://www.nesptropical.edu.au

www.synthesis.nesptropical.edu.au

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ACRONYMS AND ABBREVIATIONS

AIMS .... Australian Institute of Marine Science
AMPTO………Association of Marine Park Tourism Operators
I_{bPAR} .... Benthic photosynthetically active radiation
CERF .... Commonwealth Environmental Research Facility
CLCAC………Carpentaria Land Council Aboriginal Corporation
COTS………..Crown-of-thorns starfish
CRC Reef .... Cooperative Research Centre for the GBRWHA
CSIRO .... Commonwealth Scientific and Industrial Research Organization
CYP…………Cape York Peninsula
DAWE .... Department of Agriculture, Water and the Environment
DEM .... Digital elevation models
DIN .... Dissolved inorganic nitrogen
DO……………Dissolved Oxygen
DOC .... Dissolved organic carbon
EOS .... End of system
ERF ....Emission Reduction Fund
ERTs .... Ecologically relevant targets
ES…………… Ecosystems services
GBR .... Great Barrier Reef
GBRMPA ..... Great Barrier Reef Marine Park Authority
GBRWHA .... Great Barrier Reef World Heritage Area
JCU .... James Cook University
LiDAR .... Airborne light detection and ranging
MTSRF .... Marine and Tropical Science Research Facility
NAER………..Northern Australia Environmental Resources
NERP .... National Environment Research Program
NESP .... National Environmental Science Program
NRM………….Natural Resource Management agencies
PAE…………. Potentially Active Erosion
PN……………Particulate Nitrogen
RRAP………..Reef Restoration and Adaptation Program
RRF………….Reef Restoration Foundation
RRRC .... Reef and Rainforest Research Centre
TNSC .... Total non-structural carbohydrates
TO……………Traditional Owners
TRARC………Tropical Rapid Appraisal of Riparian Condition
TSS .... Total suspended solids
TWQ .... Tropical Water Quality
UQ .... University of Queensland
WQ .... Water quality

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EXECUTIVE SUMMARY

The loss of values and functions provided by healthy coastal ecosystems has been identified as one of the major threats to the GBR. Ecosystem restoration can contribute to water quality improvements while providing additional hydrological, biodiversity, cultural and social benefits, despite requiring efforts, resources, and long-term commitment. Unfortunately, research effort into effective restoration of ecosystem values and function has been sporadic, and usually focused on very small-scale, short-term projects, not enabling a whole-of-catchment approach. Accordingly, several research projects were undertaken within the National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub to assist in developing and implementing practical solutions in ecosystem restoration, with a focus on the GBR catchment to reef (including freshwater, estuarine and marine ecosystems) and with specific objectives linked to long-term outcomes in a changing climate, from research to action.

The outcomes of these NESP TWQ Hub projects have:

- Investigated and trialled remediation methods for gully and streambank erosion, including the establishment of best practice guidelines; and developed a range of techniques for identifying, characterising, prioritising and evaluating future investments;
- Explored and identified potential cost-effective options for land use transition of high dissolved inorganic nitrogen risk marginal cane areas to alternative land uses to reduce nitrogen losses in wet and dry tropical catchments;
- Highlighted the need to incorporate long-term maintenance and protection of the restoration asset within the planning and funding of all restoration projects (e.g., removal of aquatic weeds from wetlands will likely be an on-going challenge);
- Developed monitoring programs and contributed to improve local technical skills to assess mangrove recovery in remote areas of the Gulf of Carpentaria. Proposed management strategies to mitigate the adverse impacts of future extreme climatic events in tidal wetland ecosystems;
- Developed a Mangrove Management Plan with Traditional Owners in the southern GBR. Built essential capacity amongst the Gidarjil Development Corporation Rangers and the local community to conduct ecological monitoring and assessment of key local estuarine resources;
- Contributed to guide seagrass conservation planning through prioritisation of at-risk communities that are continuing to fail desired states; Specifically, acute management thresholds (suited to compliance guidelines for managing short-term impacts) were proposed, from 2 to 6 mol quanta m^{-2} d^{-1} depending on species. Similarly, long-term thresholds (suited to the setting of water quality guidelines for catchment management) were suggested at around 10-12 mol quanta m^{-2} d^{-1} depending on species. This new knowledge is critical for assessing seagrass resilience, for deciding whether active seagrass restoration may be required or not and for identifying suitable donor sites if intervention is warranted;
- Identified the features of successful small-scale seagrass restoration projects and the technologies required to up-scale them in Australia. Suggested techniques included physical planting of seagrasses, distribution or planting of seagrass seeds, or coastal engineering to modify sediment regimes. New tools identified included buoy-deployed

seeding systems, dispenses injection seeders, artificial in-water structures to protect restoration sites, and land-based nurseries for propagation;
- Identified and trialled several coral restoration intervention types, with coral restoration at small scales (e.g., coral nursery and gardening projects), macroalgae removal, and COTS control being among the most successful strategies to improve the health of local reefs while educating the general public and providing stewardship opportunities. However, substantial scaling-up of these techniques would be required for restoration to be a useful tool to support the recovery and persistence of reefs on the GBR;
- Trialled methods for coral adaptation (through the Reef Restoration and Adaptation Program -RRAP), including the identification of the traits of corals that have survived bleaching (e.g., *sacsin* gene within *Acropora millepora*);
- Established that 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; and
- Contributed to building indigenous livelihoods and co-management opportunities in the Cape York Peninsula, with a focus on potential ecosystems services (particularly in water and catchment management).

Some of the innovations in research funded through the NESP TWQ Hub in the topic of ecosystem restoration included:

- Innovations in methodology and delivery in the field, including semi-automated gully mapping and gully databases, real-time water quality sampling at gully sites, mapping for land use transition projects, use of drone technology to support restoration following feral pig fencing, among others;
- Development and validation of new methods for streambank and gully remediation, such as the use of LiDAR;
- Additional development of methodology in wetlands research, such as the Shore Video Assessment Method (S-VAM);
- Shift from traditional passive habitat protection of the GBR towards the acceptance of active restoration and assisted coral adaptation as complementary tools for resilience-based management; and
- Identification of new livelihood opportunities through collaborations with Traditional Owners and Indigenous rangers.

It is clear that this integrated long-term approach in ecosystem restoration requires partnerships that span beyond the applied ecological research space to include engineers, social scientists, Traditional Owners, modellers, economists, infrastructure development experts, project managers and in-field practitioners. It is important to note that restoration to some arbitrary historical ecosystem condition is not the goal. Rather, this work is focused on how restoration can be used to help regain and maintain ecosystem values and services, and facilitate adaptation to increasing frequency and/or intensity of disturbances under future climate change and burgeoning human impacts.

This synthesis of research findings and learnings will contribute to inform investments in ecosystem restoration and environmental improvement works in GBR catchments (e.g., Reef Trust) and reef environments (e.g., RRAP), as well as to the development of key environmental policies and major reef programs and initiatives, including the next Scientific Consensus Statement on Water Quality, the Reef 2050 Water Quality Improvement Plan, Wetlands in the GBR Catchments Management Strategy 2016-2021, Reef Blueprint for Resilience, among others. Additionally, this synthesis provides advice on the practical on-ground actions for land and sea managers, policy implications and remaining gaps for future research and management investments.

1. 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 in environmental and climate science since 2015. All NESP-funded projects have been 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) and the Australian Climate Change Science Program (ACCP) 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), primarily in Great Barrier Reef (GBR) and adjacent tropical waters (Figure 1). It was structured into three main themes (or research priorities):

Theme 1: Improved understanding of the impacts, including cumulative impacts, and pressures on priority freshwater, coastal and marine ecosystems and species;
Theme 2: Maximising 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 a sound understanding of (long-term) trends in the status of priority species and systems.

Research projects within the TWQ Hub covered a wide spectrum of fields ranging from genes to ecosystems and included study of damaging species such as the crown-of-thorns starfish, iconic organisms such as dugong and marine turtles, resilience of seagrass and coral reefs, as well as study of the source, impacts and management responses of and to sediments and nutrients in the marine environment. The TWQ Hub research had a strong focus on cumulative impacts and climate resilience and sought to build 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) and under the supervision of a Steering Committee constituted by key end-users. These partner institutions have collaborated for over 20 years and have established an extensive network of research end-users, including government, industry, non-government organisations, Traditional Owners (TOs) and other community groups. The partners contributed to the hub through co-funded research programs (via in-kind contributions to specific projects through staff

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

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 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 (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 (this report; 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] (linked through the NESP TWQ Hub website).

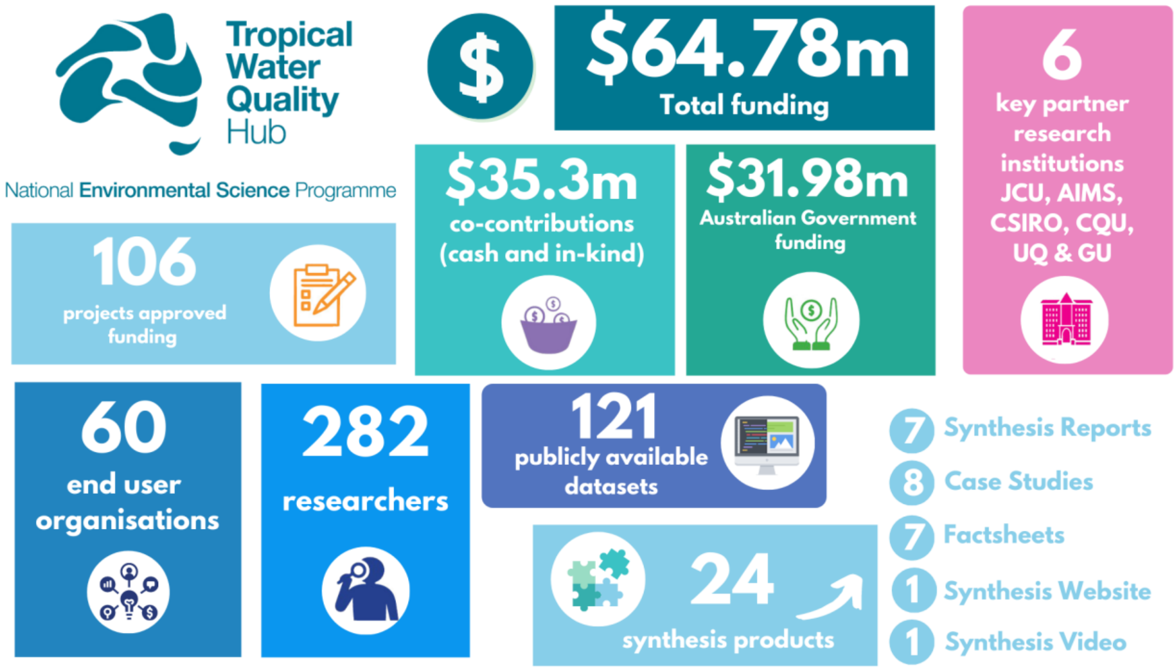

Figure 1. NESPS TWQ Hub investment and networks. Source: RRRC.

1.2 Loss of ecosystem services and need for restoration

There is a global recognition that natural ecosystems are already diminishing in extent and condition, and that the next decade will be a period of unprecedented rate of change (Costanza et al., 2014; McDonald et al., 2016). Species and their ability to adapt to change are the foundation of ecosystems that provide many key services to humans ranging from

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

cleaning water and air, to providing renewable natural resources, to making up the composition of valued parks and reserves and much more (Overpeck, 2014). While protecting remaining ecosystems is vital to conserving our natural heritage, protection alone is no longer sufficient (McDonald et al., 2016). Both natural and social systems will eventually adapt to these environmental changes, either autonomously (without intervention) or in ways that can be planned to avoid detrimental impacts on ecosystem services and the human communities and industries that rely upon them (Doherty et al., 2017).

Numerous studies worldwide suggest that active restoration/intervention is needed to ensure ecosystems - and the services they deliver - follow trajectories towards desirable states during this time of unprecedented change (Bush et al., 2014; Vanderklift et al., 2020). It is important to note that global environmental change is driving some ecosystems beyond their limits so that restoration to modern approximations of historical benchmarks is no longer an option; in such cases, new approaches will be needed to facilitate ecosystem services in novel ecosystems (Pettorelli et al., 2018). Overpeck (2014) concluded that adaptation science and implementation will be defining human endeavours for the rest of the twenty-first century and beyond.

Unfortunately, research effort into effective restoration of ecosystem function has been sporadic, especially in tropical Australia, and usually focused on very small-scale, short-term projects. Rarely has it been possible to maintain effort for ecologically-relevant periods of time, or evaluate success such that subsequent efforts can be improved (Kanowski et al., 2010; McDonald et al., 2016). Even on land, ecological restoration research could be considered a frontier field, and in the sea, it is in its infancy, while a number of barriers have been slowing down wetland restoration progress (Stewart-Sinclair et al., 2020). Simultaneous pressures on the linked ecosystems of the region continue to mount, with climate change and extremes of weather such as fires, floods, cyclones, coral bleaching, and mangrove dieback occurring with increased frequency and intensity (e.g., Turton, 2019).

Landscape and environmental characteristics play a significant role in the choice and success of restoration activities. In the GBR, the region is dominated by two major climate areas - the Wet Tropics and the Dry Tropics. The Wet Tropics, typically the coastal area from Townsville north to Cooktown, is characterised by higher and more regular wet season rainfall ever year, while the Dry Tropics (south of Townsville including the Burdekin and Fitzroy) experience less frequent large rainfall or river discharge events (potentially every 5 years) (Furnas, 2003). These differences affect how restoration activities are progressed both in the catchment, and the Reef, and are referenced in this report.

The practice of ecological restoration is widespread in Australia and the demand for this activity is increasing across terrestrial, freshwater, and marine biomes (McDonald et al., 2016). In a recent study of the views of the Australian public, Matzek et al. (2019) found that the ecosystem services/functions concept does have potential to create new avenues of support for ecological restoration. There is evidence that Australian natural resource managers and decision-makers thoroughly incorporate ecosystem services arguments into their value judgments at the funding and implementation level, and that the public, when informed about ecosystem services, value them highly (Matzek et al., 2019).

However, Matzek et al. (2019) also noted the dearth of data suitable for informing policymaking and land-management decisions in terms of ecological restoration, and ongoing general absence of monitoring of outcomes in terms of either biodiversity or ecosystem services. Accordingly, science-practice partnerships would optimise our ability to gain knowledge from restoration practice while being informed by science (McDonald et al., 2016). Such partnerships can help optimize potential for innovative restoration approaches to provide reproducible data and robust guidance for future activities (McDonald et al., 2016).

1.3 Current policy and management direction relevant to ecosystem restoration in the GBR catchments

Traditionally the adjacent catchment and marine ecosystems of the GBR -and the communities and industries that depend upon their ongoing health and ecosystem function- have been managed by various agencies and their research needs have largely been considered independently. However, there is increasing recognition that in reality, the entire system is intimately linked, and with pressures on ecosystem function mounting in many directions, a more holistic catchment to reef ecosystem view is justified. For example, the loss of ecosystem function from changes to rainforests through to reefs is considered one of the major threats to the GBR (GBRMPA, 2018). The water quality improvement plans produced by both Queensland and Australian governments, and most recently the Reef 2050 Water Quality Improvement Plan (Australian and Queensland Governments, 2018), have repeatedly identified needs for large-scale system repair to improve outcomes not just in catchments but also for the GBR In addition, GBRMPA has called for a more integrated whole-of-catchment approach to not just protection but active restoration of the ecological functioning of these linked ecosystems (GBRMPA, 2018).

The Reef 2050 Long Term Reef Sustainability Plan (Reef 2050 Plan) states that there has been a significant decline in many inshore habitats and species, as well as a decline in ecosystem processes that are important for maintaining water quality (Commonwealth of Australia, 2018a, 2020). The Reef 2050 Plan includes a target for no net loss, and a net improvement in the condition of natural wetlands and riparian vegetation (Commonwealth of Australia, 2018a, 2020), which is adopted from the Reef 2050 WQIP. Achieving this target will require active and effective restoration.

There is also increasing recognition of the need for ecologically effective restoration[3] of many ecosystems and the need to understand the associated and emerging socio-economic opportunities, especially for regional Australia[4]. While small-scale restoration activities have been undertaken in the catchments, wetlands, coastal ecosystems and reefs of the GBR region for many years, the effort is increasing but is generally uncoordinated. There is little information available about the short- or long-term effectiveness of such projects, or any ability to learn from successes and failures such that return-on-investment improves over time. As a result, there is limited capacity to make decisions at a site-specific, or a whole-of-catchment scale.

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[3] For the purposes of this synthesis document, restoration is defined as an activity that aims to accelerate functional recovery of an ecosystem that has been disturbed.

[4] For example: https://terrain.org.au/wp-content/uploads/2020/08/tropical-north-qld-green-and-blue-economic-stimulus-package-2020.pdf

Many recent and current management and policy documents at a state, federal and international level (Table 1) reflect an increasing recognition of the need to develop a robust evidence base to ensure restoration policies and actions deliver on their objectives, deliver co-benefits for their communities and are as cost-effective as possible.

Table 1. Recent and current policy and management initiatives and outputs relevant to ecosystem restoration in the GBR catchments, at local, state, national and international levels.

Relevant initiative	Purpose and/or need for restoration
UN Decade for Ecosystem Restoration (2020-2030) (UNESCO)	"The UN Decade on Ecosystem Restoration aims to prevent, halt and reverse the degradation of ecosystems on every continent and in every ocean."
International Partnership for Blue Carbon (COP21)	"…working to enhance the protection and restoration of reef habitats and coastal ecosystems"
Reef 2050 Long Term Reef Sustainability Plan (2018; (Commonwealth of Australia, 2018a)	"…support for innovative approaches to Reef restoration, protection and management"
Reef 2050 Water Quality Improvement Plan (2017-2022) (Commonwealth of Australia, 2018b)	"Achieving ecosystem restoration and repair is considered particularly important, recognising that best management practice alone will not meet the water quality targets and that restoration in strategic locations is expected to contribute to better outcomes for water quality and overall Reef health"
Land Restoration Fund (Qld govt)	"The Queensland Government's $500 million Land Restoration Fund (the Fund) aims to expand carbon farming in the state by supporting land-sector projects that deliver additional environmental, social and economic co-benefits."
2017 Scientific Consensus Statement on Water Quality (Waterhouse, Brodie, et al., 2017)	"Undertake urgent action to maintain and improve the resilience of the coastal and marine ecosystems of the Great Barrier Reef through implementing … active landscape protection and restoration approaches to maintain as many biodiversity and ecosystem functions as possible…"
Reef Restoration and Adaptation Program (RRAP)	"RRAP aims to create an innovative toolkit of safe, acceptable interventions to help the Great Barrier Reef resist, adapt and recover from the impacts of climate change."
Effective and Efficient Pathways for Investment in Improved Water Quality in the Great Barrier Reef (Alluvium, 2019)	Three of the ten modelled management strategies required effective catchment remediation of gullies, streambanks and treatment systems.
Wetlands in the Great Barrier Reef Catchments Management Strategy 2016–2021 (Queensland Government, 2016)	"Wetland and riparian restoration, and stream bank management were identified as important elements in protecting water quality."
Great Barrier Reef Blueprint for Resilience (2017) (GBRMPA, 2017)	"Initiatives we will pursue include … testing and deploying methods for reef restoration."
2019 GBR Outlook Report (GBRMPA, 2019)	"Interest in habitat restoration and other interventions is increasing, and the risks posed by these activities are not yet well understood."
Aquatic Ecosystem/ Wetlands Research and Rehabilitation Project (Qld govt)	"…will use a values-based approach to develop a plan for investing in the rehabilitation, research and offsetting of impacts to aquatic ecosystems in Queensland."
Green and Blue Economic Stimulus Package (Terrain NRM)	"…aim to expand successful environmental management and restoration projects that are shovel-ready, while also igniting new industries and jobs to strengthen our economy and community."

For example, from a land-based runoff perspective, the Australian and Queensland governments have targeted about $2 billion of investment to improve the water quality of run-off from the 35 major catchments of the GBR (Australian and Queensland Governments, 2018). The ambitious end of catchment pollutant load reduction targets that have been defined in the Reef 2050 Plan and Reef 2050 WQIP cannot be met through agricultural practice change alone. For example, the ecologically relevant targets for dissolved inorganic nitrogen (DIN) load reductions by 2025 is between 70-80% in the priority Wet Tropics basins including the Russell-Mulgrave, Johnstone, Tully, Murray and Herbert basins. Even adoption of 'A-class' sugarcane management practices is predicted to only achieve around 30% reduction in DIN loads (Terrain NRM, 2015), so meeting the target will require new, innovative, costed approaches throughout the catchments. As identified in the Wet Tropics Water Quality Improvement Plan (Terrain NRM, 2015) and confirmed by the assessment of the Great Barrier Reef Water Science Taskforce, these approaches are likely to include various forms of ecosystem restoration (Great Barrier Reef Water Science Taskforce, 2016).

Other examples include the overall need to prevent, halt and reverse the degradation of ecosystems worldwide, as stated in the 'UN Decade for Ecosystem Restoration'; or at a national level, the specific examples of reef restoration led by the Reef Restoration and Adaptation Program (RRAP) and the initiatives within the Wetlands in the Great Barrier Reef Catchments Management Strategy 2016–2021 (Queensland Government, 2016) (Table 1).

In response to these identified policy and management needs and priorities(Table 1), and to fill specific knowledge gaps, the NESP TWQ Hub commissioned a solution-focused suite of research projects between 2016-2020 (Table A1, Appendix 1). Importantly, many of these projects were values-based rather than threats-based in their approach, recognise that restoration is about people and communities, not just ecosystems, and are ultimately aimed at facilitating a whole-of-catchment perspective on restoration activities.

1.4 Timeline of research on ecosystem restoration along the GBR catchments prior to NESP TWQ Hub

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 programs funded by the Queensland Government (e.g., Reef Water Quality Science Program, Queensland Wetlands Program) and CSIRO among others (e.g., CSIRO Water for a Healthy Country Research Flagship, 2003-2008). Additional collaborative research in the GBR funded by the Australian Government prior 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, crown-of-thorns starfish and box jellyfish research, impacts of ports and shipping, global warming and climate change effects and Torres Strait marine research. Figure 2 summarises the key research findings and associated literature that highlights the progress of restoration research in the 15 years previous to NESP.

Initially, research funded through the **CRC-Reef** and **CRC-Rainforest** (1999-2006) included the 'Catchment to Reef' program (2002), which began to explore links between catchments and the Reef, recognising the downstream effects of agriculture and the need to improve the ecosystem health of the GBR lagoon and its feeder catchments. The program contributed to the development of new tools much needed by landholders, industry, and other stakeholders, to both improve the water quality and ecological integrity of terrestrial and aquatic systems and to monitor the effects of land use changes and restoration on water quality (Figure 2) (Woodley et al., 2006; Pearson & Stork, 2008).

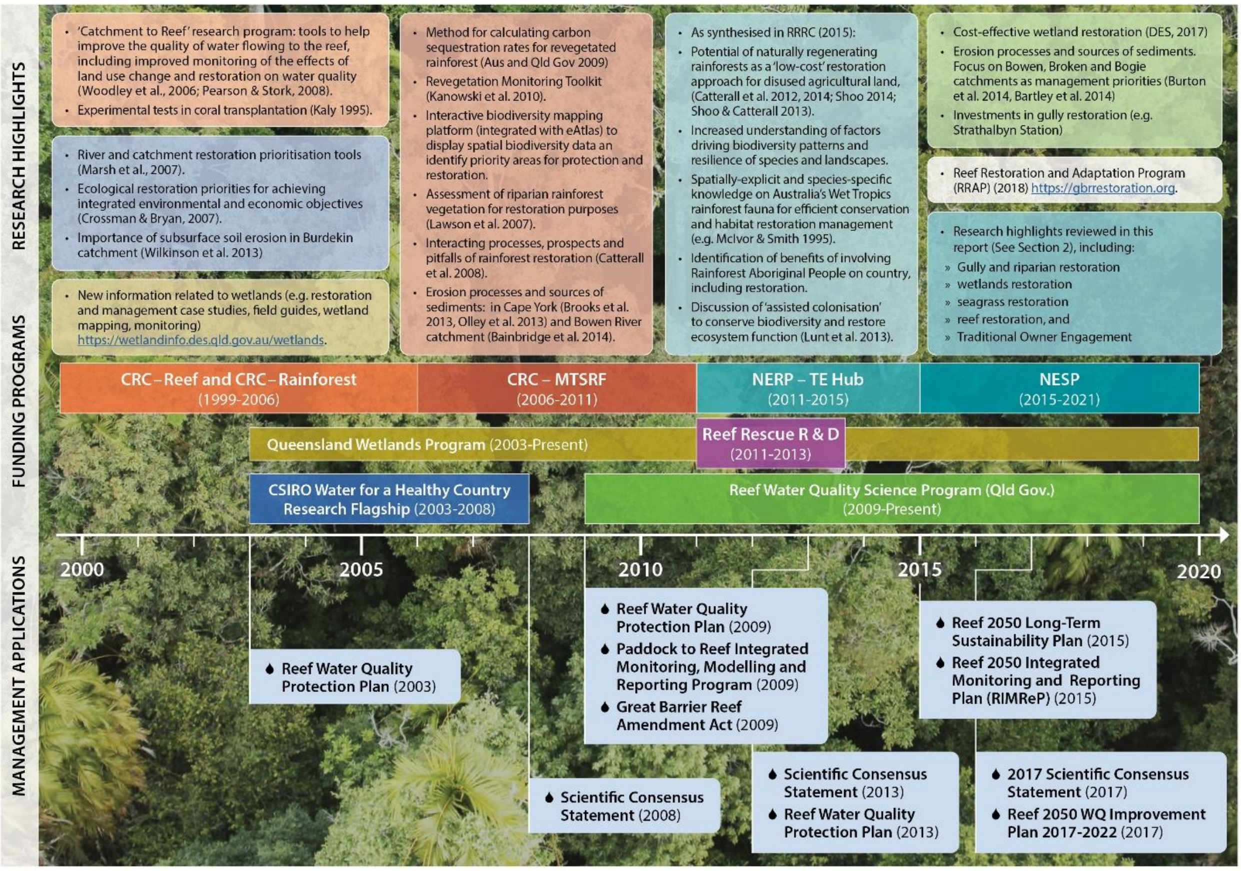

Figure 2. Diagram illustrating the progress of knowledge related to ecosystem restoration in the GBR and its catchments.

Subsequent restoration research funded through the **CERF-MTSRF** program (2005-2011) was mostly focused on rainforest, including the development of a method for calculating carbon sequestration rates for revegetated rainforest faster and more easily. Results showed that in the Wet Tropics, replanted rainforest can accumulate relatively high amounts of above-ground biomass -and hence carbon- within one to two decades of establishment, compared to monoculture plantations (Australian Government and Queensland Government, 2009). The program additionally produced a toolkit (Revegetation Monitoring Toolkit[5]) which is user-friendly and ecologically meaningful for monitoring progress of vegetation conditions and biodiversity at sites whose vegetation is changing, either because of impacts or recovery processes (Kanowski et al., 2010). The riparian rainforest vegetation change in tropical North Queensland was also assessed for management and restoration purposes by Lawson et al. (2007), while Catterall et al. (2008) addressed the interacting processes, prospects and pitfalls of rainforest restoration. Additionally, a computer-based mapping geodatabase was

[5] https://www.rrrc.org.au/biodiversity_monitoring3-html/

developed to display spatial biodiversity data and identify priority areas for habitat protection and restoration. The interactive biodiversity mapping platform was integrated within eAtlas[6] and provided practical value for planning through interpretation of options under different future threats (Australian Government and Queensland Government, 2009) (Figure 2). Erosion processes and sources of sediments were also being investigated at the time, with a focus on the Cape York Peninsula (Normanby basin) (Brooks et al., 2013; Olley et al., 2013), while the Bowen River catchment was also identified as one of the highest eroding areas influencing the GBR in terms of fine sediment load generation and delivery (Bainbridge et al., 2014).

NERP-funded research (2011-2015) in the field of restoration, still had a strong focus on rainforest ecosystems, as synthesised in RRRC (2015). For instance, the project led by Catterall (GU) and Shoo (JCU) assessed the potential of naturally regenerating rainforests to provide a 'low-cost' restoration of biodiversity and ecosystem services to disused agricultural land. The project developed a framework to assist planners and practitioners in decision-making about how to allocate financial investment towards the most appropriate restoration methods and areas of action (Catterall et al., 2012; Catterall et al., 2014; Shoo, 2014; Shoo & Catterall, 2013). Research outcomes from other projects also contributed indirectly to the rainforest restoration field, including: (i) an increased understanding of the factors driving biodiversity patterns and resilience of species and landscapes (Project led by Williams, JCU), (ii) spatially-explicit and species-specific knowledge on Australia's Wet Tropics rainforest fauna for efficient conservation and habitat restoration management (Welbergen, JCU, and McIvor & Smith, 1995), and (iii) identification of the many benefits of involving Rainforest Aboriginal people on country, including positive outcomes in biodiversity protection and restoration among others (Hill, CSIRO) (RRRC, 2015). From a more general perspective, the concept of 'assisted colonisation' was also discussed in order to conserve biodiversity and restore ecosystem function under climate change (Lunt et al., 2013).

In parallel, funding through the Water for a Healthy Country Research Flagship (CSIRO) contributed to additional tools and methods for ecosystem restoration, such as 'river and catchment restoration prioritisation tools (Marsh et al., 2007), and 'ecological restoration priorities for achieving integrated environmental and economic objectives (Crossman & Bryan, 2007). The importance of subsurface soil erosion and identification of sources of sediments, which continued to shape management actions regarding gully and streambank restoration projects were additionally addressed through several programs (Bartley et al., 2014; Burton et al., 2014; Wilkinson et al., 2013). With a stronger focus on wetlands, the Queensland Wetlands Program[7] has additionally produced, since 2003, a wealth of information on a wide range of topics, including wetland mapping, restoration and management case studies, field guides, monitoring guidelines, etc. More recently, research funded by the Queensland Reef Water Quality Science Program, focused on cost-effective restoration of wetlands that protect the water quality of the GBR (Department of Environment and Science Queensland, 2017) and investments in gully restoration (e.g., Strathalbyn Station, Brooks et al., 2021).

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[6] www.e-atlas.org.au/
[7] https://wetlandinfo.des.qld.gov.au/wetlands/

Regarding coral reef restoration, very few studies were published in Australia before the Reef Restoration and Adaptation Program (RRAP)[8] was initiated in 2018 (but see Harriott & Fisk, 1987; Heyward et al., 2002; Kaly, 1995). The main goals of the RRAP include to support a resilient GBR and sustain critical ecosystem functions and values, through developing, testing and risk-assessing novel interventions.

Despite the success of previous programs and projects, ecosystem restoration is still a relatively new discipline and numerous gaps were identified and addressed through the NESP TWQ Hub program, including a focus across the entire catchment to deliver improvements in values, ecosystem services, knowledge, skills, stewardship, and social license among others. NESP-funded knowledge additionally aimed at increasing our understanding on sociocultural values and also enabled emerging opportunities (e.g., participation in carbon markets).

2. NESP TWQ HUB RESEARCH HIGHLIGHTS: ECOSYSTEM RESTORATION

As previously discussed (Section 1.3), coastal and marine ecosystems of the GBR are interconnected with the adjacent catchment area through hydrological connections (Pearson et al., 2021). Land uses changes of the last 160 years (i.e., increased agricultural land, modification of coastal floodplains, loss of freshwater wetlands, disruption of drainage and hydrological connections) have led to declining water quality in catchment waterways and increases in the loads of pollutants that are delivered to the GBR (Lewis et al., 2021). Management strategies to maintain or restore the health of the GBR ecosystems have to consider the need to protect, maintain and restore coastal and riparian ecosystems, system functions and land-sea connectivity, under a whole-of-catchment approach (Figure 3) (Pearson et al., 2021; Waltham et al., 2019; Waterhouse et al., 2016) (see Pineda & Waterhouse, 2021 and Waterhouse & Pineda, 2021 for a synthesis in NESP TWQ Hub research on sediment and nutrients impacts on the GBR and potential reduction strategies). This approach aligns well with the underlying motivation of the decade on ecosystem restoration which was recently declared by the United Nations, which calls for the halt on destruction of ecosystems and a focus on their protection and indeed, restoration (Waltham, Elliott, et al., 2020). The success of this restoration decade requires major funding investment, which should be possible when incorporating emerging non-government market mechanisms (Canning, Jarvis et al., 2021).

[8] https://www.gbrrestoration.org/home

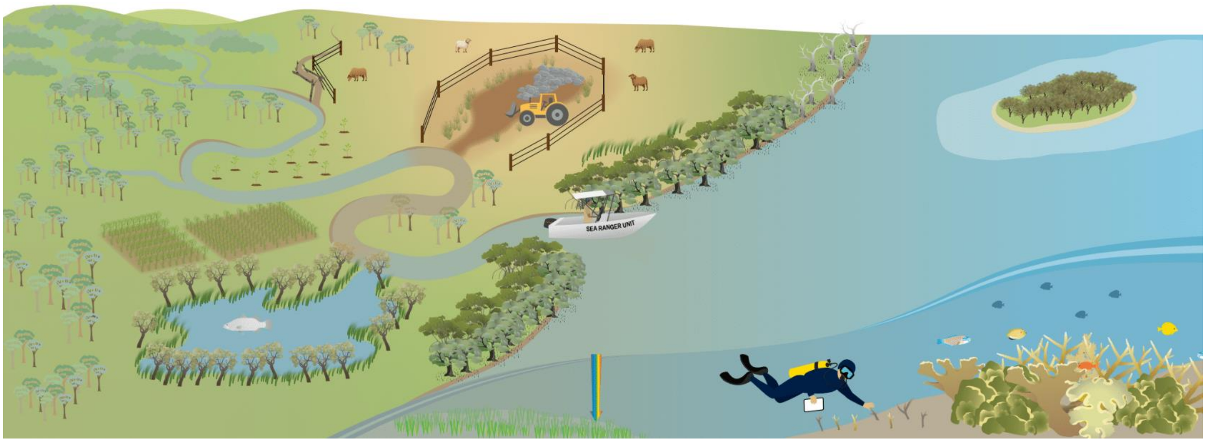

Figure 3. Diagram illustrating a hypothetical catchment with symbols representing the restoration-focus research topics (i.e., gully and riparian restoration, freshwater and tidal wetlands and mangroves, seagrass meadows and coral reef restoration).

Accordingly, a cluster of research projects were commissioned through NESP TWQ Hub (2015-2021) to assist towards developing and implementing practical solutions in ecosystem restoration, with a focus on the GBR catchment to reef (including freshwater, estuarine and marine ecosystems). The breath of restoration activities considered within this synthesis include gully and streambank repair, catchment and riparian re-planting, rehabilitation of natural wetlands, establishment of artificial wetlands, restoration and management of estuarine and coastal marine wetlands (including mangroves), and novel techniques and projects for seagrass beds and coral reef restoration (Figure 3) (projects summarised in Table A1, Appendix 1). Synthesis of the outcomes across these projects will provide easy to access practical recommendations for land and sea managers.

2.1 Gully and Riparian Restoration

Erosion of sediments into waterways from deep rills, gullies or riverbanks has been identified as a major contributor to poor water quality in the GBR (Wilkinson et al., 2013; Bartley, Waters, et al., 2017). Fine sediments and suspended particulate matter can cause stress on the marine environment through light reduction, disturbance by suspended particles, and sedimentation (Bainbridge et al., 2018; Figure 4). Increase in light attenuation and change in the spectral composition of light reduces the availability of photosynthetically usable light for benthic communities such as coral reef and seagrass and is a major stressor for these communities. Water clarity is one of the strongest water quality indicators and a strong predictor for ecosystem change, with resulting ecological impacts depending on the intensity and duration of exposure, preceding and co-occurring environmental conditions and the type of communities being affected (Robson et al., 2020). Overall reduced water clarity usually leads to slower growth or even loss of photosynthetic organisms such as corals and seagrasses (Bainbridge et al., 2018).

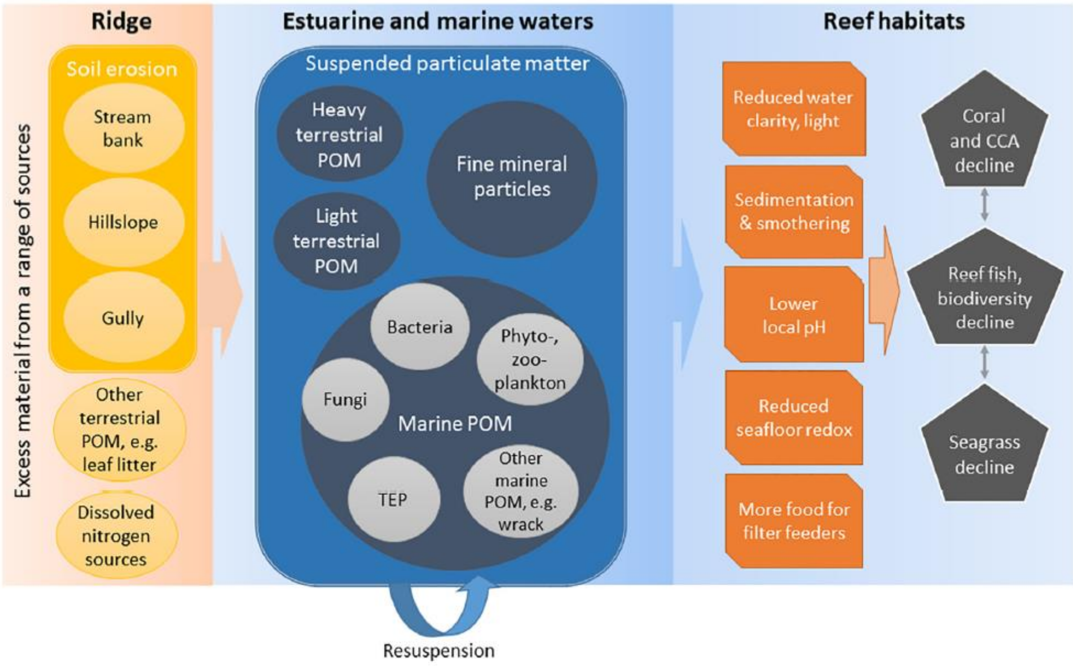

Figure 4. Conceptual diagram of suspended particulate matter sources, transport processes and tropical marine ecosystem impacts across the ridge to reef continuum. POM, particulate organic matter; mPOM, marine-derived particulate organic matter; TEP, transparent exopolymer particles; CCA, crustose coralline algae. Source: Bainbridge et al., (2018).

To help achieve the target 25% reduction in fine sediment delivery from catchments to the GBR lagoon by 2025 (Australian Government and Queensland Government, 2018), numerous projects within the NESP TWQ Hub focused on addressing different aspects of streambank and gully restoration, from measuring baseline erosion characteristics to undertaking trials using different restoration methods, characterisation of different erosion systems, developing further monitoring techniques and evaluation of the most cost-effective restoration methods.

2.1.1 Gullies

It is now understood that gully erosion contributes ~40-50% of the fine sediment load to the GBR from less than 1% of the total catchment area (Olley et al., 2013; Wilkinson et al., 2013). This knowledge has led to growing interest in gully remediation in recent years with an investment of over $65M (~$40M from Reef Trust, ~$10M from Qld Govt, ~$15M from the Great Barrier Reef Foundation with further investment pending) in water quality improvements focused on reducing sediment losses from gully erosion. However, the methods and approaches for reducing this erosion source were not well understood in the region until NESP-funded research began addressing the gap.

Gully identification and mapping

With an increase in major investments in gully restoration, there was a pressing need to identify and characterise different types of gullies in the landscape, and to prioritise management efforts (Brooks et al. 2019). Ultimately this information provides guidance for investors and practitioners to encourage the most appropriate application of treatments to different types of gullies, in the most cost-effective manner. In an initial step to address this, NESP TWQ Hub research developed a systematic classification method for alluvial gullies, based on LiDAR (airborne Light Detection And Ranging) derived mapping tools and approaches for automating the classification process and for estimating sediment yields from individual gullies (Brooks et al., 2019; Daley et al., 2021). To demonstrate the value of these tools, Daley et al., (2021) mapped gullies at 1 m resolution from 529,000 ha of LiDAR data in three locations, the Bowen, Broken and Bogie catchments of the Burdekin basin, the Fitzroy basin and the Normanby basin. The assessment highlighted that the gully population is highly skewed, with a small number of gullies contributing a large proportion of the total sediment load in all locations. In the Bowen, Broken and Bogie catchments, 2% of gullies (~450 of 22,300 mapped gullies) were estimated to contribute 30% of the total sediment load, while 50% of the gully sediment load was from 6% of the mapped gullies. In the Fitzroy basin, 1.5% of gullies contributed 30% of the gully sediment load (27 of 1,785 mapped gullies) and in the Laura/Normanby basins 3.5% of gullies contribute 30% of the of the sediment load (64 of 1,820 mapped gullies). By identifying a smaller number of gullies that contribute a large proportion of total sediment losses, NESP TWQ Hub research can provide guidance for investors to increase the cost-effectiveness and timeliness at which progress against the Reef 2050 Plan sediment targets can be achieved.

This new process of identifying priority gullies for rehabilitation is much more efficient, and can be up to four orders of magnitude more accurate than the gully density mapping previously applied in the Paddock to Reef model for gully sediment production (Daley et al., 2021). A new LiDAR-based metric (Potentially Active Erosion zone, or PAE) was also developed to predict the intensity of rehabilitation treatments required for each of the most actively eroding gullies across the mapped area, which enabled an economic analysis of the cost-effectiveness of each gully rehabilitation to be completed. This analysis provides a strong basis for prioritisation of future investment and effort (Daley et al., 2021). Some of these new methods and tools have already been adopted by the latest edition of the Reef Trust Gully and Stream Bank Toolbox (Wilkinson et al., 2019).

Gully rehabilitation techniques

In addition to successfully identifying the highest-priority alluvial gullies for rehabilitation (i.e., those that were contributing the most sediment, among other factors), another group of NESP TWQ Hub-funded projects focused on testing the effectiveness of different rehabilitation techniques. In collaboration with landholders and Traditional Owners (TOs), natural resource management agencies (NRM), the Queensland Government and groups such as Greening Australia, trials were conducted of gully rehabilitation methods including mine site rehabilitation strategies, earthworks, and different soil stabilisation strategies (Brooks et al., 2016, 2021). For example, large scale alluvial gullies on Strathalbyn Station, west of Bowen in the Burdekin, had a combined treated area of 16.2 ha (up to the 2018/19 wet season) with previous total erosion rates in the order of 4,600 tonnes per year (see BOX 1, Figure 5). After treatment, the estimated sediment erosion was reduced by around 98% after 2-3 years. Rehabilitation costs for these treatments ranged from $300 to $900 per tonne of sediment per year (based on up-front cost), depending on various factors including soil type, location, and consultation (Brooks et al., 2021) (Table 2).

Results from experimental sites at Crocodile Station (works initiated through Reef Rescue R&D; Shellberg & Brooks, 2013), near Laura in Cape York, demonstrated that a 0.6-ha gully system with a total erosion rate of around 260 tonnes per year was effectively ‘turned off’ after two years of rehabilitation effort[9] (Brooks et al., 2021) (Table 2). The results showed that the largest reductions in sediment loss were obtained in sites treated with hydromulch (seed, mulch, gypsum and fertiliser), although the most sustainable results were obtained in sites treated with compost, gypsum and grasses (Brooks, Curwen, et al., 2016). In addition, grazing exclusion trials resulted in some vegetation improvements in un-eroded high terrace surfaces, although little to no improvement in vegetation was detected inside gullies with exposed sodic sub-soils (Brooks, Curwen, et al., 2016). Thus, researchers suggested that additional management interventions beyond just cattle exclusion were required to hasten the recovery of large gully structures. Interventions may include supplementary grass seeding from the air or ground, organic mulching of sodic soils, fire and weed management, and slope stabilisation through bioengineering (Brooks, Pietsch, et al., 2016).

Results from Strathalbyn Station in the Burdekin basin and Crocodile Station in the Normanby basin showed that alluvial gullies can be cost-effectively remediated to achieve >95% effectiveness factor (i.e., reducing the sediment yield from the gully by more than 95%), with the highest effectiveness at sites that had full reshaping and rock capping, and lower effectiveness at sites treated with organic mulch and other non-rock surface treatments (Table 2). Gullies treated with rock capping and soil ameliorants were resilient to major events such as floods, although net increases in dissolved nutrients were also observed in some treatments as a result of the organic ameliorants used, which would require additional monitoring before the techniques could be recommended for wider application. The calculated end of catchment fine sediment reduction achieved at the Crocodile and Strathalbyn sites respectively (as at May 2020) was 0.165 and 4.43 kt year^{-1} (Table 2) (Brooks et al., 2021). Drawing on these findings, Brooks and others highlighted that the key features of gully rehabilitation included: (i) stock exclusion, (ii) short term erosion mitigation measures during construction phase (e.g., sediment traps) (McIvor & Smith, 1995), (iii) determination of the optimal slope for soil when reforming vertical surfaces, (iv) hardening of key slope components, (v) hydrological reconfiguration and associated drainage management, (vi) capping of unstable subsoils by covering with new soil and/or rock, and (vii) revegetation and ongoing maintenance (Brooks, Pietsch, et al., 2016). The important features of how this solution-focused research took an environmental problem from being considered “too hard” to deal with, to “do-able”, is recorded in a case study[10].

A separate group of projects led by Dr Bartley (CSIRO) in collaboration with NQ Dry Tropics and the Landholders Driving Change Project[11], evaluated a range of rehabilitation approaches including smaller scale hillslope gullies found within rangeland systems of the Burdekin catchment and two large scale gullies (Bartley, Hawdon, et al., 2020) (Table 2, BOX 2). Researchers measured fine sediment and total nitrogen concentrations downstream from the treatments and monitored the effects of the treatment on vegetation cover and biomass and land condition over time. Overall, the project found high spatial variability of

[9] Click here for a video of the works in progress in Crocodile Station (Cape York).
[10] NESP TWQ Hub Case Study: Shifting perceptions in ecosystem restoration from “too hard” to “do-able”. https://nesptropical.edu.au/index.php/round-6-projects/project-6-2/
[11] https://ldc.nqdrytropics.com.au/

erosion and water quality data among sites, with the upslope catchment area being the strongest predictor of sediment yield. The rehabilitation options implemented on the treatment gullies included fencing, livestock management, small sediment trapping check dams within the gullies, diversion banks upslope of gully heads, and larger engineered approaches such as re-shaping and rock grade control structures. All techniques trialled resulted in some improvements in percentage of vegetation cover or biomass and on sediment trapping, although effectiveness values (i.e., the % reduction in sediment loss) could only be calculated in two cases (0.95 effectiveness value after hillslope runoff diversion above the gully at Strathbogie; and 0.85 effectiveness value after gully reshaping, structural control and revegetation at Mt Wickham) (Table 2) (Bartley, Hawdon, et al., 2020). Based on a comprehensive review, the authors proposed that combining engineering and vegetation management techniques were often the most successful for erosion management, with engineering measures such as check dams being important for stabilising in the early phases, and vegetation being the key to the long-term success of gully rehabilitation. The importance of preventing gullies from forming in the first place, through reducing livestock grazing pressure and properly managing vegetation cover was also highlighted (Bartley, Hawdon, et al., 2020; Bartley, Poesen, et al., 2020; Brooks, Curwen, et al., 2016).

This research constitutes some of the first control/treatment field experiments to measure actual changes in water quality on the ground as a result of rehabilitation efforts, and results will be critical to help constrain scenario analysis in the catchment modelling undertaken as part of the Paddock to Reef program. Water quality data from these studies have been shared with other NESP TWQ Hub projects working on geochemistry, marine sedimentation and nutrient bio-availability in an effort to more robustly link catchment processes with marine impact (see Pineda & Waterhouse, 2021 for more information). Furthermore, these studies have established a set of active field sites that can be used to engage with graziers, extension officers and regional NRM staff to demonstrate practical on-ground management approaches for rehabilitating degraded landscapes.

Cost and benefits of gully rehabilitation projects

A key factor to consider in any rehabilitation process is the associated cost and benefits, including the budget required for the initial rehabilitation works and associated monitoring, the budget required for the long-term maintenance, and the study of effectiveness in sediment yield reduction at each site. Project activities should therefore focus on strategies that deliver the greatest reduction in sediment yield for the lowest cost per tonne of sediment and nutrient export avoided or reduced. For instance, rehabilitation on-ground works performed within Bartley, Hawdon, et al., (2020) ranged from \$3,500 (i.e., fence off-gully and porous check dams within the gully, at Virginia Park) up to \$595,000-840,000 (i.e., projects involving major earth works, soil treatment, rock structure and revegetation, such as those at Mt Wickham and Glen Bowen, respectively) (Table 2) Based on estimates of treatment effectiveness, this equated to >\$1,500 and \$300-600 per tonne at Virginia Park and Mt Wickham, respectively (with insufficient data at Glen Bowen to calculate cost-effectiveness). Similar results were reported by Wilkinson et al., (2019), with lower cost projects associated with grazing management and fence control activities (although those had usually low erosion control effectiveness, ~0.1-0.2), up to the more resource-intensive projects involving engineering works, rock capping and revegetation, with usually higher effectiveness values (estimated at ~0.4-0.6).

Using a different approach to assessing cost-effectiveness, which includes a 7% discount rate and 25-year lifetime assessment, Brooks et al., (2021) reported a total cost of $182,000 for the Crocodile Station project (Normanby catchment), which when using a 7% discount rate over 25 years, resulted in an estimated end of catchment cost effectiveness of $58-$128 per tonne, while the total cost at Strathalbyn Station (Burdekin) was $2,510,000 with a cost-effectiveness range of $43-$85 per tonne, depending on the specific treatments applied (Table 2). Average remediation effectiveness across all 10 treatments at Strathalbyn was 0.98 (98% sediment reduction) after 2 years, while at Crocodile Station it was 0.87 (87% reduction) after 2 years. The 7% discount rate and 25-year lifetime assessment enable the upfront cost to be converted to its annualised equivalent cost so that the cost can be compared with the annual sediment reduction. However, researchers identified that further work was needed to determine the most appropriate approach for calculating cost-effectiveness of gully rehabilitation projects, and recommended that a consistent guideline for calculating cost-effectiveness of all water quality improvements in the GBR (including cross-comparison between different approaches) be established as a matter of urgency (Brooks et al., 2021). Typically, however, the most cost-effective treatments observed thus far have been the larger sites that have a significant upfront capital cost because they achieve large sediment reductions in a short period of time (Brooks et al., 2021).

Site specific examples:

BOX 1. Strathalbyn Station

Strathalbyn Station is 45 km northwest of Collinsville and 60 km south of Ayr, on the eastern bank of the lower Burdekin River. The study gullies were a set of large alluvial gully systems along the Bonnie Doon Creek, a right bank tributary of the Burdekin River. The area is characterised by extensive alluvial sediments of considerable depth interspersed with 'blacksoil' cracking clay alluvia and local basalt origins. In total, the gullies in the study area contributed approximately 450,000 tonnes of sediment since 1945, with 37% of this amount eroded in the last 20 years and gullies currently eroding at a constant/increasing rate. Prior to remediation, these gullies were contributing, on average, 6300 tonnes of fine sediment to the GBR lagoon each year.

Ten different treatments were applied, consisting on a combination of the following actions:

- Catchment treatments: fencing, diversion and rock chutes to divert flows.
- Gully Scarp treatments: earthworks to reshape gully, soil treatment, rock capping.
- Gully bed treatments: rock bed, porous check dams, soil treatment
- Regraded batter treatments: coir mesh, blanket mulching (hay, bagasse), seeding, etc.

The total cost of the remediation on-ground cost was $2,510,000.

Figure 5. Selection of photographs showing the Strathalbyn gullies in various stages of construction: before (top left), during (top right) and after (bottom). Source: Brooks et al., (2021). (Photo credits: top and bottom left, D. Telfer; bottom right, A. Brooks).

Two years after the treatment works, overall results showed that the gully remediation measures applied in these gully systems significantly reduced erosion rates and suspended sediment losses (especially of the coarser sediment ranges) by 1-2 orders of magnitude. Average remediation effectiveness ratios for the whole site were calculated at 97-98%, with end of system cost-effectiveness at $43-$85 per tonne of sediment removed from the system. Hence, this study demonstrated that large alluvial gullies can be cost-effectively remediated to the point where they achieve an effectiveness factor of ~100% (i.e., almost complete cessation of sediment losses) after two years.

Source: NESP TWQ Hub Project 3.1.7 (Brooks et al., 2021)

BOX 2. Mt Wickham

Mt Wickham is a ~7,790 ha property in the Bowen management unit (Burdekin catchment), with all treatment and control sites draining into Sandalwood Creek which connects with the Bowen River. It is characterised by linear hillslope gullies, scalds and major alluvial gullies on highly sodic soils (including tunnel erosion).

Monitoring started at the site in 2018 and treatment was initiated in early 2019, hence treatment had been in place for 2.5 years at the time of preparing this report. The catchment area above the treatment monitoring station was 14 ha, and the treatment consisted of:

- Major earth works, soil treatment and rock chute structures installed.
- Permanent 4 barb fences.
- Significant re-vegetation using mixed exotic species.
- Additionally, cattle were excluded from the beginning of the works (although future grazing was proposed).

The total cost of the remediation on-ground cost was $595,000.

Figure 6. Selection of photographs showing the Mt Wickham site before (top), during (bottom left) and after (bottom right) treatment. Source: Bartley, Hawdon, et al., (2020). (Photo credits: Verterra/NQDT).

Two years after the treatment works, results showed statistically significant outcomes that demonstrate the success of the treatment:

- The amount of vegetation cover and biomass on the hillslope and gully walls had significantly improved.
- The water quality data (particularly suspended sediment loads) also significantly improved.

Overall, the relative effectiveness of the Mt Wickham rehabilitation works was calculated as 0.85 (85% reduction). However, the land condition in the site remained fragile and researchers remarked that it could take several more years for additional perennial native plans to take hold of this site. Until then, it was proposed that grazing had to be carefully managed.

Source: NESP TWQ Hub Projects 2.1.4 and 5.9 (Bartley, Hawdon, et al., 2020)

Table 2. Synthesis of the treatment history and monitoring results for all sites within NESP TWQ Hub Projects 5.9 (Bartley, Hawdon, et al., 2020) and 3.1.7 (Brooks et al., 2021), including sites funded by the Landholders Driving Change Project.

	NESP TWQ Hub Projects 2.1.4 and 5.9							**NESP TWQ Hub Project 3.1.7**	
	Virginia Park	**Meadowvale**	**Strathbogie**	**Minnievale**	**Mt Wickham**	**Glen Bowen**	**Mt Pleasant**	**Crocodile Station**	**Strathalbyn Station**
Basin	Upper Burdekin	Upper Burdekin	Bogie (Burdekin)	Don (Burdekin)	Bowen (Burdekin)	Bowen (Burdekin)	Bogie (Burdekin)	Normanby	Burdekin
Gully type	Linear hillslope gullies	Linear hillslope gullies	Linear hillslope gullies	Linear hillslope gullies	Major alluvial gullies	Major alluvial gullies	Linear hillslope gullies	Large alluvial gully system	Large alluvial gully system
Catchment area[a]	1.3 ha	5.0 ha	41 ha	25 ha	14 ha	2.7 ha	259 ha	37.4 ha	122 ha
Treatment area-active/passive[b]	0.13 ha / 1.17 ha	NA / 3 ha	~1 ha /40 ha (proposed)	3 ha / 23 ha	~8 ha / 9 ha (proposed)	~2.4 ha / 0.3 ha	0.5 ha / 258 ha	0.9 ha / 36.5 ha	19.8 ha /102 ha
Treatment	-Disc plough above gully -Fencing -Porous check dams in gully	-Fencing -30% gully catchment has cattle exclusion	-Hillslope flow diversion banks with drains -Fencing -Small rock revetment neat headcut	-Hillslope ripped and seeded -Fencing -Porous check dams	-Major earth works, soil treatment, rock chute structures -Fencing -Re-vegetation	-Major earth works, soil treatment, rock chute structures, earth bund, water points -Fencing (pending) -Re-vegetation	-Landscape rehydration -V-notch log rock sill structures and earth bank to divert flows -Fencing (pending)	-Gullies 2.234: Fully reshaping, soil treatment, rock capping, rock check dams -Gullies 0.1, 0.2 and 1.1: rock chutes, reshaping, soil treat.	10 gully treatments including: -Catchment treatments (e.g., fencing, diversion and rock chutes to control flows) -Gully Scarp treatments (e.g., earthworks to reshape gully, soil treatment, rock capping) -Gully bed and other soil enhancement treatments
Total cost ($)	$3,500	$3,800	$44,000	$27,000	$595,000	$840,000	$95,000	$182,000	$2,510,000
Monitoring	3-4 yrs	3-4 yrs	4 yrs	4 yrs	3 yrs	1 yr	1 yr	4 yrs	4 yrs
Land condition	Improved	Improved	Declined	Improved	Improved	Not significant	Not significant	Improved	Improved
Vegetation	Improved	Improved	Not significant	Improved	Improved	NA	NA	Improved	Improved
Erosion rate	Improved	Improved	Improved	Improved	NA	NA	NA	Improved	Improved
Sediment concentrations	Improved	Not significant	Improved	Improved	Improved	Improved	Not significant	Improved (overall)	Improved (overall)
Sediment load reductions	Not significant	Not significant	Improved	Not significant	Improved	NA	Not significant	Improved	Improved
Treatment effectiveness	NA	NA	0.95[c]	NA	0.85	NA	NA	0.62-1.00	0.51-1.00 (average 0.98)

	NESP TWQ Hub Projects 2.1.4 and 5.9							NESP TWQ Hub Project 3.1.7	
	Virginia Park	**Meadowvale**	**Strathbogie**	**Minnievale**	**Mt Wickham**	**Glen Bowen**	**Mt Pleasant**	**Crocodile Station**	**Strathalbyn Station**
Sediment delivery Ratio for EOS[e] calcs	0.5	0.5	0.85	0.96	0.87	0.87	0.85	0.45	0.96
Cost-effectiveness at EOS[f]	Estimated >$1500/t	Estimated >$1500/t	~$70/t[d]	Estimated >$1500/t	$300-$600/t	Insufficient data	Insufficient data	$58-$128/t or $673 - $1490/t/yr[g]	$43-$85/t or $282 - $680/t/yr[g]
Comment	Low baseline erosion rates and fine sediment trapping efficiency <20%	Baseline erosion rates relatively low, but good improvement in cover and biomass	Only has 1 year of post-treatment data, so this is a preliminary estimate	Low baseline erosion rates	Cost-effectiveness varies with the baseline erosion rates applied	Baseline erosion rates very high, further data pending.	Baseline erosion rates relatively low, so cost-effectiveness for erosion likely to be poor	Based on cost effectiveness method 3 yrs post treatment data	1 – 3 yrs post treatment data

NA = new site with insufficient data [a]Catchment area above monitoring station at treatment site; [b]Treatment area: active (e.g., earth works, porous check dams), passive (e.g., fencing, grazing management); [c] Estimated as a change in measured (flow derived) sediment loads between a control and treatment gully, both before and after rehabilitation; [d]Additional data needed in subsequent wet seasons to improve certainty on this result; [e]End of System (EOS); [f]Calculated using Gully Toolbox method / equivalent; [g]Calculated over 25-year period with a discount rate of 7% per annum, the figures expressed in $/t/yr are based on the full treatment cost at the time of implementation for the mean annual baseline erosion rate.

2.1.2 Streambanks

Rehabilitation of riparian vegetation and streambank stabilisation is considered an important mechanism for reducing streambank erosion in the GBR catchments, providing opportunities for water quality, and subsequently GBR health outcomes if designed and implemented correctly. In an initial phase of NESP TWQ Hub, an assessment of evidence of the success of reducing erosion from stream channels using riparian zone management in the GBR catchments was undertaken (Bartley, Goodwin, et al., 2016; Bartley, Philip, et al., 2016). This included case studies assessing the effects of riparian vegetation rehabilitation in reducing erosion rates in the Fitzroy and Mackay Whitsunday catchments through analysis of historical air photos (~1950-2012). Unfortunately, the results were not conclusive in the detection of changes in channels between sites with good and poor riparian vegetation. The resolution and quality of the historical aerial photographs was not sufficient to detect changes over time as the error associated with the aerial photos was generally greater than the bank retreat rates. This result helps justify the increasing use of LiDAR and other more recent high precision terrain analysis approaches for evaluating channel change following rehabilitation (as applied in later NESP TWQ Hub projects). The project made a useful contribution towards the assessment and improvement of monitoring methods. The lack of additional evidence for evaluating project outcomes also highlighted the importance of assigning an adequate budget to evaluating the effectiveness of on-ground remediation works on improving water quality.

Additional NESP TWQ Hub-funded research investigated natural patterns of streambank erosion in the region, assessing whether previous investments in the wet and dry tropics had been successful in terms of delivering benefits, and what mechanisms or incentives could be refined to better facilitate success in such programs in the future (Paul et al., 2018). The project identified best practices for riparian zone management, including both social and biophysical factors. For instance, field site assessments found that the likelihood of improved water quality outcomes (as measured using the ‘Tropical Rapid Appraisal of Riparian Condition’ score, Figure 7) increased with project age, especially where grazing extent had been relatively brief. However, results also showed that in some areas, even after 35 years of revegetation, riparian condition was only partially recovered, mainly due to issues related to plant cover, erosion and weeds (Paul et al., 2018). This means that full recovery of some ecological function may take longer than expected. The project also highlighted that riparian areas play a disproportionately large role in providing benefits to biodiversity and carbon mitigation due to their relatively fertile alluvial soils and increased moisture levels. Rates of carbon sequestration were 2-7 times higher than anticipated based on similar stands (i.e., rain-fed stands of similar age, species mix and stand stocking densities growing under the same climatic conditions in the dry and wet tropics or subtropics) in non-riparian areas (Paul et al., 2018).

As suggested by previous work, the research also identified that the most important drivers for landholder engagement in riparian remediation actions in the GBR catchments were private benefits and overcoming financial barriers (Paul et al., 2018). Social science surveys indicated that the widespread uptake of riparian remediation will require landholders aligning environmental and production goals, highlighting the need of adequate financial incentives to successfully engage landholders. This was especially relevant in regions with relatively low productivity, which typically offer less flexibility to landholders (Paul et al., 2018). The project additionally identified a need for landholders to overcome perceptions that remediation projects are impractical (i.e., complex and expensive), and a need for increased trust of the reported links between water quality and their management practice.

Finally, a wide range in the management intensity of riparian revegetation projects was identified by Paul et al., (2018), with some cases of large investment of resources being placed in a few small projects. It was recommended that verification is required for whether, for a given level of resources, greater outcomes would be attained through implementation of less resource-intensive projects across a larger area, rather than undertaking fewer resource-intensive projects across a limited area (Paul et al., 2018).

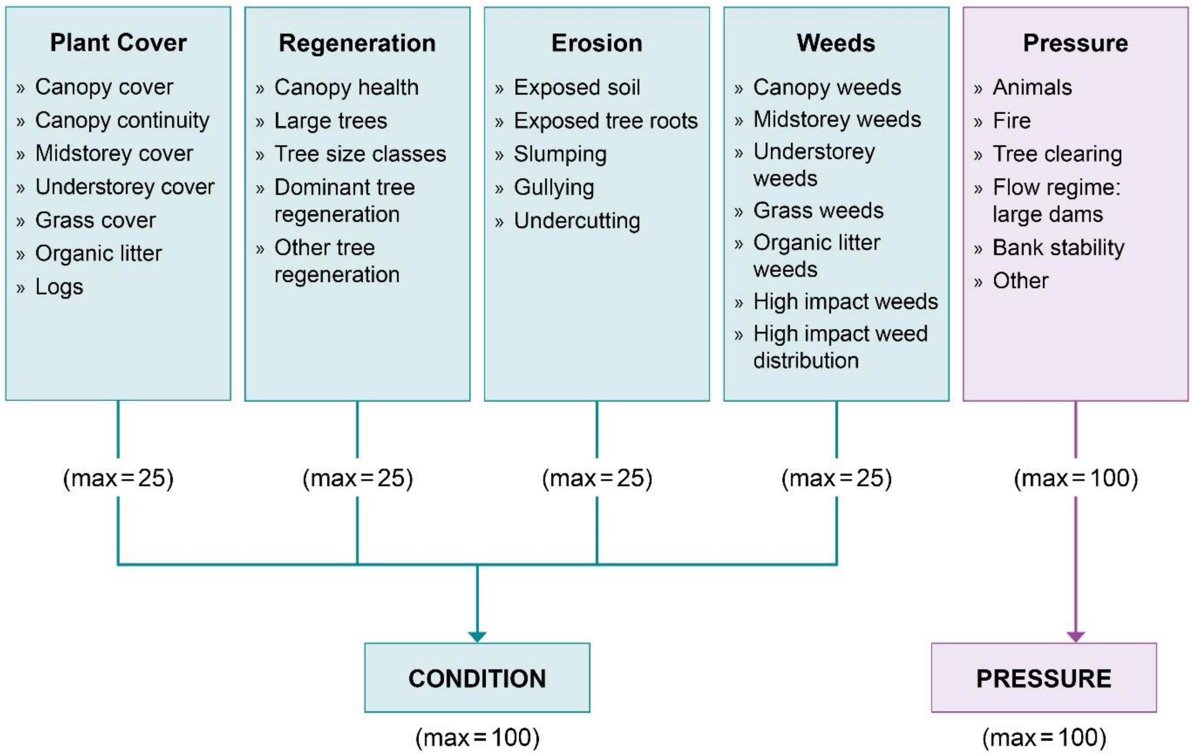

Figure 7. Tropical Rapid Appraisal of Riparian Condition (TRARC), whereby visually assessed Indicators are grouped into five categories (sub-indices) that can be combined to give an overall Condition Score and Pressure Score for the study area. Source: Paul et al., (2018).

2.2 Wetland Restoration

Wetlands and coastal ecosystems in the GBR catchments provide a vital role in protecting shores from wave action and storms, reducing the impacts of floods, retaining sediments, absorbing and transforming pollutants and providing nurseries for fish and other freshwater and marine species (Duke & Larkum, 2008, 2019; Queensland Government, 2016). However, large areas of wetlands and coastal ecosystems along the GBR catchments have been extensively modified, damaged or lost over the past century, though this rate has slowed in the past few years (Duke & Wolanski, 2001; Johnson et al., 2001; Lewis et al., 2021; Waltham et al., 2019; Wolanski & Duke, 2002).

Official wetland mapping across the GBR catchment has been carried out by the Queensland Government with the latest version in 2017 which includes pre-clear wetland extent estimates (Department of Environment and Science Queensland, 2019). The mapping program uses a modified version of the Ramsar definition that excludes riparian zones above the saturation level and intermittently covered floodplains that do not meet the hydrophyte and soil criteria. According to WetlandInfo[12] in 2017 across the GBR catchment approximately 90.5% of pre-clear (pre-European settlement extent) estuarine areas (excluding open water), 96.1% of pre-clear lacustrine, 78.8% of pre-clear palustrine, and 83.5% of pre-clear riverine wetlands remained. Between 2001 and 2017, there was a net loss of 7,688 ha across natural wetlands (i.e., excluding artificial/highly modified wetlands), with riverine wetlands accounting for 6,255 ha, estuarine salt flats and saltmarshes accounting for 605 ha, and coastal and subcoastal tree swamps (*Melaleuca spp.* and *Eucalyptus spp.*) accounting for 569 ha and 537 ha on non-floodplains and floodplains, respectively. Much of this decline was attributed to clearing and drainage for urban and agricultural development. Artificial/highly modified wetlands (including dams, ring tanks, and irrigation channels; largely for irrigation water storage), accounted for the large majority of increased wetland area, with approximately additional 21,546 ha in 2017 compared with 2001, representing a 15.2% increase. A substantial proportion of the artificial/highly modified wetland area was created through bunding (i.e., constructing a wall to exclude saltwater and retain freshwater) (Abbott et al., 2020), accounting for 8,299 ha of the increase (Department of Environment and Science Queensland, 2019). These statistics do not include wetlands smaller than 1 ha as they were not mapped (Canning & Waltham, 2021).

Grazing is the major land use covering 74% of the catchments of the reef, while intensive agriculture (predominantly sugarcane farming) occurs in lower coastal floodplains comprising 5% of the total catchment area (Queensland Government, 2016). These land uses have resulted in extensive loss of buffering freshwater wetlands and forested riparian ecosystems in some locations (Waltham et al., 2019). The Queensland government's Wetlands Management Strategy considered that restoration and rehabilitation in strategic locations would contribute to water quality improvement and the enhancement of other services and processes (Queensland Government, 2016). NESP TWQ Hub-funded research has directly contributed to Theme 3 of the Queensland Government's Wetlands Strategy, specifically: (i) 3.2. Targeted, coordinated and effective rehabilitation/restoration initiatives, and (ii) 3.5. Innovative approaches to wetland and coastal ecosystem repair (Queensland Government, 2016).

2.2.1 Land-use transitions

One of the innovative new approaches that may contribute to meeting the Reef 2050 Plan targets for end of catchment DIN loads involves transitioning low-lying sugarcane land, which is typically low-yielding, to an alternative land use which requires less or no nitrogen fertiliser application. Ideally, this alternative land use would also provide farmers with an improved long-term alternative income. Using a combination of spatial and economic analysis, Waltham et al. (2017) identified a range of land transition opportunities in the Wet Tropics catchments which require lower to non-nitrogen application compared to sugarcane, including: (i) grazing (i.e., grass-fed beef fattening); (ii) tree crops (McIvor & Smith, 1995);

[12] https://wetlandinfo.des.qld.gov.au/wetlands/

(iii) construction of wetlands to provide water treatment in runoff before discharge to receiving waters; and (iv) restoration of wetlands to provide services for aquatic ecosystems (i.e., such as fish habitat extension, or carbon sequestration) (Waltham et al., 2017).

A land use suitability analysis assessed areas of sugarcane land in terms of the relative risk of DIN loss to the GBR, and the suitability for transition to another land use. The analysis identified low-lying sugarcane areas with a high risk of DIN loss to the GBR (using sub-catchment scale modelled outputs), determined a ranking system of suitability of transition to each of the four identified land uses (listed above) and validated/vetted land suitability models and maps using expert and local knowledge. A series of maps were generated as starting points for shortlisting possible areas for land use transition (Waltham et al., 2017).

In general, wetland restoration or constructed treatment wetlands were assessed as being the most cost-effective option when conversion costs were low (purchase and construction) and DIN removal capacity was high ($7-9/kg DIN reduced) (Figure 8). Wetland restoration also had additional important ecosystem benefits. Constructed treatment wetlands and grazing, when placed in appropriate locations (where conversion costs are low and DIN reductions are high) can offer cost-effective DIN reduction in the range of $15-17/kg DIN reduced, which is cheaper than that reported for extension-based approaches (c. $50/kg DIN reduced) (Waltham et al., 2017) (Figure 8).

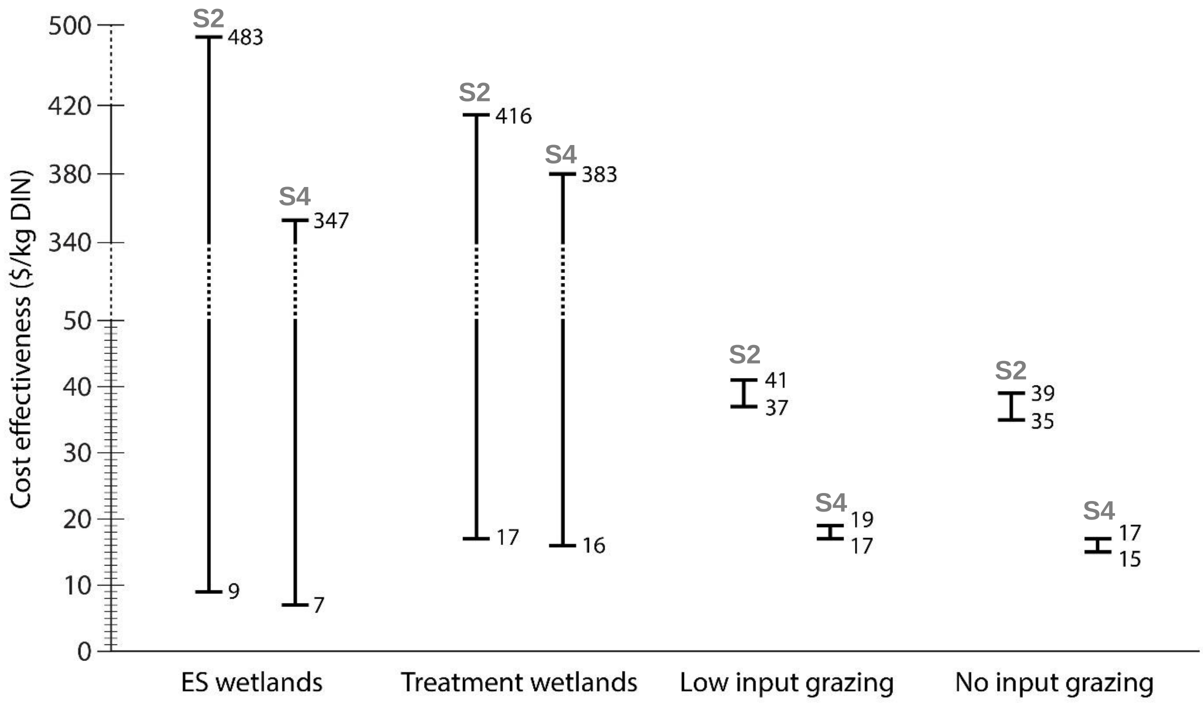

Figure 8. Modelled cost-effectiveness of low-lying sugarcane land use conversion (in terms of dollars per kg of DIN reduction) with two different soil types (S4 is "leakier" with lower cane productivity than S2). (ES: ecosystem service wetlands). Source: Waltham et al., (2017).

The research highlighted that the key to cost-effective DIN reduction from transitioning to wetlands was to identify locations which offered a favourable combination of conversion cost and DIN removal rate. These locations would need to be identified at a site-specific level using appropriate local knowledge, for example by understanding local hydrology (Wallace et al. 2020). Location was somewhat less critical to the cost-effectiveness of transitioning to grazing, but it was found to be more cost-effective to convert to grazing lands on the soils that are 'leakier' (i.e., higher drainage) with low sugarcane productivity. It is important to note that there remains some uncertainty surrounding the cost-effectiveness values for ecosystem service wetlands and treatment systems, compared to grazing where more data exists. This is due to the limited published information on the costs and efficacy of these wetland systems in the Wet Tropics (Adame, Franklin, et al., 2019), and end users need to be cognisant of the assumptions used in the framework when interpreting the results (Waltham, Canning, et al., 2020). For example, the criteria considered for ranking data sources within the framework include the amount of DIN generation at each site, proximity to wetlands, proximity to protected areas, connectivity to GBR, among others. In general, wetland restoration or constructed treatment wetlands are most cost-effective when conversion costs are low and DIN removal capacity is high. Placing constructed wetlands within an integrated treatment train might further improve water quality, though this needs to be weighed against the additional costs incurred (Waltham et al., 2017).

Extension of this work into the Lower Burdekin and Mackay Whitsunday sugarcane areas showed that opportunities for reducing DIN losses through land use transition of marginal sugarcane area may also exist in these regions (Waltham, Canning, et al., 2020). Wetland restoration, constructed treatment wetlands, low-input grazing, hardwood and softwood farm forestry and – for the Lower Burdekin only – recycle pits to capture and reuse irrigation water, all showed promise. Here again, appropriate locations would have to be identified at site-specific scale as these land use transitions will only be cost-effective under appropriate circumstances (low transition costs in combination with high levels of DIN reduction). The high gross margins from sugarcane production in the Lower Burdekin, particularly in the Burdekin Delta, would generate substantial opportunity costs from land transition. Consequently, in general, the transitions considered are likely to be more cost-effective in the Mackay Whitsunday region than in the Lower Burdekin (with the exception of irrigation recycle pits which were only considered in this region).

Land use transitions that reduce DIN losses could also generate revenues via water quality credit trading. Revenues from sale of water quality credits could be used to offset some of the opportunity costs of land transition (Smart et al., 2020). This is one of the proposed methods in the recently established Reef Credits scheme, although the method is yet to be fully developed.

2.2.2 Coastal wetland systems repair

Despite the growing interest among investors in funding GBR wetland system repair projects, there is a scarcity of scientific data to evaluate the success of such projects. A team led by Dr Waltham (JCU), in collaboration with regional NRM bodies, used advanced scientific hydrological and ecological techniques to generate data to evaluate repair efforts, providing feedback to investors. A number of approaches were evaluated including bund wall removal, feral pig fencing and removing aquatic weeds in wetlands on floodplains. The key results are summarised below.

Bund wall removal

Tidal bund walls were historically constructed in many places along the GBR coastline to provide stock with ponded pastures as a source of late dry season forage (Figure 9). These artificial wetlands are designed to exclude ingress of saline sea water and permit the growth of freshwater macrophytes including Para grass (*Urochloa mutica*), Aleman grass (*Echinochloa polystachya*) and Olive hymenachne (*Hymenachne amplexicaulis*). This provides a food source for livestock throughout the dry season, thereby saving on supplementary feed and improving farm resilience to drought (Challen & Long, 2004; Hyland, 2002). In addition to on-farm benefits, ponded pastures also support a range of other values and processes; whether those processes are deemed positive or negative is dependent on the context of the beneficiary being considered. NESP TWQ Hub research evaluated the values of several areas of ponded pastures.

For example, the artificially-built Tedlands wetland complex near Sarina supports considerable freshwater biodiversity and provides potential water quality improvement values (Canning, Adame et al., 2021). The area provides habitat for more than 150 different water and shore bird species and supports at least 15 species of fish (including species with a movement ecology between saltwater and freshwater, for example the barramundi). The complex is also estimated to potentially remove, on average, 12-15 tonnes of nitrogen each year from the contributing watercourses draining agricultural land, based on indicative estimates of denitrification on a long-term average (i.e., year-to-year estimates could vary, largely influenced by hydraulic loading patterns) (Canning, Adame et al., 2021; Canning & Waltham, 2021).

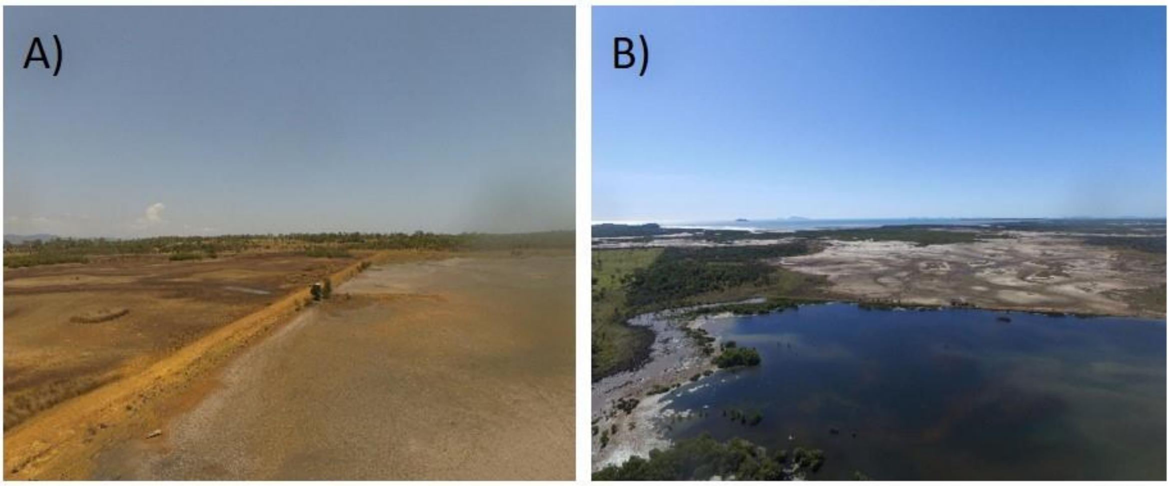

Figure 9. Ponded pasture wetland near Sarina: (a) late dry season; and (b) wet season with the wetland recharged. (Photo credits: N. Waltham).

The Mungalla ponded pasture wetland complex near Ingham was also investigated for its success in the context of previous restoration activities. At this location, a section of the earth bund wall was removed in 2012 to maximise the saltwater ingress in an attempt to destroy freshwater aquatic weeds (rather than to continue using herbicides). During the initial years following works (2012-2015) tidal ingress successfully destroyed large areas of freshwater weeds and water quality and fish connectivity improved (Abbott et al., 2020). However, this period coincided with a low rainfall wet season period which effectively maximised the saltwater ingress. In the years following (2016-2018) where wet season rainfall was generally higher (near to long term average and above average), the wetland reverted to a freshwater dominated system where invasive weeds re-established and fish numbers declined (Wallace et al., 2020). This oscillation between a freshwater and brackish state in the wetland seems to be dependent on the catchment hydrology, where in wet years the wetland functions in a freshwater state, while in dry years tidal ingress means it functions in a more saline state with less aquatic weeds (Figure 10).

To assess the likely future outcomes, modelling of the tidal ingress under future climate and sea level rise scenarios indicated that the frequency and duration of tidal ingress is likely to increase. This supports the model that the elevation of the bund wall at the restoration site is important, with project sites much lower in elevation probably providing more immediate success in terms of hydrological reconnection (Wallace et al., 2020). While removal of bund walls is of increasing interest to managers and scientists as potential restoration opportunities, little explicit data exists to date on the environmental services that would be achieved or lost, as a result of this restoration activity (Waltham et al., 2019).

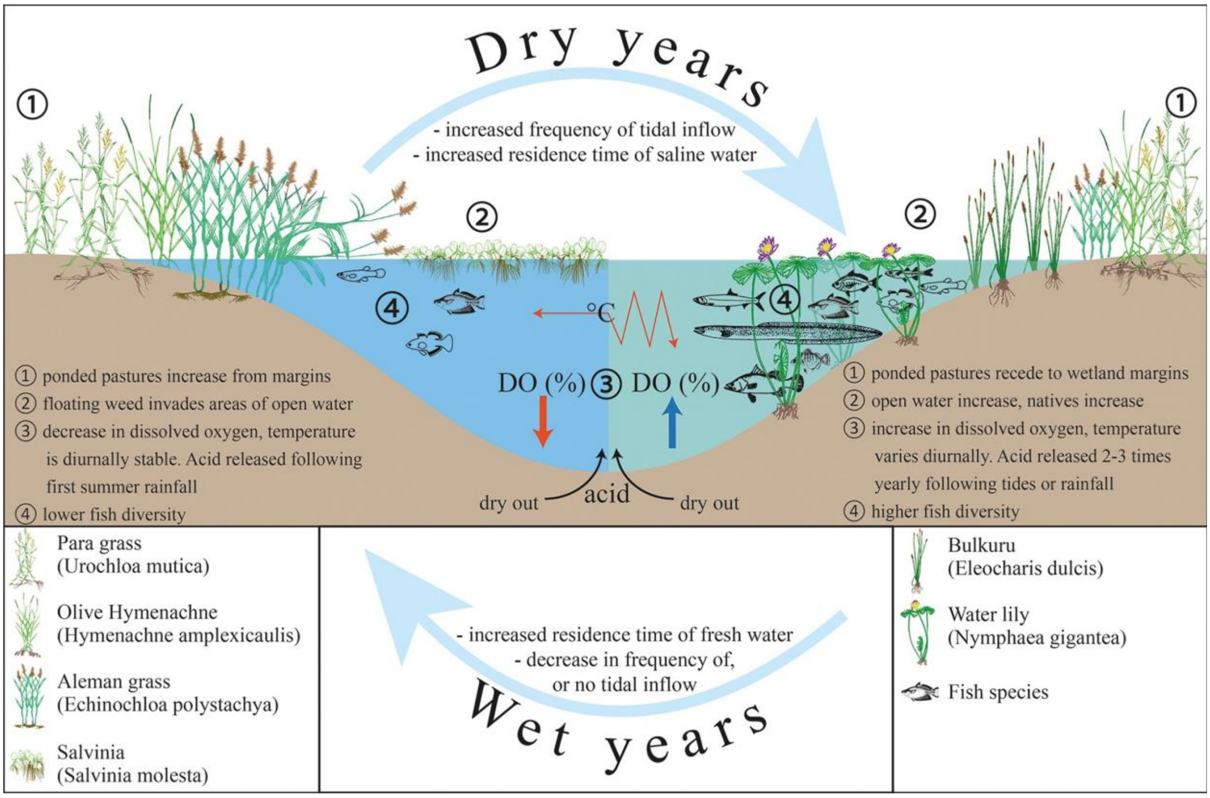

Figure 10. Conceptual model of changes due to seasonal oscillations within the Boolgooroo region of the Mungalla wetlands. Source: Abbott et al., (2020).

Feral pig fencing

Across GBR catchments, feral pigs (*Sus scrofa*) contribute wide scale negative impacts on wetland vegetation, water quality, biological communities and wider ecological processes (Waltham, Buelow, et al., 2020). Strategies to control feral pig numbers have been employed since they were introduced to Australia including aerial shooting, baits and trapping. However, these methods require constant investment and cooperation by all landholders to mitigate pig numbers. Another approach becoming popular is the installation of perimeter fences to prevent access (Figure 11). However, fencing is expensive to construct and maintain (Ross et al., 2017) and at the same time may prevent other non-target terrestrial fauna (e.g., turtles) from accessing wetlands, which becomes particularly imperative late-dry season where remaining wetlands become regional water points for many mobile fauna in the landscape (Waltham, Buelow, et al., 2020). Preliminary trials to modify the design of fences (even retrospectively) have been successful, allowing non-target species to traverse fences (see Figure 11b).

NESP TWQ Hub research lead by Waltham's team (JCU) monitored one fenced wetland area at Eurimbula National Park, Round Hill Reserve, and four additional non-fenced wetlands sites in the area, concluding that the fenced wetland supported richer vegetation communities as well as higher fish and bird diversity, initially. However, continual access to the fenced wetland by cattle (due to the land tenure agreement with adjacent landholders) started compromising those results soon after (Waltham, Buelow, et al., 2020). Researchers proposed that efforts of installing fences, building earth ramps for fauna movement and pig baited trapping needs to be also supported by changes to the land tenure agreement, to ensure that the wetland values and services are protected (Waltham, Buelow, et al., 2020). The project concluded that overall conservation fencing for wetland value protection has proven to be important and should be implemented more broadly in GBR catchments where the impact of feral pig damage is persistent and extensive (Waltham, Buelow, et al., 2020).

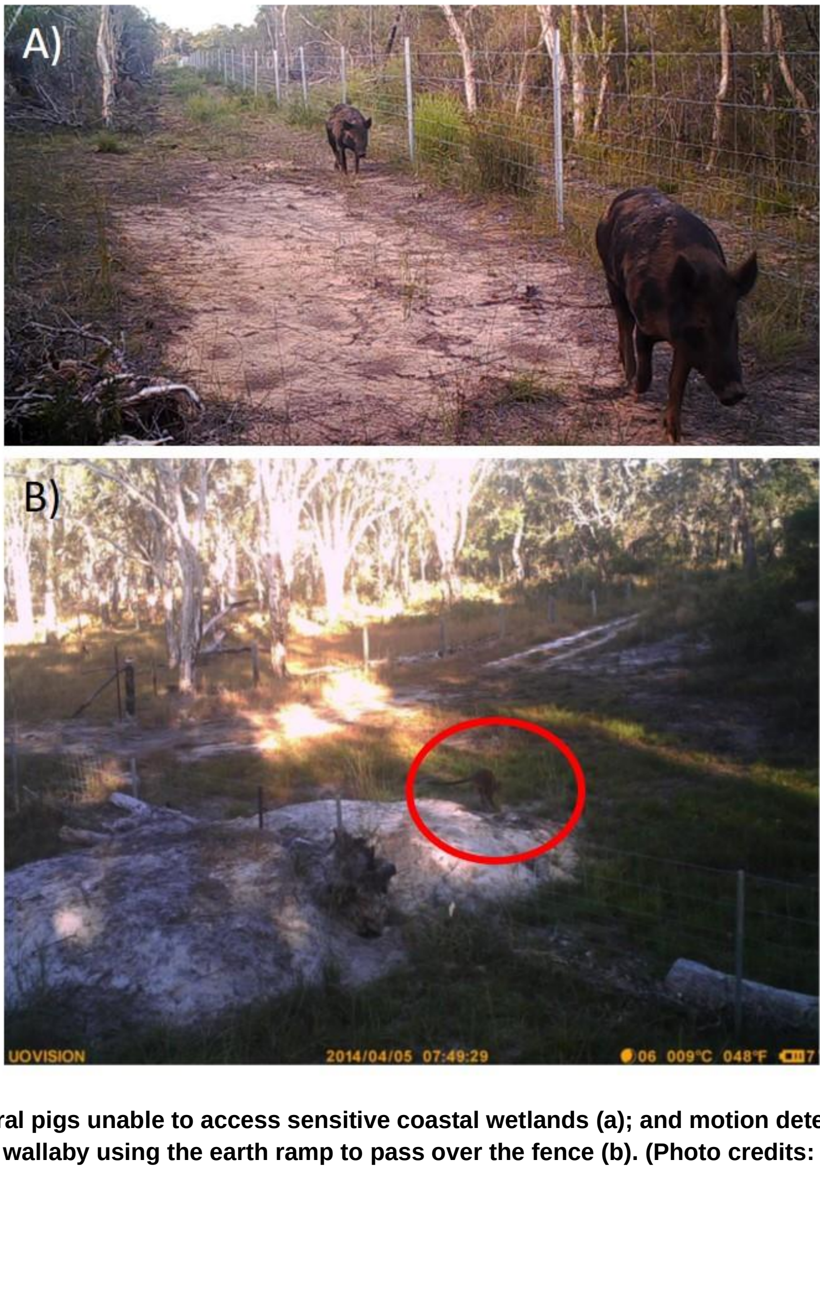

Figure 11. Feral pigs unable to access sensitive coastal wetlands (a); and motion detection camera recording a wallaby using the earth ramp to pass over the fence (b). (Photo credits: S. Jackson)

Removing aquatic weeds in wetlands on floodplains

Invasive aquatic weeds are prolific in wetlands on floodplains throughout the GBR catchments. Many species are listed under Australian legislation as Weeds of National Significance (most notably the water hyacinth *Eichhornia crassipes*, which has been described as the world's most prevalent invasive aquatic plant). These invasive aquatic weeds exist because of permanent water and high nutrients, and clearing has become an obligation for local government agencies, NRM groups, land holders and water boards (Waltham, Coleman, et al., 2020). Hyacinth growth in the Burdekin floodplain, for example, is also fuelled by an extensive water distribution network (over 1,500 km of linear channels) that deliver irrigation water to sugar cane farms, with the tail water (rich in nutrients, sediments and herbicides) then flowing via coastal wetlands to Bowling Green Bay (Davis et al., 2014). Removal of water hyacinth chokes has resulted in improved open water conditions at relatively small scales (Butler et al., 2009). For example, Perna et al., (2012) detailed how poor water quality at Sheep Station Creek in the Burdekin floodplain resulted in few fish species being present. However, after the removal of water hyacinth there was an almost immediate improvement in dissolved oxygen (DO), and subsequent return of additional native fish species. Through NESP TWQ Hub research, a similar treatment was undertaken in Crooked Waterhole (Burdekin floodplain, near Giru) to further trial the potential benefits that could arise from applying such treatments at a larger scale in the catchment. While initial months following weed removal resulted in improved water quality (particularly for DO) and fish numbers increased, on-going weed maintenance lapsed which resulted in the system returning to a weed choked state (Waltham, Pyott, et al., 2020; Waltham & Canning, 2021).

For as long as sugar production occurs on GBR floodplains and delivery of excessive available nutrients reach local creeks (Brodie et al., 2017; Waterhouse, Schaffelke, et al., 2017), aquatic invasive plants will continue to require some form of management intervention. The issue continues to be more critical for the clear water lagoons, located at the end of the distribution network or off-channel sections (Perna et al., 2012), where submerged aquatic vegetation biomass is high because of a deeper euphotic (light penetration) zone (Waltham & Canning, 2021). High plant biomass (particularly water hyacinth, and submerged aquatic vegetation, such as *Ceratophyllum sp*.), places a high net demand on available oxygen in the water column, resulting in extreme diel cycling compared to turbid lagoons which, because they have less aquatic plant biomass, generally have lower daily amplitudes and higher minimum values. Maintaining most creeks in the floodplain in a moderately turbid state would reduce the threat of eutrophic-driven hypoxia and fish kills (in the absence of floodplain-scale water treatment of sugar farm runoff) (Waltham & Canning, 2021). This result would mostly be due to the suppression of excessive growth of submerged aquatic vegetation that would otherwise occur in the current catchment context (of being surrounded by intensive agriculture) (Burrows & Butler, 2012).

This management approach is counterintuitive when considering broader GBR initiatives set under the Reef 2050 plan which have centred on reducing land derived suspended sediment that are known to cause effects on offshore (downstream) coral reefs (Bartley, Waters, et al., 2017) and seagrass meadows (Coles et al., 2015), which form part of the Bowling Green Bay RAMSAR wetland complex (Queensland Government, 2016). However, in managing the threat of aquatic plant overgrowth and poor water quality conditions, the best strategy seems to be to keep the floodplain creek network in a turbid state, as a means towards at least giving the best chance of better DO cycling, thereby reducing the risk of fish kills (Waltham & Canning, 2021).

The impact of water hyacinth on water and habitat quality is a challenge for managers requiring considerable investment in control measures (Masifwa et al., 2001; Villamagna & Murphy, 2010). Although costly, the return in terms of water delivery for irrigation, flood risk immunity, water quality conditions, lowered risk of fish kills, and habitat value should not continue to be undersold. While spraying herbicides is the most cost-effective way to control floating plants, it can have detrimental secondary effects when the organic material decomposes, creating a massive oxygen demand on the water column (Villamagna & Murphy, 2010; Waltham & Fixler, 2017). Alternative approaches are available, such as mechanical excavation, a technique considered to be the most effective ecosystem-responsive technique (Greenfield et al., 2007; Güereña et al., 2015; Masifwa et al., 2001), or even removing barriers and allowing tidal ingress which is possible in some places along the coast (Abbott et al., 2020). Opportunities to decompose vegetation material on nearby sugarcane farms are possible and have the added benefit of supplementing fertiliser application to cane fields (Waltham & Canning, 2021).

2.2.3 Tidal wetland monitoring and restoration

Being located at the land-sea interface, tidal wetlands (mangroves and salt marsh) are particularly susceptible to a wide range of external factors that result in changes to their condition and extent (UNEP, 2014). Projects undertaken by the NESP TWQ Hub have focused on two fundamental issues for the management of tidal wetlands in the northeast region of Australia: 1) the involvement of TO ranger groups in the on-going assessment and monitoring of these vulnerable but valued coastal habitats as locally-committed observers and managers; and 2) advancing our understanding of the causes behind each instance of changes in condition. The outcomes of this research contribute to better management of tidal wetland ecosystems. The findings support improved understanding of the range, severity and complexity of processes involved in tidal wetland function, and therefore, the most suitable methods of restoration. As with any restoration project, further knowledge of the key threats responsible for the initial wetland degradation, and how they can be removed or accommodated, is important to minimise restoration failure.

Improved monitoring of GBR tidal wetlands

Tidal wetlands face a wide range of threats and pressures, each manifesting differently in different parts of the estuarine tidal landscape. Estuarine wetlands provide essential ecosystem services that protect the GBR. However, shoreline habitats within estuaries of the southern GBR have been badly damaged by repeated, recent extreme flood events, and there are no existing national strategies for prioritising sites of estuarine wetland rehabilitation, to minimise anthropogenic stressors that maximise water quality improvement and other ecosystem services. A whole-of-system assessment is necessary, incorporating socio-cultural, ecological, and economic considerations, to inform cost-effective, successful investment in shoreline habitat rehabilitation (Duke, 2014; Duke & Larkum, 2019).

In response to this need, a Mangrove Management Plan was developed with Traditional Owners in the southern GBR, while building essential capacity amongst the Gidarjil Development Corporation Rangers and the local community to conduct ecological monitoring and assessment of key local estuarine resources. More specifically, NESP TWQ Hub research led by Dr Duke (JCU) applied an integrated assessment method, the Shoreline Video Assessment Method (S-VAM), to undertake systematic assessments of shoreline and estuarine condition across large coastal areas. The S-VAM assessments have been developed in two quite distinct but complementary formats. One is for use from small vessels as undertaken by TO rangers and community volunteers (Mackenzie & Duke, 2019), with participants involved in image and data acquisition receiving training and equipment from the researchers, but with the researchers being responsible for systematically processing and assessing the data. The second format is for use from low-flying helicopter surveys undertaken by researchers (Duke & Mackenzie, 2018).

Also, the S-VAM used a series of informative indicators which were developed based on observed changes in tidal wetlands including erosion, deposition, dieback, recruitment, storm damage, root burial, terrestrial retreat, ecotone shift, fire scorching, feral pig digging, noxious weeds, and more (Duke, Hutley, et al., 2021). A scoring system was developed for each indicator based on its severity and extent (Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021). Assessments of these indicator scores were used in the identification and quantification of active processes of change (also see Duke & Mackenzie, 2018). For example, rising sea levels are largely indicated by shoreline erosion, saltpan scouring and terrestrial retreat.

The S-VAM method was applied by the project team in collaboration with TO rangers of the Gidarjil Development Corporation in assessing eight major estuarine systems of the southern GBR region from Hervey Bay to Gladstone (Duke et al., 2019a; MangroveWatch, 2019) (see Figure 12). Estuarine wetlands are an integral component of this sea country, comprising sites of immense cultural heritage significance, including middens, fish traps, and traditional fishery resources.

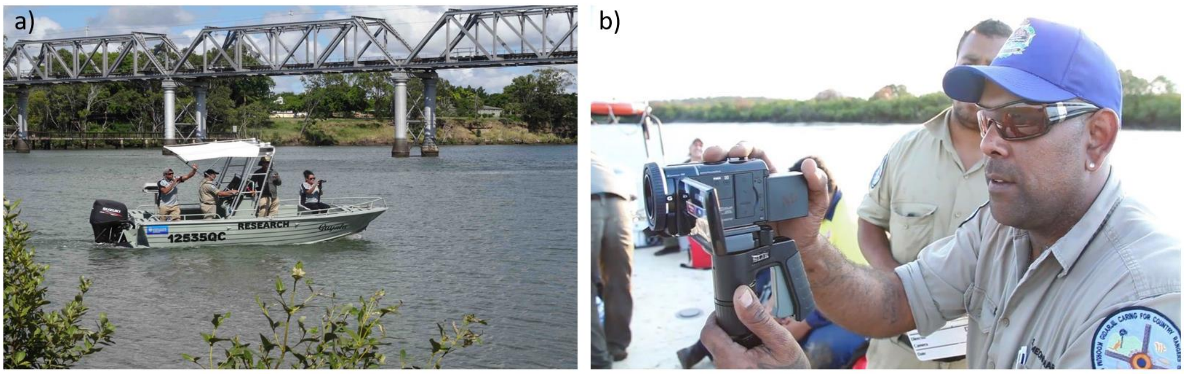

Figure 12. SVAM (Shoreline Video Assessment Method) shoreline surveys by Gidarjil rangers on the Burnett River estuary near Bundaberg in Central Queensland (a); and Gidarjil rangers conducting S-VAM surveys in 8 estuaries of the southern GBR region between 2017 and 2019 (b) (Duke et al., 2019a, 2019b).

Regional impacts related to climate change and sea level rise were apparent in all eight estuarine systems surveyed, with specific indicators including unusually high proportions of shoreline and bank erosion, saltmarsh-saltpan scouring, upland migration, and terrestrial retreat. These factors were exacerbated further by severe weather events (i.e., intense periods of drought, cyclonic winds, torrential rains, severe flooding) combined with local environmental issues associated with a range of direct (e.g., land reclamation, direct damage by vehicles, cutting or cattle) and indirect human activities (e.g., altered hydrology by restricted flow or waterway barriers, pollutants such as herbicides and nutrients). These variables contributed to overall conditions that differ for each estuary, reflected in the condition score (summarised in Table 3, with the highest condition scores reported for the estuaries of the Burnett River (89), Kolan River (84), Baffle Creek (79) and Elliot River (79) (Duke et al., 2019a, 2019b).

Table 3. Summary of results for the shoreline and estuarine condition assessment at 8 major estuarine systems monitored as part of NESP TWQ Hub research (Duke et al., 2019b).

Estuary	Total tidal wetland area (ha)	Total shoreline surveyed (km)	Time of monitoring	Overall Condition Score[a]	% Human related impacts[b]	Main issues identified
Calliope River	794	51	2015, 2017 and 2018	74	~53%	Development expansion, shoreline habitat modification, and loss of area.
South Trees Inlet	1,802	32	2014 and 2018	73	~50%	Development expansion, altered hydrology, and loss of area.
Boyne River	105	21.5	2014, 2015, 2016 and 2018	73.5	~48%	Development expansion, agricultural intensification and flood damage.
Baffle Creek	1,209	89.7	2017 and 2018	79	~59%	Cattle grazing, vehicle damage and extreme weather events.
Kolan River	969	51.6	2013, 2016 and 2018	84	~69%	Altered hydrology, agricultural intensification, bank erosion damage and extreme weather events.
Burnett River	540	52	2013, 2016 and 2018	89	~69%	Development expansion, agricultural intensification, altered hydrology, extreme weather events, and loss of area.
Elliott River	589	19.4	2013, 2016 and 2017	79	~48%	Development expansion, ground water extraction, and vehicle damage.
Burrum River	644	58.4	2013, 2016 and 2018	65	~60%	Development expansion, agricultural intensification, altered hydrology, and loss of area.

[a]Overall condition score was calculated as the multiple of ‘severity’ and ‘scale’ scores for each indicator, both ranking from minimal (1) to high (5) impact; [b]% Human related impacts was the sum of ‘direct’ (e.g., direct damage by vehicles, cattle grazing, cutting/clearing, habitat fragmentation) and ‘indirect’ (e.g., altered hydrology, pollutants, faunal damage, bank erosion due to riparian clearing) human drivers, and excluded natural drivers (e.g., bank erosion, saltpan scouring, depositional gain, drought, frost, terrestrial retreat, light gaps, upland migration, flood damage).

Figure 13 provides an example of the application of the survey work undertaken by the Gidarjil Rangers in the Burnett River following the severe damage to tidal wetlands as a result of the 2013 flood event in the Burnett River. The assessment method allows reporting of change in mangrove extent in different reaches of the river, and the historical change over time.

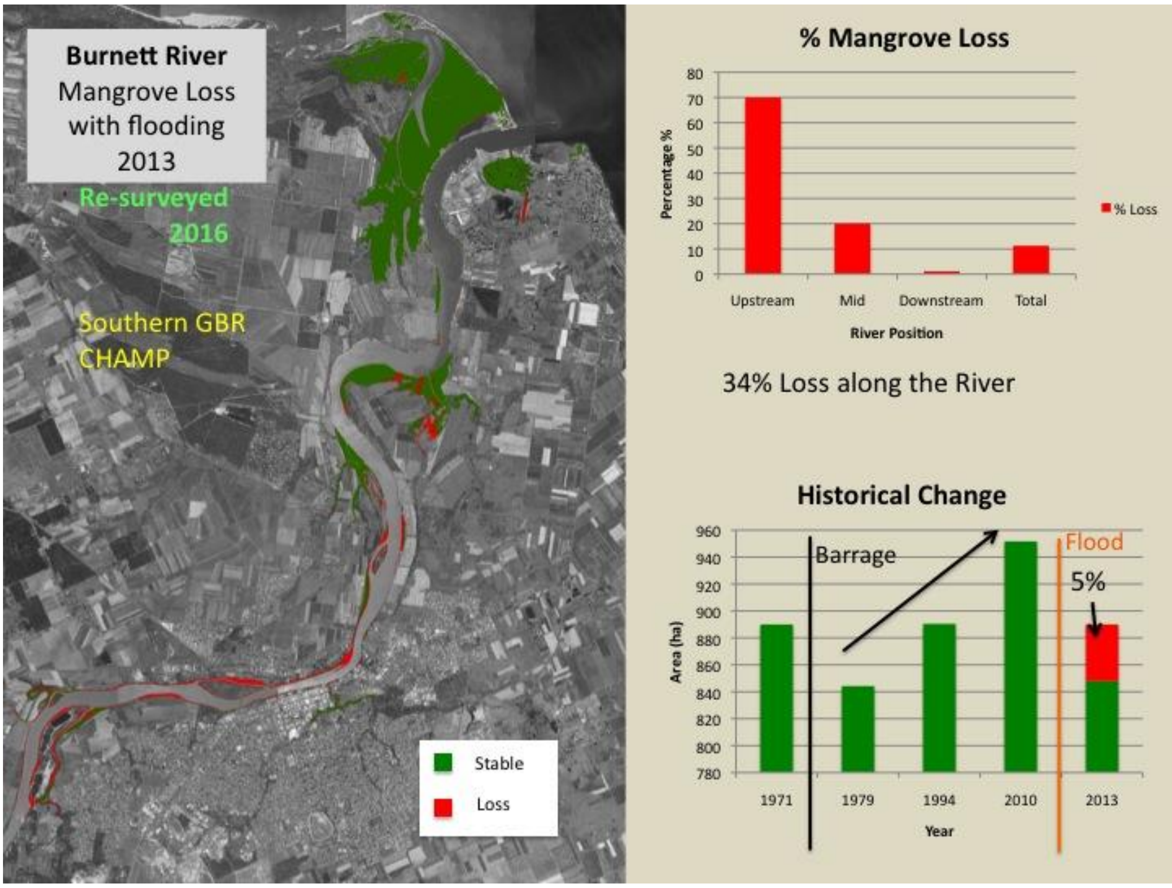

Figure 13. Gidarjil surveys of the Burnett River in the southern GBR region helped characterise the upstream severe flood damage to tidal wetlands following the 2013 flood event (Duke et al., 2019a, 2019b).

Overall, this project assessed over 375 km of estuary length in the southern GBR and involved more than 15-20 TO rangers over a three-year period (2017-2019). The training and capacity building gained by the rangers was a major outcome of the research, and also led to successful commissioning of a number of additional projects linked to this experience. For example, a project funded by the Department of Foreign Affairs involved a delegation of Gidarjil rangers travelling to Brazil to identify opportunities and share knowledge for the monitoring of mangrove estuaries by local Indigenous communities.

Lessons from the mass dieback of mangroves in the Gulf of Carpentaria

When mangrove ecosystems are healthy, they provide valuable structure, carbon sequestration, shoreline protection, shelter, nursery habitat, and food for estuarine, coastal, and reef fisheries and other marine life of cultural and economic importance (Duke et al., 2007). These benefits extend to the maintenance of shoreline stability with the buffering of exposed shorelines from erosion and retreat inland. These shoreline protection benefits are much needed where sea levels are rising and storm severity is increasing, as is already the case with global climate change. In this context, it is noteworthy that healthy living mangrove habitats hold considerable carbon reserves both in their woody structure and below ground in peaty sediments. These underground reserves, however, only persist while the living vegetation on top remains intact and protected. So, it is vital that living mangrove stands be maintained, especially since it is very difficult and impractical to replace these ecosystems once they have been lost (Duke, Hutley, et al., 2021; Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021).

In 2016, NESP TWQ Hub researchers received reports of significant shoreline mangrove dieback from fishers, birdwatchers and TO's from various locations in the Gulf of Carpentaria. While the reports spread over ~2,000 km, they all indicated widespread dieback around the same time. Further investigation identified that these reports were part of a connected dieback event that extended across most of the Gulf of Carpentaria shoreline. Subsequent investigation revealed that this was the largest mangrove dieback event ever recorded in the world (Duke et al., 2017),coinciding with an extreme El Niño weather pattern in late 2015 (Duke et al., 2017) (See also NESP TWQ Hub Case Study[13]) (Figure 14a). In response, the NESP TWQ Hub, in collaboration with the Northern Australia NESP Hub, initiated further studies to identify the cause of the dieback and advise on any required management actions (Duke, Hutley, et al., 2021; Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021).

Figure 14. Mangrove dieback in the gulf of Carpentaria (Photo credits: N. Duke) (a); and researchers inspecting mangrove dieback in the Gulf with Anthawirriyarra land and sea rangers near Borroloola in the Northern Territory (Photo Credits: J. Mackenzie) (b).

[13] NESP TWQ Hub Case Study: Facilitating natural regeneration processes. Planting seedlings is not the best response to mass mangrove dieback in the Gulf of Carpentaria: https://nesptropical.edu.au/wp-content/uploads/2021/08/Project-6.2-Case-Study-Booklet-1-Mangroves_COMPLETE_FINAL2.pdf

Shoreline mapping and aerial surveys revealed that the 2015 dieback event resulted in the loss of 80 km^2 of mangroves across ~1,500 km of the Gulf of Carpentaria shorelines (Duke, Hutley, et al., 2021; Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021) (Figure 14). A range of possible causes were investigated, but the widespread impact and synchronicity of this unprecedent event was key evidence of its cause: a sudden (though temporary) drop in mean sea level which was coincident with strong El Niño events, especially in the shallow Gulf of Carpentaria. The drop in mean sea level leads to extreme moisture deficit in the mangroves, precipitating their demise across the region. These investigations additionally discovered that there was an earlier mangrove dieback event in 1982 (also a strong El Niño year) that had not been detected or reported previously (Duke, Hutley, et al., 2021; Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021).

These discoveries also identified a clear link between the previously unknown direct damage to shoreline mangroves from extreme ENSO events with the damage to other shallow-water marine habitats, like coral bleaching, as a direct result of climate change affecting broad-scale oceanographic processes. This knowledge has profound and lasting benefits for future assessments of shoreline and estuarine condition in that future occurrences of the mass dieback of mangroves should be generally predictable.

The research has also highlighted the absolute dependence of shoreline mangroves on regular tidal inundation, and that the lack of seawater wetting in semi-arid tropical settings has dire consequences after about six months. After such long exposure, these mangroves die from desiccation and severe moisture stress, especially in the absence of water coming from other sources like groundwater seepage or rainfall (Figure 14). This knowledge is considered a fundamental part of a targeted management strategy in response to such damaging events in the future.

Research on the Gulf of Carpentaria mangrove dieback has therefore provided standardised methods, strategies, novel classification systems for scoring ecosystem condition, new information on impacts, and recommendations for mitigation actions, which will be extremely useful for management (Duke, Hutley, et al., 2021; Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021), especially considering that future re-occurrences of severely damaging mangrove diebacks are anticipated across northern Australia in the future due to climate change.

The study additionally concluded that intervention involving replanting of mangrove propagules is not a recommended strategy in this area, as field observations revealed adequate natural recruitment, although cumulative impacts (e.g., severe cyclones, flooding and rising sea level) were hindering the natural regeneration process. Hence, while abundant recruitment was observed, the main issue was with the survival and successful establishment of recruits due to both episodic and continuous events of strong storms, fires, weeds, and feral pigs, coupled with constantly rising sea levels. Such cumulative impacts have disrupted recovery, reducing normal growth and establishment of young mangrove plants. Strategies to ensure the long-term health and resilience of mangrove ecosystems were recommended to take place at the local, national and global scale concurrently, including:

1. Climate change abatement schemes at national and global levels to reduce the risk posed to mangrove ecosystems from desiccation, flooding, sea level rise and more frequent and severe tropical storms and cyclones.

2. The resilience of mangrove communities and associated habitats will be strengthened by either removing or managing the impacts of local pressures (e.g., feral pig damage, fires and weed invasions).

3. To deal with the likelihood of future collapse events, the study recommended a remedial strategy to keep affected trees alive during periods of extreme low moisture conditions. Knowing the threshold low sea level that could kill mangrove trees, and a properly designed monitoring scheme that signals when weather and sea level conditions become threatening, enables a locally-based response network of Indigenous ranges to deliver life-sustaining watering when needed (Figure 14b). This could be part of an on-going program of regular maintenance of localised threats to control feral pigs, weeds and fires.

Strategies 2 and 3 will be most effective when enacted by the local Traditional Owners and Indigenous ranger groups. In addition to their substantial traditional knowledge and vested interests in the health of their mangrove forests, they now have many of the scientific and monitoring skills that will be needed to care for their country (Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021).

2.3 Seagrass Restoration

Seagrass meadows are facing declines around the world due to global and local threats such as rising ocean temperatures, coastal development and poor water quality. While active seagrass restoration is not a widely adopted management response in the GBR as yet, continuing to improve the knowledge base for preventing further degradation and maximising recovery from disturbance is critically important. Accordingly, NESP TWQ Hub research on seagrasses has provided valuable information on light thresholds for GBR seagrass species (Collier, Chartrand, et al., 2016), biological indicators for seagrass condition (Collier, Langlois, et al., 2016) and ecologically relevant load targets to meet desired seagrass ecosystem conditions in the GBR (Carter et al., 2018, 2020; Collier et al., 2020; Lambert et al., 2020, 2019). The findings of these studies are contributing to improved design in integrated monitoring programs and enhanced seagrass management in the GBR (as synthesised in Pineda & Waterhouse, 2021). For example, to assess the impact of change in water quality and the light environment from anthropogenic activities such as coastal and port development, Dr Collier's team (JCU) identified light (photosynthetically active radiation) thresholds for seagrasses in the GBR, with results oscillating between 2-6 mol quanta m^{-2} d^{-1}, depending on species. If benthic light levels are lower than the thresholds for just days or weeks, again depending on species, then seagrass loss might occur (Collier, Chartrand, et al., 2016). To avoid chronic impacts and to restore seagrass habitats, thresholds of 10-12 mol quanta m^{-2} d^{-1} (when measured using the spatial benthic light from remote sensing, bPAR; Robson et al., 2020) would be required.

Decision support tools are needed for strategic management and prioritisation of restoration efforts, and the research by Dr Collier's team contributed to this need in the GBR. For instance, Carter et al. (2020) used more than 20 years of historical seagrass biomass data (1995-2018) from 25 seagrass communities to develop 'desired state' benchmarks. The results showed a historical, decadal-scale cycle of decline and recovery in most coastal intertidal communities; however, a number of estuarine, and coastal subtidal communities have failed to attain desired state in recent years (Carter et al., 2020). These declines were correlated with extreme weather events that included high rainfall and suspended particulate matter discharge, but the processes governing recovery could not be fully understood (Carter et al., 2020). Overall, the updated seagrass data, seagrass distribution mapping and modelling, community classification and desired state targets provided within Carter et al., (2020) can guide conservation planning through prioritisation of at-risk communities that are continuing to fail to attain desired states. This new knowledge of seagrass community distribution is a critical pre-requisite for assessing seagrass resilience and dispersal, and for deciding whether active seagrass restoration may be required or if the potential for natural recovery is sufficient. These areas are also relevant for identifying suitable donor sites if intervention is warranted (Carter et al., 2020).

Additional research within the NESP Marine Biodiversity Hub[14] is incorporating traditional knowledge with emerging restoration techniques to improve the efficiency, cost effectiveness and scalability of seagrass restoration programs in Australia[15]. The research consortium which included scientists from across Australia and New Zealand, was led by Deakin University, and was part of the Australian and New Zealand Seagrass restoration network[16]. Researchers identified the features of successful small-scale restoration projects around the world and the technologies which could allow these to be applied across large areas (Tan et al., 2020). Habitat restoration and creation may include efforts such as the physical planting of seagrasses, distribution or planting of seagrass seeds, or coastal engineering to modify sediment regimes. New tools were identified and included buoy-deployed seeding systems, dispenser injection seeders, artificial in-water structures to protect restoration sites and land-based nurseries for propagation (see examples in Figure 15) (Tan et al., 2020). Combined, these lessons and emerging approaches show that seagrass restoration is possible, and efforts should be directed at upscaling seagrass restoration into the future to maintain these important ecosystems and the ecological coastal communities they support (Tan et al., 2020).

Another study in the NESP Marine Biodiversity Hub applied integrated economic frameworks to understand the trade-offs between different restoration projects, and established which restoration configuration would deliver the largest benefits (including intangible or non-financial benefits) relative to costs (Rogers et al., 2019). The different scenarios that were analysed included replanting and reseeding methods, professional and volunteer-based methods, urban and remote locations, and different spatial extents of restoration (from 1 ha up to 100 ha plot sizes). Economic benefits were estimated for the carbon sequestration capabilities of restored seagrass meadows, and for the non-market (intangible) values that seagrass habitats generate, while costs were estimated based on recent seagrass restoration trials. Results from the benefit-cost analysis revealed that (i) replanting methods relying on professional staff were not economically viable, (ii) reseeding methods were more economically viable, (iii) projects using volunteers had larger net benefits, and (iv) net benefits were largest for larger projects. Hence, all scenarios had positive net present values (excluding the professional-labour replanting scenarios), with net benefits ranging from $40,000 for a 1 ha replanted volunteer-based plot, to over $ 7.8 million for a 100-ha

[14] https://www.nespmarine.edu.au/

[15] https://www.cqu.edu.au/cquninews/stories/research-category/2020-research/old-and-new-knowledge-key-to-seagrass-restoration

[16] https://seagrassrestorationnetwork.com/

reseeded volunteer-based plot. Payback periods (when project costs were recovered) ranged from 6-17 years (Rogers et al., 2019).

Figure 15. Emerging tools and techniques developed within the international seagrass restoration community. First row left to right: buoy-deployed seeding (© J. Heusinkveld); Dispenser Injection Seeding (© L. Govers). Second row left to right: seagrass nurseries (© G. Kendrick and J. Statton); anchoring shoots using iron nails (© T. Lange). Third row left to right: artificial in-water structures (© P. Macreadie), and collection and use of alternative sources of transplantation (© H. Spark). Source: Tan et al., (2020).

2.4 Coral Reef Restoration

Like many reefs around the world, the GBR is suffering from the combined effects of many threats and disturbances, including mass coral bleaching events, pollution, cyclonic storm damage, and outbreaks of pests like crown-of-thorns starfish (COTS), among others (for a detailed synthesis on NESP TWQ Hub research on cumulative impacts and reef resilience see Pineda & Johnson, 2021). While some of these threats are caused or exacerbated by global issues such as climate change, other threats may be amenable to local or regional-scale intervention, restoration and management (GBRMPA, 2019). Although coral reef restoration and adaptation practices are increasingly gaining interest among researchers and reef managers, at the commencement of the NESP TWQ Hub there was limited knowledge about reef restoration options and their potential effectiveness on the GBR. To address this knowledge gap and also prompted by three mass coral bleaching events on the GBR in five years (i.e., 2016, 2017 and 2020), NESP TWQ Hub commissioned a number of projects aiming at increasing practical knowledge in this area (as summarised in McLeod et al., 2020). Since then, there has been considerable investment in developing interventions (e.g., the $100 million Reef Restoration and Adaptation Program, RRAP), and Australia is in a better position to become an emerging global leader in this context. It is important to note, however, that the objective of restoration activities on the GBR is not to re-achieve an arbitrary historical condition. Rather, the focus is on how restoration can be used to facilitate ecosystem adaptation to the forecast of increasing frequency and/or intensity disturbances due to climate change and other potential human impacts across GBR catchments and the reefs themselves.

2.4.1 Identification of potential key refugia reefs

An important first step in the reef restoration field is to understand all the cumulative impacts occurring in the environment and the inherent ability of the reef to recover (i.e., reef resilience). As a good example of this, NESP TW Hub research 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.

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 (Holbrook et al., 2020). 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 (Holbrook et al., 2020). In addition, NESP TWQ Hub-funded research further assessed how multiple stressors overlap in time and space, reducing the overall health and resilience of the reef, and contributed to the development of an interactive tool on eAtlas[17], consisting of pressure maps to explain changes in coral cover and its potential to recover from disturbances. The tool illustrates issues and concepts of cumulative impacts for managers and the interested public (Uthicke et al., 2020).

2.4.2 Protecting and restoring key ecosystem functions on the GBR

Cumulative pressures such as those identified above also threaten key functions of the GBR, including those for habitats (e.g., reef growth) and production (e.g., fisheries). While biodiversity conservation is a core management strategy for reef ecosystem management, a subset of species might be critical to maintain and/or facilitate ecosystem functioning. In support of this concept, Wolfe et al., (2019) focused on how to preserve the functions of key reef species 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 in the GBR, including branching

[17] https://eatlas.org.au/gbr/nesp-twq-5-2-cumulative-impacts#distribution;exposure=year:2017;distribution=year:2017

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 16) (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 16). 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 could be used to inform the analyses of reef ecosystem resilience and identification of ecologically valuable reefs (Wolfe et al., 2019).

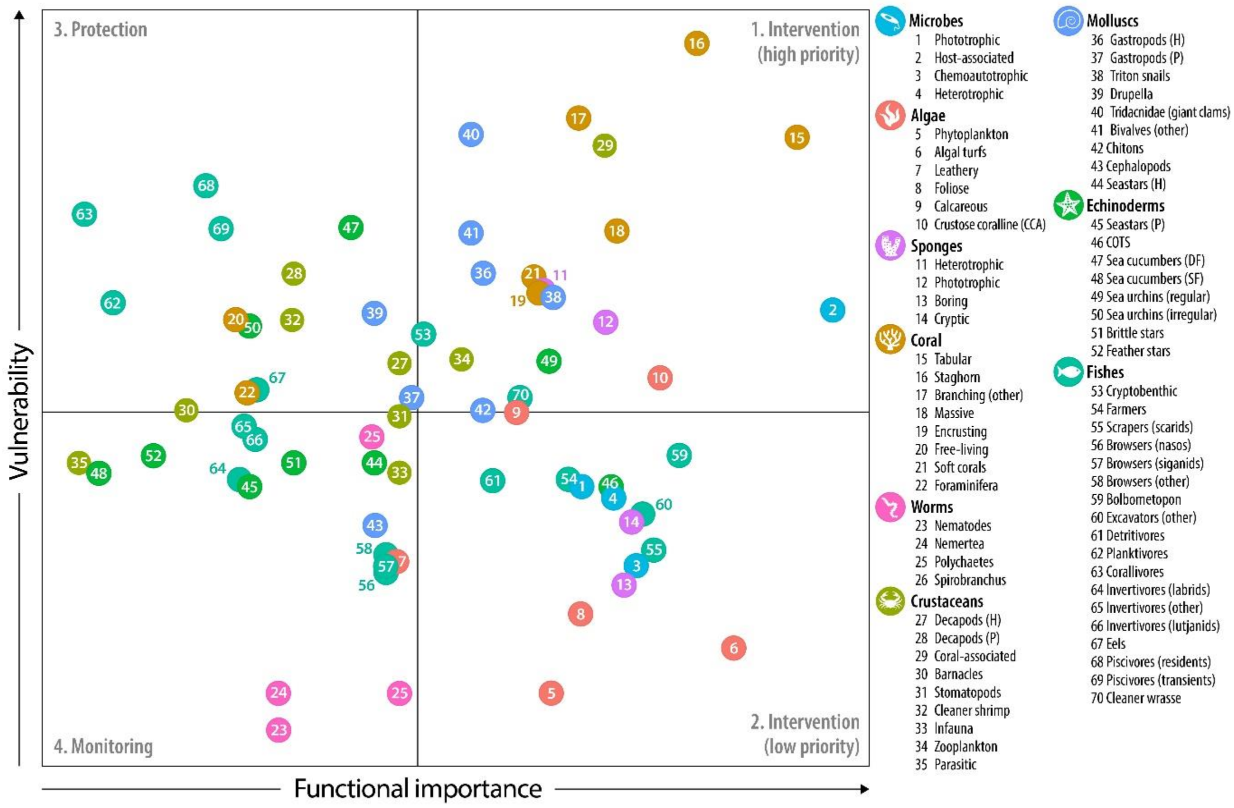

Figure 16. Functional importance and vulnerability of 70 functional groups common to the GBR coloured by phyla. Source: Wolfe et al., (2019).

2.4.3 Coral reef restoration

Until recently, management of the GBR has focused on facilitating natural resilience and resistance of reefs by reducing stressors such as fishing and poor water quality, while 'in-water' interventions were rare (except for COTS control programs, as synthesised in Erdmann et al., 2021). A summary and evaluation of success of coral restoration and assisted recovery techniques worldwide led by Dr McLeod (JCU) 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 and larval enhancement and microfragmentation. Most methods documented successful growth and survival (reported average survivorship of ~60-70%.) (Figure 17), however, 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). Substantial scaling-up would be required for restoration to be a useful tool to support the recovery and persistence of reefs on the GBR under global climate change. Key challenges for implementation included lack of clear restoration objectives, lack of appropriate monitoring and reporting and poorly designed projects. These (often substantial) challenges need to be overcome 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, while raising community awareness of the effects of climate change. McLeod et al., (2020) concluded that COTS control, macroalgae removal and coral restoration at small scales (e.g., coral nursery and gardening projects) were deemed appropriate to improve the health of local reefs, while educating the general public and providing stewardship opportunities. This was demonstrated through the delivery of hands-on participatory projects undertaken by 10 tourism operators along the GBR between 2017 and 2019 (Hein, Newlands, et al., 2020), with growing interest and participation of more operators since (described further below).

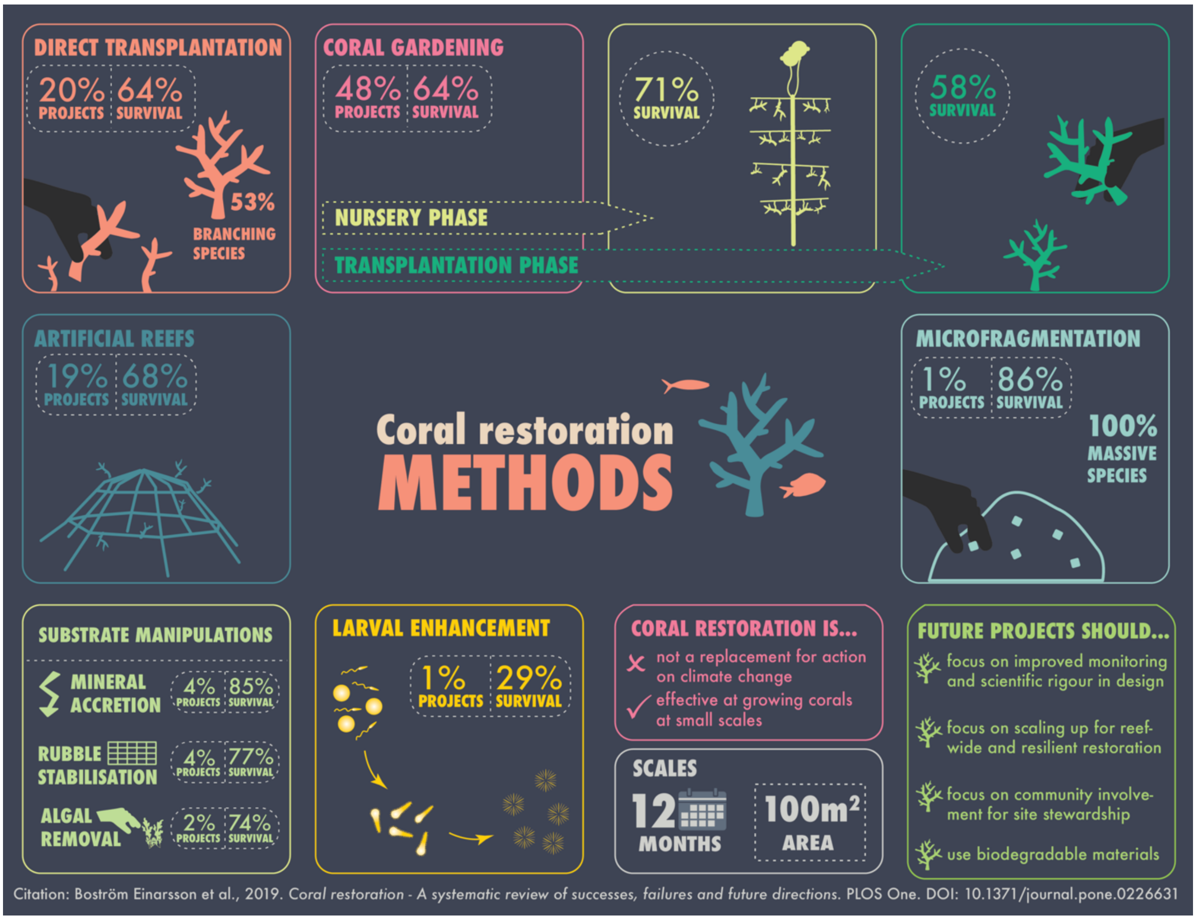

Figure 17. Summary of the different coral restoration intervention types that are available for use on the GBR. Source: Boström-Einarsson et al., (2020).

The motivations, success, and cost of global coral reef restoration were additionally assessed by Bayraktarov et al., (2019). Researchers identified that the main motivation to restore coral reefs across all the reviewed studies was to further the ecological knowledge and improve restoration techniques, with coral growth, productivity, and survival being the main variables measured. The median project cost was USD 400,000 ha^{-1}, ranging from USD 6,000 ha^{-1} for the nursery phase of coral gardening to USD 4,000,000 ha^{-1} for substrate addition to build an artificial reef (Bayraktarov et al., 2019). Despite the high cost associated with some reef restoration initiatives, NESP TWQ Hub research investigated and proposed a prototype calculation approach for determining financial liability for marine biodiversity offsets, which could contribute towards cofunding restoration activities (Maron et al., 2016).

Other common motivators for coral restoration identified by tourism operators on the GBR were related to the desire to improve coral cover and resilience at designated tourist sites, to protect the reef from increasing pressures, idealistic motivations (i.e., passion for the reef), and an opportunity to use restoration as a way to improve public awareness of current threats to coral reefs (Hein, Newlands, et al., 2020). GBR tourism operators additionally recognised the challenges they are facing in their restoration efforts, including: (i) regulatory systems and approvals, (ii) uncertainties and challenges linked to weather and climate events, and (iii) perceived risk that coral restoration could cause more damage to both the reef and their businesses (Hein, Newlands, et al., 2020).

In parallel to the NESP TWQ Hub-funded research on coral restoration, a multi-disciplinary initiative to investigate the best science and technology to support the GBR to resist, repair, and recover from disturbances – the Reef Restoration and Adaptation Program (RRAP)[18] – 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 direct intervention was possible and could double the likelihood of sustaining the GBR in good condition by 2050 (Hardisty et al., 2019). 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 through the Reef Trust Partnership[19]. 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 on the GBR (See also NESP TWQ Hub Case Study[20]).

Some examples of coral restoration projects in the GBR included the installation of the first coral nursery on Fitzroy Island (offshore from 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. Outplanting commenced in 2019. Since then, coral nursery and gardening projects have been established in other locations along the GBR including the Whitsunday Islands and

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[18] https://gbrrestoration.org/
[19] https://www.barrierreef.org/what-we-do/reef-trust-partnership/reef-restoration-and-adaptation-science
[20] NESP TWQ Hub Case Study: Starting the hard conversation -the GBR Restoration Symposium: https://nesptropical.edu.au/wp-content/uploads/2021/07/Project-6.2-Case-Study-Booklet-2-Restoration-Symposium-DIGITAL_COMPLETE.pdf

Opal Reef (offshore from Daintree) and have incorporated the development of new technology for attaching coral fragments (i.e., Coralclip®).

Other projects within the GBR are trialling other techniques including:

- substrate stabilisation e.g., a rehabilitation project at Agincourt Reef by Reef Ecologic and Quicksilver (McLeod et al., 2020);
- coral repositioning e.g., relocation of over 400 tonnes of *Porites* spp. in the Whitsunday Islands to allow for a pipeline (McLeod et al., 2019);
- macroalgae removal to aid reef recovery through increasing available substrate for coral settlement, and reducing competition for coral recruits e.g., trials at Florence Bay and Arthur Bay, Magnetic Island, mostly by hand (Ceccarelli et al., 2018); and
- larval enhancement to increase rates of larval settlement and recruitment on damaged reef areas using large numbers of coral larvae e.g., trials on Heron Island and One Tree Island (2016-2017), followed by larger-scale trials on other sites such as Moore Reef, off Cairns, and Magnetic Island (McLeod et al., 2020).

If successful, these techniques could help support reef resistance 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 kilometres of coral reefs in the GBR and Australia, and current evidence indicates that no existing restoration techniques can currently be scaled-up to a sufficient degree to support the vast expanse of these areas. Ultimately however, coral restoration techniques are likely to be integrated into the coral reef management ‘toolbox’ along with stress reduction (e.g., reduced land-based pollutant runoff), zonation for managing direct uses and direct control of predators such as COTS 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).

2.4.4 Coral reef adaptation

Human-assisted evolution is being considered as a tool to increase coral reef adaptation by testing transplanting manipulated (i.e., more climate resistant) coral species and or symbiont stock onto reefs. As described in Quigley et al., (2021), these methods generally include four approaches: (i) stress exposure and acclimatisation 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 undertaken by Dr Quigley’s team (AIMS) 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).

More specifically, investigations 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 (Quigley et al., 2021). In particular, the *sacsin* gene (associated with resistance to heat stress) found within *Acropora millepora* was identified as playing an important role in the variability of tolerance to bleaching (Fuller et al., 2020). 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 specimens of *A. millepora* that survived mass bleaching compared to other *Acroporid* species such as *Acropora hyacinthus* and *Acropora tenuis* (Figure 18) (Quigley et al., 2021). These characteristics could be used to help identify reef locations for targeted management actions, such as specific locations for spatial protection (e.g., refuges) or sites for future restoration activities where there is greater tolerance to higher temperatures. 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 18) (Quigley et al., 2021).

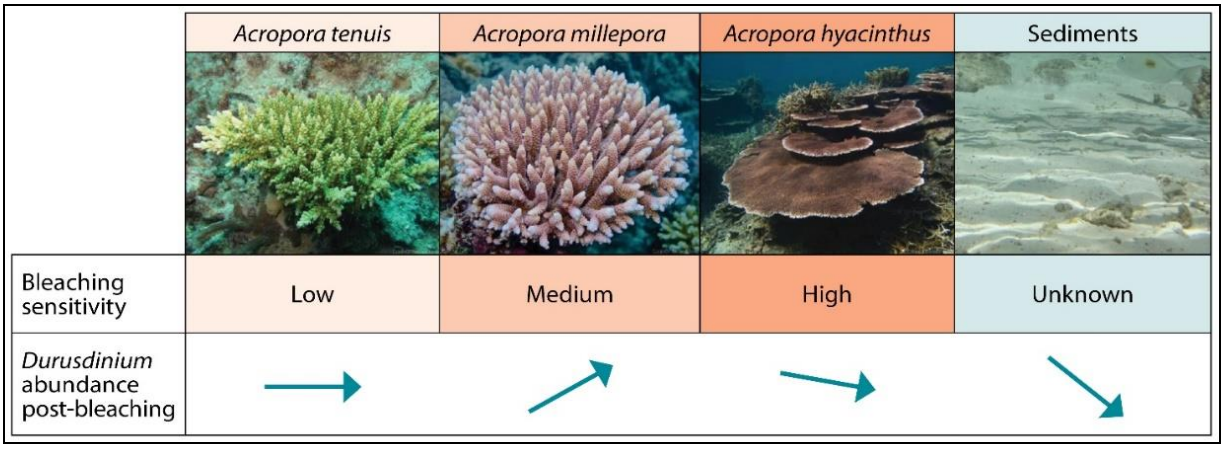

Figure 18. Summary of the changes in prevalence of stress tolerant photosymbionts (genus *Durusdinium*) within surviving corals sampled after bleaching and in the environmental pool. Arrows indicate direction and magnitude in changes in the relative abundance of *Durusdinium* within the four sample types (increase, no change, decrease; more drastic arrow angle signifies a larger change). Source: Quigley et al., (2021).

2.5 Social aspects of restoration activities

In recognition that restoration is about people, not just ecosystems, the NESP TWQ Hub commissioned socio-economic research to generate more explicit understanding of the economic benefits for regional communities associated with ecosystem restoration activities, beyond the restoration of ecosystem services (e.g., Barber & Jackson, 2017). For example, research led by Dr Barber (CSIRO) aimed at building indigenous livelihoods and co-management opportunities in the Cape York Peninsula (CYP), and documenting these processes and outcomes. The main goal of the project was to consider how ecosystem services in Eastern CYP (particularly in water and catchment management) that contribute to the health of the McIlwraith Rangers in particular and the GBR more broadly, can act as a suite of income streams to support sustainable local Indigenous livelihoods. These livelihoods (and the economic and cultural recognition that they entail) in turn have a range of beneficial effects, both locally and regionally. The project approach focused on community-based evaluation, governance, and strategic planning for Indigenous ecosystem services (Barber et al., 2017).

Ecosystem services focused on water and catchment management are a relatively common feature of ecosystem service markets internationally, where they are often known as watershed services or nutrient offsets. They are far less prevalent and well conceptualised in the Australian context and at the time of the project, had not been applied to Indigenous-controlled estates. Eastern CYP represents a crucial confluence of interest in water quality and marine ecosystem outcomes associated with the GBR, combined with growing Indigenous tenures. Indigenous ecosystem services represent one crucial pathway to support medium- and long-term Indigenous country-based livelihoods in CYP, and across Indigenous Australia more generally, as well as generating desirable outcomes for major environmental assets. The project considered the existing provision of ecosystem service by Indigenous-managed catchments in relatively good condition, as well as the benefits created from the active restoration of coastal wetlands (e.g., blue carbon) (Barber et al., 2017).

This research sets the foundations for a strategic business document for an Indigenous country-based management agency, Kalan Enterprises, and it effectively demonstrated ‘proof of concept’ for Indigenous provision of ecosystem services in CYP, while highlighting a series of additional steps required for successful implementation. These include the need to:

(i) strengthen local and regional Indigenous governance systems;
(ii) develop policy frameworks to support ecosystem service valuation;
(iii) build partnerships with agencies with skills in monitoring and evaluation;
(iv) identify commercial opportunities and build revenue streams that support the provision of ecosystem services; and
(v) build livelihoods based in Indigenous natural and cultural resource management that can generate substantial social, cultural, political, economic, and health co-benefits.

The project demonstrated that Indigenous ecosystem services represent one crucial pathway to support medium- and long-term Indigenous country-based livelihoods in CYP, as well as generating desirable outcomes for major environmental assets. The project, however, highlighted that these ecosystem services must be developed as part of a broader business and enterprise strategy containing mutually supportive elements (e.g., ecotourism, research services, feral animal management and biodiversity protection) (Figure 19).

Figure 19. Potential Indigenous-led development opportunities for member groups enabled by a strong and well governed Kalan Enterprises. Source: Barber et al., (2017)

2.6 Innovations in methodology and delivery

NESP TWQ Hub research has developed and applied a wide range of innovations both in research methods, and also in project delivery.

Some examples of innovations in the research methodology and delivery related to the suite of projects discussed in this report are listed below (information summarised in Table A1).

2.6.1 Gully and Riparian Restoration

- A gully database was developed and made available on eAtlas to facilitate systematic collection of data on gullies along with purpose-built-Excel-based data entry forms to allow for easy data upload to the centralised database (Brooks et al., 2019).
- The application of High-Resolution Airborne LiDAR (100-500 pts m^{-2}) from an ultralight plane as a significant innovation for cost-effective monitoring (Brooks et al., 2021). In support of this, semi-automated gully mapping approaches were refined and new tools developed in order to automate the attribute extraction and assignment of types to the mapped gullies from LiDAR Digital Elevation Models (DEMs) data, which should aid prioritisation, management and catchment modelling (Daley et al., 2021).
- In conjunction with the automated gully mapping methodology, a new method was developed for reconstructing the pre-existing land surface (or Prior Land Surfaces) before gully erosion as a means of accurately determining the whole of life sediment yield from gully erosion. When coupled with analysis of the average commencement dates of gullies, calculation of the total sediment yield delivered to the GBR from gullies in the areas mapped since European settlement can be undertaken (Daley et al., 2021).

- Comparison of different tools for monitoring and evaluating channel change (i.e., two terrestrial laser scanning instruments RIEGL VZ400 and Zebedee, and an airborne LiDAR), showing that the RIEGL was more accurate than the Zebedee, although the LiDAR could be useful to cover large areas rapidly (Bartley, Goodwin, et al., 2016).
- Development of a new method for identifying Potentially Active Erosion from gullies from a single LiDAR image (Daley et al., 2021). These mapping tools, including those above, have contributed to characterisation of different type of gullies (Brooks et al., 2019).
- Trial of the 'Pump Activated Suspended Sediment' (PASS) sampler (a new time integrated suspended sediment sampler) showing that the sampler is ideally suited for the cost-effective and rigorous collection of pre- and post- treatment sediment concentration data (Brooks et al., 2021).
- Installation of real-time water quality sampling instrumentation that can be monitored via web-based portals for landholders and regional delivery providers at the gully rehabilitation monitoring sites (Bartley, Hawdon, et al., 2020).

2.6.2 Wetland Restoration

- Development of a decision support tool integrating spatial and economic information to assist with examining options for transitioning low-lying cane land, with a high risk of DIN loss, to lower DIN-risk uses in the Wet Tropics (Waltham et al., 2017) and Burdekin and Mackay Whitsunday (Waltham, Canning, et al., 2020).
- Mapping generated from land use transitioning projects (Waltham et al. 2017, Waltham, Canning, et al., 2020) has been used by regional NRM groups, Traditional Owners and non-government organisations to populate funding proposals that target mapped sites to maximise return on investment for on-ground works and water quality improvement (e.g., Wallace et al. 2020).
- Utilising drone technology to generate wetland orthomosaics and classification analysis to map and examine vegetation community restoration following feral pig fencing (Waltham, Buelow, et al., 2020).
- Trials to improve non-target species movement where fencing is proposed for a wetland restoration site. These trials could generate new innovative ways to improve services and values of this restoration approach, that can be even retrofitted to existing wetland fencing sites (Waltham, Buelow, et al., 2020).
- Development of the package of methods for shoreline condition assessments of coastlines and estuaries (the Shore Video Assessment Method, S-VAM, Mackenzie et al., 2016). The package builds primary knowledge for stakeholders and managers on the status of shoreline habitats along large and significant sections of the northern Australian coastline (totalling ~15,000 km; Duke et al., 2010, 2019a; Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021; Duke & Mackenzie, 2018; Johnson et al., 2015; Mackenzie & Duke, 2016), noting habitat presence and its condition metre by metre. There are also permanent baseline records in high-resolution imagery from which initial assessments were made, and are available for on-going future reference. The results have proven valuable for State of the Environment reporting, especially for remote northern areas, for example, these surveys have for example identified significant shoreline locations of previously unknown severe cyclone damage like that around the Starcke River area (Duke & Mackenzie, 2018). Another example is the broadscale and significant influences of rising sea levels observed now in four major coastline sections of northern Australia including the Torres Strait Islands (Johnson et al., 2015), Princess

Charlotte Bay (Mackenzie & Duke, 2016), the east coast of Cape York (Duke & Mackenzie, 2018), and the Gulf of Carpentaria (Duke, Hutley, et al., 2021; Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021).

- The new mangrove dieback assessment technique identified the occurrence of two extreme low sea level events (Taimasa events) on the northern Australian coastline, especially in the Gulf of Carpentaria, in 1982 and 2015 causing the mass dieback of shoreline mangroves extending across thousands of kilometres (Duke, Hutley, et al., 2021). These events are a consequence of strong ENSO conditions leading to extreme low oscillations in mean sea level being further coincident with major coral bleaching events on Australia's east coast and beyond. The events show that like coral reefs, shoreline mangroves are also vulnerable to changing climatic conditions, especially in the semi-arid regions, typical of northern Australia.

2.6.3 Seagrass Restoration

- NESP TWQ Hub research on seagrasses has provided valuable information on light thresholds for GBR seagrass species (Collier, Chartrand, et al., 2016), biological indicators for seagrass condition (Collier, Langlois, et al., 2016) and ecologically relevant load targets to meet desired seagrass ecosystem conditions in the GBR (Carter et al., 2018, 2020; Collier et al., 2020; Lambert et al., 2020, 2019), contributing to improved design in integrated monitoring programs and enhanced seagrass management in the GBR. The updated seagrass data, seagrass distribution mapping and modelling, community classification and desired state targets provided within Carter et al., (2020) can guide conservation planning through prioritisation of at-risk communities that are continuing to fail to attain desired states. This new knowledge is critical for assessing seagrass resilience, for deciding whether active seagrass restoration may be required or not and for identifying suitable donor sites if intervention is warranted (Carter et al., 2020).
- The features of successful small-scale seagrass restoration projects and the technologies required to up-scale them were identified by Tan et al., (2020). Suggested techniques included physical planting of seagrasses, distribution or planting of seagrass seeds, or coastal engineering to modify sediment regimes. New tools identified included buoy-deployed seeding systems, dispenses injection seeders, artificial in-water structures to protect restoration sites, and land-based nurseries for propagation (Tan et al., 2020).

2.6.4 Coral Reef Restoration

- 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.
- 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).

- Nutrient availability (i.e., increases in nitrogen:phosphorous ratios) and impacts on carbon metabolism were identified to have a likely negative effect on the stability of coral-Symbiodiniaceae symbiosis and its 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).

2.6.5 Social aspects

- The on-going collaboration with TOs and Indigenous rangers has identified new livelihood opportunities (Barber et al., 2017) and formed an integral part of foundation projects of broadscale shoreline monitoring of tidal wetlands in the Gulf of Carpentaria (Duke, Hutley, et al., 2021; Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021) and along the southern GBR coastline (Duke et al., 2019a).

3. RESEARCH INFORMING MANAGEMENT

NESP TWQ Hub research has generated an impressive collection of valuable findings for advancing the ecosystem restoration field within the GBR and its catchments, which are relevant to many stakeholders and can be applied at a range of scales. With the emphasis on providing management solutions, a key feature of all of the NESP TWQ Hub projects has been the delivery of highly applied science and co-designed multi-disciplinary projects, coupled with close collaboration with stakeholders in project implementation including the NESP TWQ Hub Steering Committee, thereby enhancing the likelihood of research uptake.

Several examples of how the suite of projects highlighted in this report already have, and potentially could, inform management are summarised below.

3.1 Gully and Riparian Restoration

The effectiveness of investment in riparian management and other streambank and gully remediation works to reduce end of catchment sediment loads were addressed by several projects within the NESP TWQ Hub, with valuable outcomes for management. Bartley, Philip, et al., (2016), for example, highlighted the need to incorporate a ‘lag effect’ in the models used to evaluate GBR remediation investments (i.e., Source Catchment models), as the physical water quality benefits are only noticeable 2-18 years after remediation has taken place.

The importance of maintaining vegetation upstream and to apply a holistic catchment scale approach to tackling sediment sources was recommended within various projects (Bartley, Philip, et al., 2016; Brooks, Curwen, et al., 2016). NESP TWQ Hub-funded research also highlighted the need to prevent the initiation of additional gullies through appropriate grazing management and promoting passive ecosystem recovery where possible (Bartley, Hawdon, et al., 2020; Brooks, Curwen, et al., 2016).

Estimation of cost-effectiveness was another management outcome, and included optimal strategies to calculate it in order to capture realistic costs of on-ground projects and their effectiveness over the long term (Bartley, Hawdon, et al., 2020; Brooks et al., 2021). For instance, the use of ‘End of System’ cost effectiveness (calculated using a 7% discount rate and a 25-year lifetime to enable the upfront cost to be converted to its annualised equivalent cost so that it can be compared with annual sediment reduction) was suggested as a metric to inform investments in gully remediation across different GBR catchments (Brooks et al., 2021).

Scenario analyses using the Source Catchment models within the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program) could also be refined with data coming from those projects, allowing for improved accuracy to support decision-making. However, one of the most important messages for management from gully remediation science is that cost-effective remediation seems to be possible, reaching levels of >95% sediment yield reductions within two years, and it was also estimated that, for instance, 130 sites (i.e., alluvial gullies) would have to be remediated in order to meet the 2025 water quality targets in the Bowen catchment (Brooks et al., 2021).

The need to develop innovative and cost-effective monitoring techniques also become very evident from the research. Gullies are difficult landscape features to monitor accurately in terms of assessing fine sediment or particulate nutrient reductions, and it has been assumed that to do it effectively is extremely expensive. As such it was assumed that only a few gullies could be fully monitored, and the remainder would only be able to be monitored qualitatively. Through NESP TWQ Hub research, however, methods for assessing fine sediment outcomes and treatment effectiveness have been developed that can be deployed at scale, significantly reducing the monitoring costs per gully. Cost effectiveness, and objectivity, could be optimised if a standard strategy was deployed by an expert group (Brooks et al., 2021).

3.2 Wetland Restoration

Identifying and examining possible land use transition options for farmers with low-lying sugar cane has presented new innovative ways to consider reducing DIN from reaching the GBR, while also providing alternative land use options that are still profitable to farmers. These data has been already used by NRM and Indigenous groups to plan restoration projects, and potentially access funding mechanisms on the horizon (Waltham, Wegscheidl, et al., 2021).

In general, wetland restoration or constructed treatment wetlands are most cost-effective when conversion costs are low and DIN removal capacity is high. These options can also provide additional important ecosystem benefits, such as Improved water quality, fish habitat extension or carbon sequestration. There is an opportunity to combine these methods with pollutant credit or trading schemes that provide both improved water quality outcomes that are profitable for land holders (Waltham, Wegscheidl, et al., 2021).

The Shoreline Video Assessment Method (S-VAM) allows for an integrated and systematic assessment of shoreline and estuarine condition across large coastal areas. The S-VAM outputs (overall condition scores and % human-related impacts) can directly inform managers on which coastal areas may require action to mitigate the main issues identified, such as coastal development, agricultural intensification, cattle grazing, vehicle damage, modified hydrology, among others (Duke et al., 2019a, 2019b).

Shoreline mapping and aerial surveys revealed the extent of the 2015 mangrove dieback event in NE Australia (i.e., Gulf of Carpentaria). The source of the massive mangrove die-off event was identified (i.e. mostly due extreme El Niño weather patterns in combination with other pressures) and management measures were proposed including: (i) to include support for Indigenous rangers to monitor the condition of shoreline tidal wetlands while also helping manage other threats such as feral pigs, bush fires and weeds in areas surrounding vulnerable mangrove tidal wetlands, and (ii) to initiate a further program and partnership between researchers, managers and Indigenous rangers in an attempt to remove the damaging outcomes (i.e., which are now predictable) of desiccation periods associated with extreme low oscillations in mean sea level (Duke, Hutley, et al., 2021; Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021).

3.3 Seagrass Restoration

Continuing to improve the knowledge base for preventing further degradation of seagrass communities and maximising recovery from disturbance is critically important for the future management of seagrass communities in the GBR. Quantifying the complexity of seagrass communities and the environmental conditions that define community boundaries has improved our understanding of when and where it may be appropriate to intervene with restoration after a seagrass meadow has been lost or adversely impacted following an anthropogenic or climate-related event (Carter et al., 2020). Knowledge of potential seagrass habitat is essential to support these decisions, and this was modelled throughout the GBR through NESP TWQ Hub research. The approach used high resolution environmental data in seagrass habitat models, which was then applied as the basis to predict potential habitat. It is possible to predict whether seagrass is expected to occur under average conditions as a comparison to any other point in time, including following impacts.

In addition, guidelines for light quantity (I_{bPAR}) were recommended as a management trigger for seagrass meadows at risk from declining water quality (Collier, Chartrand, et al., 2016). Specifically, acute management thresholds (suited to compliance guidelines for managing short-term impacts) were proposed, from 2 to 6 mol quanta m^{-2} d^{-1} depending on species. Similarly, long-term thresholds (suited to the setting of water quality guidelines for catchment management) were also suggested for seagrasses, although researchers highlighted the need to determine the desired state for seagrasses at a regional scale beforehand (Collier, Chartrand, et al., 2016; Robson et al., 2020). Finally, new research tools were identified to determine thresholds of suspended particulate matter exposure, allowing for an improved appreciation of marine risk. These tools can be used to determine ecologically-relevant end-of-basin load targets and reliable marine water quality guidelines, thereby enabling enhanced prioritisation and management of fine sediment export from the GBR catchments (Lambert et al., 2020).

3.4 Coral Reef Restoration

Given the increasing occurrence of major disturbance events on the GBR (i.e., three mass coral bleaching events in the past five years -2016, 2017 and 2020) and the overall poor state of the GBR (GBRMPA, 2019), there has been a recent shift in strategy from traditional passive habitat protection towards the acceptance of active restoration and assisted coral adaptation as complementary tools for resilience-based management in the GBR.

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). Additionally, all this NESP TWQ Hub-funded research on reef restoration has led to international collaborations resulting in the co-authorship of important management documents such as 'A Manager's Guide to Coral Reef Restoration Planning and Design' (Shaver et al., 2020) and the 'Coral reef restoration as a strategy to improve ecosystem services - A guide to coral restoration methods' (Hein, McLeod, et al., 2020), together with substantial contributions to the 'GBR local-scale coral restoration toolkit[21]' produced in partnership with the GBRF and RRAP. This extensive toolkit aims to provide best-practice guidelines for reef restoration efforts on the GBR and is freely and publicly available.

Additionally, 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). For example, some coral species are more likely to be heat-stress sensitive with fixed symbiont communities (i.e., *Acropora hyacinthus* versus more heat tolerant species such as *Acropora millepora*). These characteristics could be used to help identify reef locations for targeted management actions, such as specific locations for spatial protection (e.g., refuges) or sites for future restoration activities where there is greater tolerance to higher temperatures (Quigley et al., 2021).

NESP TWQ Hub research also confirmed the importance of protecting reefs from extractive activities (i.e., enforcing no-take zones) and other direct uses (such as through no anchoring areas) to maximise reef resilience, the relevance of identifying potential key refugia reefs to facilitate replenishment and recovery of degraded reefs, and the need to protect and restore key ecosystem functions in the GBR (Emslie et al., 2015; Sweatman et al., 2015; Williamson et al., 2014, 2016; Wolfe et al., 2019). A seasonal prediction capability tool was also developed to assist GBR managers identify heatwaves and hence prioritise intervention on those reefs at higher risk of bleaching (Holbrook et al., 2020).

An interactive decision tool was also developed and integrated in eAtlas with exposure maps combining environmental pressures in time and space. The tool illustrates issues and concepts of cumulative impacts for managers and the interested public (Uthicke et al., 2020).

3.5 Social aspects

Of critical importance was the direct engagement of TOs in NESP TWQ Hub research. The research conducted by Barber et al., (2017) in Eastern CYP demonstrated that Indigenous ecosystem services represent one crucial pathway to support medium- and long-term Indigenous country-based livelihoods in CYP, as well as generating desirable outcomes for major environmental assets. The project, however, highlighted that these ecosystem

[21] https://gbrrestoration.org/resources/coral-restoration-toolkit/

services must be developed as part of a broader business and enterprise strategy containing mutually supportive elements (e.g., ecotourism, research services, feral animal management and biodiversity protection).

Furthermore, in collaboration with the Gidjaril Rangers, Duke and other assessed over 375 km of estuary length in the southern GBR and involved more than 15-20 TO rangers over a three-year period (2017-2019). The training and capacity building gained by the rangers was a major outcome of the research, and also led to successful commissioning of a number of additional projects linked to this experience. For example, a project funded by the Department of Foreign Affairs involved a delegation of Gidarjil rangers travelling to Brazil to assess opportunities and share knowledge for the monitoring of mangrove estuaries by local Indigenous communities. The involvement of the TO rangers in the research demonstrated the high level of competency, dedication and skill development that can be created in TO ranger teams, and highlighted the opportunities for TO groups to make significant contributions to the environmental monitoring of coastal ecosystems in an ongoing role. The Gidarjil Development Corporation project manager Ric Fenessey said involvement with the program had been very beneficial for the organisation's Indigenous rangers, particularly the development of skills needed to meet its strict scientific standards. "The program has been great for the rangers, it's provided a very good opportunity for them to reconnect with their sea country and learn a lot more about mangroves and saltmarshes in the area," he said. "It's quite a demanding methodology so they have had to zone into the fact that quality control on the data is essential to make sure the data is useable for scientific purposes, the method has to be followed to the letter. "These skills are transferrable to use in other areas - we have had one ranger who's now doing compliance training work with GBRMPA, and another that has enrolled in Environmental Management studies at university for next year because of his experiences in this program."

3.6 Project legacies

One of the main impacts of NESP TWQ Hub research related to the ecosystem restoration field, was the direct reduction in end of catchment fine sediment loads associated with proposed management practices such as streambank and gully remediation projects (estimated at >4,500 tonnes per year by only one of the projects (Brooks et al., 2021). A potential reduction in ecosystem impacts could also be expected from the increased knowledge and efforts in wetland restoration, from land conversion to wetland rehabilitation projects, resulting in improved water quality, connectivity and overall ecosystem services (Waltham et al., 2019). In the reef environment, the change in paradigm towards active seagrass and reef restoration and adaptation interventions is also contributing to increase its overall resilience towards current and future threats (Boström-Einarsson et al., 2020; Tan et al., 2020).

Outcomes from the research summarised in this synthesis are also contributing to the development of policy documents and frameworks, such as to the current review of the Reef 2050 Long Term Sustainability Plan (Commonwealth of Australia, 2020). For example, the review of the Plan incorporated NESP TWQ Hub research related to the improvement in water quality, reduction in cumulative impacts, increased biodiversity protection, and restoration and adaptation initiatives among others. All these research outcomes already are and will continue to inform investments in improved water quality such as the Reef Trust

Partnership in terms of management options, site selection and prioritisation, monitoring and evaluation techniques, and understanding the variability in treatment options and cost-effectiveness.

For example, the outcomes of Waltham et al., (2017) were applied in the design of the wetland treatment and restoration component of the Wet Tropics Major Integrated Project[22]. In addition, the research on wetlands has provided important and necessary learnings for restoration practitioners overall, and its results will be integrated into the planned revisions to the Queensland Government's Wetland and Catchment Strategy. Those learnings have been shared and disseminated via the GBR Wetlands Network, a group formed by representatives from NRM, NGOs, industry, state government, and academia. Finally, NESP results are also expected to contribute to the development of the next Scientific Consensus Statement and review of the Reef 2050 Water Quality Improvement Plan.

Additionally, NESP TWQ Hub research has allowed numerous improvements in management strategies, including more objective and reliable systems for decision making, improved monitoring programs, and facilitated reporting processes. For instance, reporting by stakeholders (e.g., GBRMPA, Reef Trust) could be facilitated by tools such as eAtlas[23], eReefs[24] or Source Catchment models[25], which offer open-access data, ecosystem models and predictions that enable the integration of information to provide potential future scenarios for the reef, as was presented in the Great Barrier Reef Outlook Report 2019 (GBRMPA, 2019).

4. FUTURE DIRECTIONS

Several NESP TWQ Hub projects built on previous work, or received extensions during the term of the NESP TWQ Hub either to enable further exploration of specific aspects of the research findings or to fully demonstrate a concept. This longevity has enabled several projects to generate results with a reasonably high degree of confidence, which is of significant benefit to managers. It has also highlighted which areas would benefit from further investigation.

NESP TWQ Hub projects evaluating the effectiveness of streambank and gully remediation highlighted the need to continue investment in the evaluation of restoration projects. There is now considerable understanding of the effectiveness of a range of rehabilitation treatments on some gully types (e.g., large alluvial gullies). However, there are other erosion processes and approaches for which there is little measured empirical data (e.g., streambanks and hillslopes in vulnerable soil types). These data are needed to provide support for the Paddock to Reef models and make investment decisions in order to achieve the desired water quality targets by 2025 (Australian Government and Queensland Government, 2018). The research highlighted the need to (Bartley, Hawdon, et al., 2020; Brooks et al., 2021; Paul et al., 2018):

[22] https://terrain.org.au/major-integrated-project/
[23] https://eatlas.org.au/home
[24] https://research.csiro.au/ereefs/
[25] https://www.data.qld.gov.au/dataset/reef-catchment-modelling-results

- Carefully prioritise remediation sites.
- Priority sites should have (i) high fine sediment baseline erosion rates; (ii) high sediment delivery or connectivity to the coast; and (iii) be most cost effective to manage (large alluvial gullies are relatively cost-effective to treat, but other smaller gullies can also be cost-effective to manage).
- Carefully design field monitoring studies. Treatment effectiveness can be accurately assessed within 2-3 years with a good design (Before-After-Control-Treatment). It will take longer if adequate baseline data is not captured.
- Apply a multiple-lines of evidence approach to monitoring. Each technique has strengths and weaknesses, and no one technique can provide all the answers.
- Carefully manage grazing within the remediation areas. For most gully remediation sites, stock reduction/exclusion is needed to maintain the integrity of the engineering structures and allow vegetation re-establishment. Re-introducing cattle into remediation sites poses a significant risk to the project if grazing is poorly timed with the rainfall season.
- Improve understanding of the role of sediments in delivering nutrients that affect water clarity beyond the immediate zone of influence of river plumes in nearshore waters.
- Increased monitoring of the water quality impacts of practices at a paddock and catchment scale to overcome remaining scepticism of reported links between water quality and landholder’s management practices.

Paul et al., (2018) identified the need for funding to support landholder groups working together to utilise learnings from local demonstrations and knowledge to develop guidelines for recommended management practices, thereby contributing to overcoming normalising behaviour and ensuring guidelines for management are practical and provide benefits to agricultural production. Several knowledge gaps were additionally identified within the riparian vegetation restoration space, including:

- The need to explore merits of implementing incentive schemes that provide landholders with payments that are directly linked to outcomes of improved water quality (e.g., indicated by a ‘Condition Score’), biodiversity (e.g., indicated by Plant Cover Index) and carbon mitigation (e.g., indicated by Emission Reduction Funds -ERF- methodologies). With all environmental services considered, payments should contribute to overcome the financial barriers (e.g., opportunity costs of foregone agricultural production), thereby facilitating the scale of participation required to have significant outcomes to the health of the GBR. Moreover, as landholder payment are outcome-based (as opposed to paying for fencing, etc. via grants), they incentivise not just the establishment of the project, but its on-going maintenance (Paul et al., 2018).
- It is also required to ascertain a condition scoring method that provides an improved estimate of likely benefits to water quality from remediation of riparian vegetation.
- Assess possible trade-offs between grazing extent and environmental benefits, and requirements to optimise environmental benefits by better understanding the possible trade-offs between project quality and the quantity of projects.
- Explore whether remediation projects are more likely to approach optimal Condition Scores when they have increasing extents of remnant vegetation within the project area, are relatively wide, and/or are well connected.
- Develop cost-effective methodologies for indicators of improvements in water quality and biodiversity, and refine ERF methodologies such that they account for the: (i) high

carbon mitigation potential of riparian zones, and; (ii) carbon stocks protected in remnant vegetation within the project areas.

In the field of wetland restoration:

- On-going research into wetlands and drains as treatment environments (e.g., water treatment, vegetated drains, denitrification bioreactors) under variable environmental conditions and hydrology, including water balance and nutrient budget.
- On-going validation of the cost-effectiveness of DIN removal by constructed treatment systems.
- Each restoration site should be approached as an experiment, and therefore data collected for "monitoring" needs to be relevant and appropriate to support the restoration objective – experimental designs for monitoring requires expert input to ensure that the learnings are rigorous, publishable, and valid for the project objectives.
- Ensure that all wetland restoration projects, particularly those involving aquatic weed management, can demonstrate long term maintenance funding models to ensure the investment is protected (Waltham, Coleman, et al., 2020).
- Australian restoration efforts relating to wetlands is decades behind the trials and knowledge held by countries overseas – for example, saltmarsh restoration has been on-going in the US for decades, with only a small number of trials here in Australia (Waltham, Alcott, et al., 2021).
- Support on-going shoreline video assessment analyses along with the development of a regional report card on southern GBR estuarine waters (Duke et al., 2019a; Mackenzie et al., 2016).
- Continue supporting TO and Indigenous rangers' engagement in the monitoring of estuarine shorelines (Duke et al., 2019a; Duke, Mackenzie, Kovacs, et al., 2021).

The outcomes of the on-ground studies, combined with the research investigating new instruments, highlight some noteworthy integrated outcomes that may warrant further investigation. For example, the role of transitioning low-lying cane fields with a high DIN risk potential to a wetland designed to intercept and treat water runoff was shown to be a cost-effective solution in some situations. The exploration of ES trading credits also highlighted wetlands as a potentially valuable and cost-effective alternative for reducing N losses in some areas. However, the opportunity to fully test and refine the data used in the economic modelling and measure the downstream benefits is still required via pilot projects. Pilot projects such as the Wet Tropics Major Integrated Project (MIP) are emerging and are hope to provide an important opportunity to test the land use transition and/or trading possibilities. While the Wet Tropics MIP is expected to provide some data on the treatment performance and cost-effectiveness, other designs need testing and under different landscape and climate contexts – for example, comparative projects in the Dry Tropics are needed.

Within the field of seagrass research, the project additionally highlighted the need for comprehensive data sets across a range of spatial and temporal scales and across gradients of environmental pressures, in order to track ecological health and for setting and assessing progress in meeting management targets. Existing data sets should also continue to be built upon, with greater spatial and temporal resolution, and even further capacity so that monitoring data can continue to answer increasingly specific management questions (Lambert et al., 2020). Finally, Carter et al., (2020) identified some additional opportunities for further research, including: (i) expanding the spatial extent of models to incorporate connected areas to the GBR such as Torres Strait and Fraser Island and other regions in

Australia (i.e., Gulf of Carpentaria), (ii) Evaluating indirect risks and benefits of different level of protection on seagrass communities, and (iii) assessing additional challenges for the future of seagrass communities (e.g., cumulative risks and vulnerability, appropriateness to intervene with restoration techniques when required, and a better understanding of desired states in terms of resilience) (Carter et al., 2020).

Additional integrated research and on-ground actions were also proposed in the fields of 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 ecological research and include engineers, social scientists, modellers, economists, infrastructure development experts and potentially the GBR tourism industry 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 dominant causes of coral damage are addressed (e.g., climate change) (Boström-Einarsson et al., 2018, 2020; McLeod et al., 2020).

Finally, successful Traditional Owners engagement would benefit from further work with research and business partners to alight commercial development opportunities, build potential markets and generate customers. Future partner support may encompass the underpinning infrastructure that enables Indigenous people to deliver such services; the development and commercialisation of the ecosystem services themselves; the creation of commercial products associated with those services; and the lobbying for changes to key national and/or State policies limiting service development and commercialisation.

5. CONCLUSIONS

Research undertaken through the NESP TWQ Hub has assisted towards developing and implementing practical solutions in ecosystem restoration, with a focus on the GBR catchment to reef (including freshwater, estuarine and marine ecosystems). This body of work focused on how restoration can be used to help regain and maintain long-term ecosystem values and services and facilitate adaptation to increasing frequency and/or intensity of disturbances (i.e., resilience) due to climate change and human impacts.

The outcomes of these NESP TWQ Hub projects have:

- Investigated and trialled remediation methods for gully and streambank erosion, including the establishment of best practice guidelines; and developed a range of techniques for identifying, characterising, prioritising and evaluating future investments;
- Explored and identified potential cost-effective options for land use transition of high DIN risk marginal cane areas to alternative land uses to reduce nitrogen losses in wet and dry tropical catchments;
- Highlighted the need to incorporate long-term maintenance and protection of the restoration asset within the planning and funding of all restoration projects (e.g., removal

of aquatic weeds from wetlands will likely be an on-going challenge if broader nutrient supply issues are not addressed);

- Developed monitoring programs and contributed to improve local technical skills to assess mangrove recovery in remote areas of the Gulf of Carpentaria. Proposed management strategies to mitigate the impacts of future extreme climatic events in tidal wetland ecosystems;
- Developed a Mangrove Management Plan with Traditional Owners in the southern GBR. Built essential capacity amongst the Gidarjil Development Corporation Rangers and the local community to conduct ecological monitoring and assessment of key local estuarine resources;
- Contributed to guide seagrass conservation planning through prioritisation of at-risk communities that are continuing to fail desired states. Specifically, acute management thresholds (suited to compliance guidelines for managing short-term impacts) were proposed, from 2 to 6 mol quanta m^{-2} d^{-1} depending on species. Similarly, long-term thresholds (suited to the setting of water quality guidelines for catchment management) were suggested at around 10-12 mol quanta m^{-2} d^{-1} depending on species. This new knowledge is critical for assessing seagrass resilience, for deciding whether active seagrass restoration may be required or not and for identifying suitable donor sites if intervention is warranted;
- Identified the features of successful small-scale seagrass restoration projects and the technologies required to up-scale them in Australia. Suggested techniques included physical planting of seagrasses, distribution or planting of seagrass seeds, or coastal engineering to modify sediment regimes. New tools identified included buoy-deployed seeding systems, dispenses injection seeders, artificial in-water structures to protect restoration sites, and land-based nurseries for propagation;
- Identified and trialled several coral restoration intervention types, with coral restoration at small scales (e.g., coral nursery and gardening projects), macroalgae removal, and COTS control being among the most successful strategies to improve the health of local reefs while educating the general public and providing stewardship opportunities. However, substantial scaling-up of these techniques would be required for restoration to be a useful tool to support the recovery and persistence of reefs on the GBR;
- Trial methods for coral adaptation (through the Reef Restoration and Adaptation Program -RRAP), including the identification of the traits of corals that have survived bleaching (e.g., *sacsin* gene within *Acropora millepora*);
- Results suggested that 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; and
- Contributed to building Indigenous livelihoods and co-management opportunities in the Cape York Peninsula, with a focus on potential ecosystems services (particularly in water and catchment management).

It is anticipated that this synthesis of research findings and learnings will contribute to inform investments in ecosystem restoration and environmental improvement works in GBR catchments (e.g., Reef Trust) and reef environments (e.g., RRAP), as well as to the development of key environmental policies and major reef programs and initiatives, including the next Scientific Consensus Statement, the Reef 2050 Plan, Wetlands in the GBR Catchments Management Strategy 2016-2021, Reef Blueprint for Resilience, among others. Additionally, this synthesis provides advice on practical on-ground actions for land and sea managers, policy implications and remaining gaps for future research and management investments.

This NESP TWQ Hub research has been conducted in collaboration with a wide range of stakeholder groups and is of interest to an even larger audience. The research findings are significant to the future management of the GBR and its catchments. Future programs should ensure that these results are built on, and continue to be communicated in a way that can be fully understood and utilised by a range of interested people. This will ensure that the legacy of the program will continue well into the future.

REFERENCES

Abbott, B. N., Wallace, J., Nicholas, D. M., Karim, F., & Waltham, N. J. (2020). Bund removal to re-establish tidal flow, remove aquatic weeds and restore coastal wetland services—North Queensland, Australia. *PLOS ONE*, *15*(1), e0217531. https://doi.org/10.1371/journal.pone.0217531

Adame, M. F., Arthington, A. H., Waltham, N. J., Hasan, S., Selles, A., & Ronan, M. (2019). Managing threats and restoring wetlands within catchments of the Great Barrier Reef, Australia. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *29*(5), 829–839. https://doi.org/10.1002/aqc.3096

Adame, M. F., Franklin, H., Waltham, N. J., Rodriguez, S., Kavehei, E., Turschwell, M. P., Balcombe, S. R., Kaniewska, P., Burford, M. A., & Ronan, M. (2019). Nitrogen removal by tropical floodplain wetlands through denitrification. *Marine and Freshwater Research*, *70*(11), 1513–1521. https://doi.org/10.1071/MF18490

Alluvium. (2019). *Effective and Efficient Pathways for Investment in Improved Water Quality in the Great Barrier Reef: Final Report. A report for the Great Barrier Reef Foundation*. Brisbane

Australian Government and Queensland Government. (2009). *Impacts of the MTSRF*. Reef and Rainforest Research Centre Limited, Cairns

Australian Government and Queensland Government. (2018). *Reef 2050 Water Quality Improvement Plan, 2017-2022*.

Bainbridge, Z.T., Lewis, S.E., Bartley, R., Fabricius, K. E., Collier, C., Waterhouse, J., Garzon-Garcia, A., Robson, B. J., Burton, J., Wenger, A., & Brodie, J. (2018). Fine sediment and particulate organic matter: A review and case study on ridge-to-reef transport, transformations, fates, and impacts on marine ecosystems. *Marine Pollution Bulletin*, *135*(July), 1205–1220. https://doi.org/10.1016/j.marpolbul.2018.08.002

Bainbridge, Z. T., Lewis, S. E., Smithers, S. G., Kuhnert, P. M., Henderson, B. L., & Brodie, J. E. (2014). Fine-suspended sediment and water budgets for a large, seasonally dry tropical catchment: Burdekin River catchment, Queensland, Australia. *Water Resources Research*, *50*(11), 9067–9087. https://doi.org/10.1002/2013WR014386

Barber, M., Dale, A. P., Pearse, R., Everson, B., Perry, J., Jaffer, T., Winer, M., & Creek, D. (2016). *Scoping market-based opportunities for indigenous provision of water quality services and associated conservation governance in the Northern Great Barrier Reef*. *Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Barber, M., Dale, A. P., Pearse, R., Perry, J., Winer, M., Jaffer, T., & Creek, D. (2017). *Community-based evaluation, governance, and strategic planning for Indigenous Ecosystem Services in Eastern Cape York Peninsula. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Barber, M., & Jackson, S. (2017). Identifying and categorizing cobenefits in state-supported Australian indigenous environmental management programs: international research implications. *Ecology and Society*, *22*(2), art11. https://doi.org/10.5751/ES-09114-220211

Bartley, R., Bainbridge, Z. T., Lewis, S. E., Kroon, F. J., Wilkinson, S. N., Brodie, J. E., & Silburn, D. M. (2014). Relating sediment impacts on coral reefs to watershed sources, processes and management: A review. *Science of The Total Environment*, *468–469*, 1138–1153. https://doi.org/10.1016/j.scitotenv.2013.09.030

Bartley, R., Goodwin, N., Henderson, A., Hawdon, A., Tindall, D., Wilkinson, S. N., & Brett, B. (2016). *A comparison of tools for monitoring and evaluating channel change. Report to the National Environmental Science Programme*. Reef and Rainforest Research Centre Limited, Cairns

Bartley, R., Hawdon, A., Henderson, A., Abbott, B., Wilkinson, S. N., Goodwin, N., & Ahwang, K. (2020). *Quantifying the effectiveness of gully rehabilitation on off-site water quality: results from demonstration sites in the Burdekin catchment (2019/20 wet season). Report to the National Environmental Science Programme*. Reef and Rainforest Research Centre Limited, Cairns

Bartley, R., Hawdon, A., Henderson, A., Wilkinson, S. N., Goodwin, N., Abbott, B., Baker, B., Matthews, M., Boadle, D., Telfer, D., Smith, B., Jarihani, B., & Burkin, G. (2017). *Quantifying the effectiveness of gully remediation on offsite water quality: preliminary results from demonstration sites in the Burdekin catchment. Project 2.1.4. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Bartley, R., Hawdon, A., Henderson, A., Wilkinson, S. N., Goodwin, N., Abbott, B., Baker, B., Matthews, M., Boadle, D., Telfer, D., Smith, B., Jarihani, B., & Burkin, G. (2018). *Quantifying the effectiveness of gully remediation on off-site water quality: preliminary results from demonstration sites in the Burdekin catchment (second wet season). Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Bartley, R., Philip, S., Henderson, A. E., & Tindall, D. (2016). *Investing in riparian zone management to reduce erosion from stream channels: how do we evaluate success? Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Bartley, R., Poesen, J., Wilkinson, S. N., & Vanmaercke, M. (2020). A review of the magnitude and response times for sediment yield reductions following the rehabilitation of gullied landscapes. *Earth Surface Processes and Landforms*, *45*(13), esp.4963. https://doi.org/10.1002/esp.4963

Bartley, R., Waters, D., Turner, R., Kroon, F. J., Wilkinson, S. N., Garzon-Garcia, A., Kuhnert, P. M., Lewis, S. E., Smith, R. A., Bainbridge, Z. T., Olley, J., Brooks, A. P., Burton, J. M., Brodie, J. E., & Waterhouse, J. (2017). *Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 2: Sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef*. State of Queensland

Bartley, R., Wilkinson, S. N., Henderson, A., & Hawdon, A. (2018). *Cost effectiveness of gully remediation in the Burdekin catchment: preliminary insights based on measured data from monitoring sites Technical Report. Report to the National Environmental Science Programme*. Reef and Rainforest Research Centre Limited, Cairns

Bayraktarov, E., Stewart-Sinclair, P. J., Brisbane, S., Boström-Einarsson, L., Saunders, M. I., Lovelock, C. E., Possingham, H. P., Mumby, P. J., & Wilson, K. A. (2019). Motivations, success, and cost of coral reef restoration. *Restoration Ecology*, *27*(5), 981–991. https://doi.org/10.1111/rec.12977

Bergstrom, D. M., Wienecke, B. C., Hoff, J., Hughes, L., Lindenmayer, D. B., Ainsworth, T. D., Baker, C. M., Bland, L., Bowman, D. M. J. S., Brooks, S. T., Canadell, J. G., Constable, A. J., Dafforn, K. A., Depledge, M. H., Dickson, C. R., Duke, N. C., Helmstedt, K. J., Holz, A., Johnson, C. R., Shaw, J. D. (2021). Combating ecosystem collapse from the tropics to the Antarctic. *Global Change Biology*, *27*(9), 1692–1703. https://doi.org/10.1111/gcb.15539

Boström-Einarsson, L., Babcock, R. C., Bayraktarov, E., Ceccarelli, D. M., Cook, N., Ferse,

S. C. A., Hancock, B., Harrison, P., Hein, M., Shaver, E., Smith, A. K., Suggett, D., Stewart-Sinclair, P. J., Vardi, T., & McLeod, I. M. (2020). Coral restoration – A systematic review of current methods, successes, failures and future directions. *PLOS ONE*, *15*(1), e0226631. https://doi.org/10.1371/journal.pone.0226631

Boström-Einarsson, L., Ceccarelli, D. M., Babcock, R. C., Bayraktarov, E., Cook, N., Harrison, P., Hein, M., Shaver, E., & Smith, A. K. (2018). *Coral restoration in a changing world A global synthesis of methods and techniques. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Brodie, J. E., Lewis, S. E., Collier, C. J., Wooldridge, S., Bainbridge, Z. T., Waterhouse, J., Rasheed, M. A., Honchin, C., Holmes, G., & Fabricius, K. (2017). Setting ecologically relevant targets for river pollutant loads to meet marine water quality requirements for the Great Barrier Reef, Australia: A preliminary methodology and analysis. *Ocean & Coastal Management*, *143*, 136–147

Brooks, A. P., Spencer, J., Doriean, N. J. C., Thwaites, R., Garzon-, A., Hasan, S., Daley, J., Burton, J., & Zund, P. (2021). *NESP Project 3.1.7 Final Report: Effectiveness of Alluvial Gully Remediation in Great Barrier Reef Catchments. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Brooks, A. P., Thwaites, R. N., Spencer, J., Pietsch, T., & Daley, J. (2019). *A Gully Classification Scheme to Underpin Great Barrier Reef Water Quality Management: 1st Edition. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Brooks, A. P., Spencer, J., Olley, J., Pietsch, T., Borombovits, D., Shellberg, J., Howley, C., Gleeson, A., Simon, A., Klimetz, D., Eslami-Endargoli, L., & Bourgeault, A. (2013). *An Empirically-based Sediment Budget for the Normanby Basin: Sediment Sources, Sinks, and Drivers on the Cape York Savannah.* Griffith University, 506 pp.

Brooks, A. P., Curwen, G., Spencer, J., Shellberg, J., Garzon-Garcia, A., Burton, J., & Iwashita, F. (2016). *Reducing sediment sources to the Reef: Managing alluvial gully erosion. Report to the National Environmental Science Programme*. Reef and Rainforest Research Centre Limited, Cairns

Brooks, A. P., Pietsch, T., Thwaites, R., Loch, R., Pringle, H., Eccles, S., Baumgartl, T., Biala, J., Spencer, J., Zund, P., Spedding, T., Heap, A., Burrows, D. W., Andrewartha, R., Freeman, A., Lacey, S., Higham, W., & Goddard, M. (2016). *Communique: Alluvial Gully Systems Erosion Control & Rehabilitation Workshop, Collinsville 8-10 August 2016. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Brooks, A. P., Thwaites, R., Spencer, J., Pietsch, T., & Daley, J. (2019). *A Gully Classification Scheme to Underpin Great Barrier Reef Water Quality Management: 1st Edition. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Burrows, D. W., & Butler, B. (2012). *Preliminary studies of temperature regimes and temperature tolerance of aquatic fauna in freshwater habitats of northern Australia*. Australian Centre for Tropical Freshwater Research, Townsville, Australia.

Burrows, D. W., Purandare, J., Bay, L. K., Cook, N., Koopman, D., Long, S., Lundgren, P., Mead, D., Morris, S., Newlands, M., Roth, C., Wachenfeld, D. R., Smith, A. K., & McLeod, I. M. (2019). Symposium report: Great Barrier Reef restoration symposium, 2018. *Ecological Management & Restoration*, *20*(2), 175–178. https://doi.org/10.1111/emr.12368

Burton, J. M., Furuichi, T., Lewis, S. E., Olley, J., & Wilkinson, S. N. (2014). *Identifying Erosion Processes and Sources in the Burdekin Dry Tropics Catchment - Synthesis Report. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Bush, M. B., Restrepo, A., & Collins, A. F. (2014). Galápagos History, Restoration, and a Shifted Baseline. *Restoration Ecology*, *22*(3), 296–298. https://doi.org/10.1111/rec.12080

Butler, B., Loong, D., & Davis, A. (2009). *Water for Bowen freshwater ecology.* Australia: Australian Centre for Tropical Freshwater Research, James Cook University. Townsville

Canning, A. D., Adame, M. F., & Waltham, N. J. (2021). *Evaluating services provided by ponded pasture wetlands in Great Barrier Reef catchments – Tedlands case study. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Canning, A. D., Jarvis, D., Costanza, R., Hasan, S., Smart, J., Finisdore, J., Lovelock, C., Greenhalgh, S., Marr, H., Beck, M., Stephenson, K., Gillies, C., Wilson, P., & Waltham, N. J. (2021). *Financial incentives for wetland restoration: beyond markets to common asset trusts. One Earth*, 4(7), p. 937-950 https://doi.org/10.1016/j.oneear.2021.06.006

Canning, A. D., & Waltham, N. J. (2021). Ecological impact assessment of climate change and habitat loss on wetland vertebrate assemblages of the Great Barrier Reef catchment and the influence of survey bias. *Ecology and Evolution*, ece3.7412. https://doi.org/10.1002/ece3.7412

Carter, A. B., Coles, R. G., Rasheed, M. A., & Collier, C. J. (2020). *Seagrass communities of the Great Barrier Reef and their desired state: Applications for spatial planning and management. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Carter, A. B., Collier, C. J., Rasheed, M. A., Mckenzie, L. J., & Udy, J. (2018). *A framework for defining seagrass habitat for the Great Barrier Reef, Australia. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Catterall, C. P., Kanowski, J., & Wardell-Johnson, G. (2008). Biodiversity and New Forests: Interacting Processes, Prospects and Pitfalls of Rainforest Restoration. In N. E. Stork & S. M. Turton (Eds.), *Living in a Dynamic Tropical Forest Landscape*. Wiley-Blackwell. Oxford, UK

Catterall, C. P., Freeman, A. N. D., Kanowski, J., & Freebody, K. (2012). Can active restoration of tropical rainforest rescue biodiversity? A case with bird community indicators. *Biological Conservation*, *146*(1), 53–61. https://doi.org/10.1016/j.biocon.2011.10.033

Catterall, C. P, Shoo, L. P., & Freebody, K. (2014). *Natural regeneration and rainforest restoration-outcomes, pathways and management of regrowth. NERP Tropical Ecosystems Hub Factsheet*. Reef and Rainforest Research Centre Limited, Cairns

Ceccarelli, D. M., Loffler, Z., Bourne, D. G., Al Moajil-Cole, G. S., Boström-Einarsson, L., Evans-Illidge, E., Fabricius, K. E., Glasl, B., Marshall, P. A., McLeod, I. M., Read, M., Schaffelke, B., Smith, A. K., Jorda, G. T., Williamson, D. H., & Bay, L. K. (2018). Rehabilitation of coral reefs through removal of macroalgae: state of knowledge and considerations for management and implementation. *Restoration Ecology*, *26*(5), 827–838. https://doi.org/10.1111/rec.12852

Challen, S., & Long, P. (2004). *Fisheries guidelines for managing ponded pastures*. Department of Primary Industries and Fisheries. Brisbane

Coles, R. G., Rasheed, M. A., McKenzie, L. J., Grech, A., York, P. H., Sheaves, M., McKenna, S., & Bryant, C. (2015). The Great Barrier Reef World Heritage Area seagrasses: managing this iconic Australian ecosystem resource for the future. *Estuarine, Coastal and Shelf Science*, *153*, A1–A12.

Collier, C. J., Chartrand, K., Honchin, C., Fletcher, A., & Rasheed, M. (2016). *Light thresholds for seagrasses of the GBR: a synthesis and guiding document. Including knowledge gaps and future priorities. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Collier, C. J., Langlois, L., Zemoi, R., Martin, K., & Mckenzie, L. (2016). *Developing and refining biological indicators for condition assessments in an integrated monitoring program. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Collier, C. J., Carter, A. B., Rasheed, M. A., Mckenzie, L. J., Udy, J., Coles, R. G., Brodie, J. E., Waycott, M., O'Brien, K. R., Saunders, M., Adams, M. P., Martin, K., Honchin, C., Petus, C., & Lawrey, E. (2020). An evidence-based approach for setting desired state in a complex Great Barrier Reef seagrass ecosystem: A case study from Cleveland Bay. *Environmental and Sustainability Indicators*, *7*(June 2019), 100042. https://doi.org/10.1016/j.indic.2020.100042

Commonwealth of Australia. (2018a). *Reef 2050 Long-Term Sustainability Plan - July 2018*.

Commonwealth of Australia. (2018b). *Reef 2050 Water Quality Improvement Plan 2017-2022*.

Commonwealth of Australia. (2020). *Reef 2050 Long-Term Sustainability Plan—Public Consultation Draft May 2020*.

Cook, N., Smith, A. K., McLeod, I. M., & Boström-Einarsson, L. (2018). *Fitzroy Island Coral Nursery: Baseline Report to the National Environmental Science Program.* Reef. In *Baseline* Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., Farber, S., & Turner, R. K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change*, *26*, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

Crossman, N., & Bryan, B. (2007). Ecological restoration priorities for achieving integrated environmental and economic objectives. *7th IALE World Congress: 25 Years of Landscape Ecology: Scientific Principles in Practice*.

Daley, J., Stout, J. C., Curwen, G., Brooks, A. P., & Spencer, J. (2021). *Development and application of automated tools for high resolution gully mapping and classification from LiDAR data. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Davis, A. M., Lewis, S. E., O'Brien, D. S., Bainbridge, Z. T., Bentley, C., Mueller, J. F., & Brodie, J. E. (2014). Water Resource Development and High Value Coastal Wetlands on the Lower Burdekin Floodplain, Australia. In E. Wolanski (Ed.), *Estuaries of Australia in 2050 and beyond* (pp. 223–245). Springer Netherlands. https://doi.org/10.1007/978-94-007-7019-5_13

Department of Agriculture Water and the Environment (DAWE). (2020). *About the National Environmental Science Program*. http://www.environment.gov.au/science/nesp/about

Department of Environment and Science Queensland. (2017). *Research Case Study: Cost-effective restoration of wetlands that protect the water quality of the Great Barrier Reef*.

Department of Environment and Science Queensland. (2019). *Addendum to wetland* *mapping and classification methodology - overall framework. A method to provide baseline mapping and classification for wetlands in Queensland*.

Doherty, M. D., Lavorel, S., Colloff, M. J., Williams, K. J., & Williams, R. J. (2017). Moving from autonomous to planned adaptation in the montane forests of southeastern Australia under changing fire regimes. *Austral Ecology*, *42*(3), 309–316. https://doi.org/10.1111/aec.12437

Duke, N. C. (2014). Mangrove coast. In J. Harff, M. Meschede, S. Petersen, & J. Thiede. (Eds.), *Encyclopedia of Marine Geosciences* (pp. 424–422). Springer: Dordrecht, Netherlands.)

Duke, N. C. (2020). 4. Mangrove harbingers of coastal degradation seen in their responses to global climate change coupled with ever-increasing human pressures. *Human Ecology Journal of the Commonwealth Human Ecology Council – Mangrove Special Issue*, *30*, 19–23.

Duke, N. C., Hutley, L. B., Mackenzie, J. R., & Burrows, D. W. (2021). Processes and factors driving change in mangrove forests – an evaluation based on the mass dieback event in Australia's Gulf of Carpentaria. In J. G. Canadell & R. B. Jackson (Eds.), *Ecosystem Collapse - and Climate Change*. Springer.

Duke, N. C., Kovacs, J. M., Griffiths, A. D., Preece, L., Hill, D. J. E., van Oosterzee, P., Mackenzie, J. R., Morning, H. S., & Burrows, D. W. (2017). Large-scale dieback of mangroves in Australia. *Marine and Freshwater Research*, *68*(10), 1816. https://doi.org/10.1071/MF16322

Duke, N. C., & Larkum, A. W. D. (2008). Mangroves and seagrasses. In P. Hutchings, M. Kingsford, & O. Hoegh-Guldberg (Eds.), *The Great Barrier Reef: biology, environment and management* (pp. 156–170). CSIRO Publishing.

Duke, N. C., & Larkum, A. W. D. (2019). Mangroves and seagrasses. In Pat Hutchings, M. Kingsford, & O. Hoegh-Guldberg (Eds.), *The Great Barrier Reef: biology, environment and management, 2nd Edition.* (pp. 219–228). Csiro publishing.

Duke, N. C., & Mackenzie, J. R. (2018). *Final Report: East Cape York Shoreline Environmental Surveys. Report to the Commonwealth of Australia. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER). Publication 17/67*.

Duke, N. C., Mackenzie, J. R., Fennessy, R., Cormier, R., & Kovacs, J. (2019a). *Southern Great Barrier Reef Coastal Habitat Archive and Monitoring Program: Developing a Mangrove Management Plan Volume 1. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Duke, N. C., Mackenzie, J. R., Fennessy, R., Cormier, R., & Kovacs, J. (2019b). *Southern Great Barrier Reef Coastal Habitat Archive and Monitoring Program: Mangrove Management Plan Volume 2. Report to the National Environmental Science Programme*. Reef and Rainforest Research Centre Limited, Cairns

Duke, N. C., Mackenzie, J. R., Hutley, L., Staben, G., & Bourke, A. (2021). *Assessing the Gulf of Carpentaria mangrove dieback 2017–2019. Volume 2: Field studies. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Duke, N. C., Mackenzie, J. R., Kovacs, J., Staben, G., Coles, R., Wood, A., & Castle, Y. (2021). *Assessing the Gulf of Carpentaria mangrove dieback 2017–2019. Volume 1: Aerial surveys. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Duke, N. C., Meynecke, J.-O., Dittmann, S., Ellison, A. M., Anger, K., Berger, U., Cannicci, S., Diele, K., Ewel, K. C., & Field, C. D. (2007). A world without mangroves? *Science*, *317*(5834), 41–42.

Duke, N. C., & Wolanski, E. (2001). Muddy coastal waters and depleted mangrove coastlines–depleted seagrass and coral reefs. In E. Wolanski (Ed.), *Oceanographic processes of coral reefs: Physical and biological links in the Great Barrier Reef* (pp. 77–91). CRC Press.

Duke, N. C., Wood, A., Hunnam, K., Mackenzie, J. R., Haller, A., Christiansen, N., Zahmel, K., & Green, T. (2010). *Shoreline Ecological Assessment Aerial and Ground Surveys, 7-19 November 2009. As part of the Scientific Monitoring Study of the West Atlas Monitoring Plan*.

Emslie, M. J., Logan, M., Williamson, D. H., Ayling, A. M., MacNeil, M. A., Ceccarelli, D., Cheal, A. J., Evans, R. D., Johns, K. A., Jonker, M. J., Miller, I. R., Osborne, K., Russ, G. R., & Sweatman, H. P. A. (2015). Expectations and Outcomes of Reserve Network Performance following Re-zoning of the Great Barrier Reef Marine Park. *Current Biology*, *25*(8), 983–992. https://doi.org/10.1016/j.cub.2015.01.073

Erdmann, S., Johnson, J. E., Abom, R., Waterhouse, J., & Haynes, D. (2021). *Innovations in crown-of-thorns starfish control on the Great Barrier Reef: A Synthesis of NESP Tropical Water Quality Hub research. Report to the National Environmental Science Programme*. Reef and Rainforest Research Centre Limited, Cairns

Frade, P. R., Glasl, B., Matthews, S. A., Mellin, C., Serrão, E. A., Wolfe, K., Mumby, P. J., Webster, N. S., & Bourne, D. G. (2020). Spatial patterns of microbial communities across surface waters of the Great Barrier Reef. *Communications Biology*, *3*(1), 442. https://doi.org/10.1038/s42003-020-01166-y

Fuller, Z. L., Mocellin, V. J. L., Morris, L. A., Cantin, N. E., Shepherd, J., Sarre, L., Peng, J., Liao, Y., Pickrell, J., Andolfatto, P., Matz, M., Bay, L. K., & Przeworski, M. (2020). Population genetics of the coroal *Acropora millepora*: Toward genomic prediction of bleaching. *Science*, *369*(6501). https://doi.org/10.1126/science.aba4674

Furnas, M. (2003). Catchments and corals: terrestrial runoff to the Great Barrier Reef. Australian Institute of Marine Science Townsville.

GBRMPA. (2017). *Great Barrier Reef blueprint for resilience*. Great Barrier Reef Marine Park Authority. Townsville

GBRMPA. (2018). *Position Statement: Coastal ecosystems*. Great Barrier Reef Marine Park Authority. Townsville

GBRMPA. (2019). *Great Barrier Reef Outlook Report 2019*. Great Barrier Reef Marine Park Authority. Townsville

Gilby, B. L., Weinstein, M. P., Baker, R., Cebrian, J., Alford, S. B., Chelsky, A., Colombano, D., Connolly, R. M., Currin, C. A., Feller, I. C., Frank, A., Goeke, J. A., Goodridge Gaines, L. A., Hardcastle, F. E., Henderson, C. J., Martin, C. W., McDonald, A. E., Morrison, B. H., Olds, A. D., … Ziegler, S. L. (2020). Human Actions Alter Tidal Marsh Seascapes and the Provision of Ecosystem Services. *Estuaries and Coasts*. https://doi.org/10.1007/s12237-020-00830-0

Greenfield, B. K., Siemering, G. S., Andrews, J. C., Rajan, M., Andrews, S. P., & Spencer, D. F. (2007). Mechanical shredding of water hyacinth (Eichhornia crassipes): Effects on water quality in the Sacramento-San Joaquin River Delta, California. *Estuaries and Coasts*, *30*(4), 627–640.

Güereña, D., Neufeldt, H., Berazneva, J., & Duby, S. (2015). Water hyacinth control in Lake Victoria: Transforming an ecological catastrophe into economic, social, and environmental benefits. *Sustainable Production and Consumption*, *3*, 59–69.

Hardisty, P., Roth, C., Silvey, P., Mead, D., & Anthony, K. (2019). *Reef Restoration and Adaptation Program – Investment Case. A report provided to the Australian Government from the Reef Restoration and Adaptation Program*.

Harriott, V. J., & Fisk, D. A. (1987). *Accelerated Regeneration of Hard Corals: A Manual for Coral Reef Users and Managers No. 16*.

Harris, R. M. B., Beaumont, L. J., Vance, T. R., Tozer, C. R., Remenyi, T. A., Perkins-Kirkpatrick, S. E., Mitchell, P. J., Nicotra, A. B., McGregor, S., Andrew, N. R., Letnic, M., Kearney, M. R., Wernberg, T., Hutley, L. B., Chambers, L. E., Fletcher, M.-S., Keatley, M. R., Woodward, C. A., Williamson, G., … Bowman, D. M. J. S. (2018). Biological responses to the press and pulse of climate trends and extreme events. *Nature Climate Change*, *8*(7), 579–587. https://doi.org/10.1038/s41558-018-0187-9

Harris, T., Hope, P., Oliver, E., Smalley, R., Arblaster, J., Holbrook, N., Duke, N. C., Pearce, K., Braganza, K., & Bindoff, N. (2017). *Climate drivers of the 2015 Gulf of Carpentaria mangrove dieback. Australia, NESP Earth Systems and Climate Change Hub*.

Hein, Margaux, Newlands, M., Elms, A., Vella, K., & Mcleod, I. (2020). *Why do Great Barrier Reef tourism operators engage in coral restoration? An exploration of motivations, opportunities, and challenges. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Hein, MY, McLeod, I., Shaver, E., Vardi, T., Pioch, S., Boström-Einarsson, L Ahmed, M., & Grimsditch, G. (2020). *Coral Reef Restoration as a strategy to improve ecosystem services – A guide to coral restoration methods. United Nations Environment Program*. https://doi.org/10.1016/S0925-8574(00)00085-9

Heyward, A., Smith, L., Rees, M., & Field, S. (2002). Enhancement of coral recruitment by in situ mass culture of coral larvae. *Marine Ecology Progress Series*, *230*, 113–118. https://doi.org/10.3354/meps230113

Holbrook, N. J., Sen Gupta, A., Oliver, E. C. J., Hobday, A. J., Benthuysen, J. A., Scannell, H. A., Smale, D. A., & Wernberg, T. (2020). Keeping pace with marine heatwaves. *Nature Reviews Earth & Environment*, *1*(9), 482–493. https://doi.org/10.1038/s43017-020-0068-4

Hyland, S. L. (2002). *An investigation of the impacts of ponded pastures on Barramundi and other finfish populations in tropical coastal wetlands.* D. o. P. Industries. Queensland Government, Brisbane

James. (2021). *Principles for establishing greater trust between scientists and farmers: A synthesis of NESP Tropical Water Quality Hub research. Report to the National Environmental Science Programme*. Reef and Rainforest Research Centre Limited, Cairns

Johnson, A. K. L., Bramley, R. G. V, & Roth, C. H. (2001). Landcover and water quality in river catchments of the Great Barrier Reef Marine Park. In E. Wolanski (Ed.), *Oceanographic Processes of Coral Reef: Physical and Biological Links in the Great Barrier Reef* (pp. 19–35). CRC Press.

Johnson, J. E., Marsh, H., Hamann, M., Duke, N. C., Burrows, D. W., Bainbridge, S., Sweatman, H. P. A., Brodie, J. E., Bohensky, E., Butler, J., & Laurance, S. (2015). *Tropical Research in Australia's Torres Strait region. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Kaly, U. L. (1995). *Experimental test of the effects of methods of attachment and handling on the rapid transplantation of corals.* CRC Reef Research Centre. Technical Report No. 1 (Issue Technical Report No. 1).

Kanowski, J., Catterall, C. P., Freebody, K., Freeman, A. N. D., & Harrison, D. A. (2010). *Monitoring Revegetation Projects in Rainforest Landscapes. Toolkit Version 3*.

Kentula, M. E., Brooks, R. P., Gwin, S. E., Holland, C. C., & Sherman, A. D. (1992). *Approach to improving decision making in wetland restoration and creation*.

Lambert, V. M., Adams, M. P., Collier, C. J., Carter, A. B., Saunders, M., Brodie, J. E., Bainbridge, Z. T., Rasheed, M. A., Turner, R., & O'Brien, K. R. (2019). Towards Ecologically Relevant Targets: Impact of flow and sediment discharge on seagrass communities in the Great Barrier Reef. *23rd International Congress on Modelling and Simulation, Canberra, ACT, Australia*, *December*, 624–630. https://doi.org/10.36334/modsim.2019.G1.lambert

Lambert, V. M., Collier, C. J., Brodie, J. E., Adams, M. P., Baird, M. E., Bainbridge, Z. T., Carter, A. B., Rasheed, M. A., Saunders, M., & O'Brien, K. R. (2020). *Connecting Sediment Load Targets to Ecological Outcomes for Seagrass. Report to the National Environmental Science Programme*. Reef and Rainforest Research Centre Limited, Cairns

Lawson, T., Gillieson, D., & Goosem, M. (2007). Assessment of Riparian Rainforest Vegetation Change in Tropical North Queensland for Management and Restoration Purposes. *Geographical Research*, *45*(4), 387–397. https://doi.org/10.1111/j.1745-5871.2007.00477.x

Lewis, S. E., Bartley, R., Wilkinson, S. N., Bainbridge, Z. T., Henderson, A. E., James, C. S., Irvine, S. A., & Brodie, J. E. (2021). Land use change in the river basins of the Great Barrier Reef, 1860 to 2019: A foundation for understanding environmental history across the catchment to reef continuum. *Marine Pollution Bulletin*, *166*, 112193. https://doi.org/10.1016/j.marpolbul.2021.112193

Long, S. (2021). *Learnings from applied environmental research programs: Elements for success. A synthesis of NESP Tropical Water Quality Hub research. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Lunt, I. D., Byrne, M., Hellmann, J. J., Mitchell, N. J., Garnett, S. T., Hayward, M. W., Martin, T. G., McDonald-Maddden, E., Williams, S. E., & Zander, K. K. (2013). Using assisted colonisation to conserve biodiversity and restore ecosystem function under climate change. *Biological Conservation*, *157*, 172–177. https://doi.org/10.1016/j.biocon.2012.08.034

Mackenzie, J. R., & Duke, N. C. (2016). *Improving climate change resilience and reducing sediment runoff through better mangrove management in Princess Charlotte Bay. Townsville, MangroveWatch Science Hub, Centre for Tropical Water & Aquatic Ecosystem Research*.

Mackenzie, J. R., & Duke, N. C. (2019). *Indigenous Ranger field guide to the Shoreline Video Assessment Method.* Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Report 20/26.

Mackenzie, J. R., Duke, N. C., & Wood, A. L. (2016). The Shoreline Video Assessment Method (S-VAM): Using dynamic hyperlapse image acquisition to evaluate shoreline mangrove forest structure, values, degradation and threats. *Marine Pollution Bulletin*, *109*(2), 751–763. https://doi.org/10.1016/j.marpolbul.2016.05.069

MangroveWatch. (2019). *Indigenous Ranger field guide to the Shoreline Video Assessment Method*.

Maron, M., Walsh, M., Shumway, N. & Brodie, J. (2016) *Reef Trust Offsets Calculator: A prototype calculation approach for determining financial liability for marine biodiversity offsets voluntarily delivered through the Australian Government Department of the Environment (Reef Trust). Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Marsh, N., Linke, S., Ogden, R., Wettin, P., & Cottingham, P. (2007). River and catchment restoration prioritisation tools. In A. Wilson, R. Dehaan, R. Watts, K. Page, K. Bowmer,

& A. Curtis (Eds.), *Proceedings of the 5th Australian Stream Management Conference. Australian rivers: making a difference*.

Masifwa, W. F., Twongo, T., & Denny, P. (2001). The impact of water hyacinth, Eichhornia crassipes (Mart) Solms on the abundance and diversity of aquatic macroinvertebrates along the shores of northern Lake Victoria, Uganda. *Hydrobiologia*, *452*(1), 79–88.

Matzek, V., Wilson, K. A., & Kragt, M. (2019). Mainstreaming of ecosystem services as a rationale for ecological restoration in Australia. *Ecosystem Services*, *35*, 79–86. https://doi.org/10.1016/j.ecoser.2018.11.005

McDonald, T., Jonson, J., & Dixon, K. W. (2016). National standards for the practice of ecological restoration in Australia. *Restoration Ecology*, *24*, S4–S32. https://doi.org/10.1111/rec.12359

McIvor, C. C., & Smith, T. J. (1995). Differences in the Crab Fauna of Mangrove Areas at a Southwest Florida and a Northeast Australia Location: Implications for Leaf Litter Processing. *Estuaries*, *18*(4), 591. https://doi.org/10.2307/1352379

McLeod, I. M., Bourne, D. G., Ceccarelli, D. M., Boström-Einarsson, L., Cook, N., Hancock, B., Fulton, S., Harrison, P., Hein, M., Le Port, A., Smith, H. A., & Smith, A. K. (2020). *Best practice coral restoration for the Great Barrier Reef: Synthesis of results. Report to the National Environmental Science Programme*. Reef and Rainforest Research Centre Limited, Cairns

McLeod, I. M., Williamson, D. H., Taylor, S., Srinivasan, M., Read, M., Boxer, C., Mattocks, N., & Ceccarelli, D. M. (2019). Bommies away! Logistics and early effects of repositioning 400 tonnes of displaced coral colonies following cyclone impacts on the Great Barrier Reef. *Ecological Management & Restoration*, *20*(3), 262–265. https://doi.org/10.1111/emr.12381

NESP (2020). *National Environmental Science Program Tropical Water Quality Hub (NESP TWQ)*. https://nesptropical.edu.au/

Olley, J., Brooks, A. P., Spencer, J., Pietsch, T., & Borombovits, D. (2013). Subsoil erosion dominates the supply of fine sediment to rivers draining into Princess Charlotte Bay, Australia. *Journal of Environmental Radioactivity*, *124*, 121–129. https://doi.org/10.1016/j.jenvrad.2013.04.010

Overpeck, J. T. (2014). The challenge of biodiversity adaptation under climate change. In *Applied Studies in Climate Adaptation* (Vol. 9781118845011, pp. 61–67). Wiley Blackwell. https://doi.org/10.1002/9781118845028.ch8

Paul, K. I., Bartley, R., & Larmour, J. S. (2018). *Optimising the management of riparian zones to improve the health of the Great Barrier Reef Final Report. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Pearse, R. (2018). *Drivers and trends in environmental markets: Applications for Australia. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Pearson, R. G., Connolly, N. M., Davis, A. M., & Brodie, J. E. (2021). Fresh waters and estuaries of the Great Barrier Reef catchment: Effects and management of anthropogenic disturbance on biodiversity, ecology and connectivity. *Marine Pollution Bulletin*, *166*, 112194. https://doi.org/10.1016/j.marpolbul.2021.112194

Pearson, R., & Stork, N. E. (2008). Catchment to Reef: Water Quality and Ecosystem Health in Tropical Streams. In *Living in a Dynamic Tropical Forest Landscape* (pp. 557–576). Blackwell Publishing, Ltd. https://doi.org/10.1002/9781444300321.ch45

Perna, C. N., Cappo, M., Pusey, B. J., Burrows, D. W., & Pearson, R. G. (2012). Removal of aquatic weeds greatly enhances fish community richness and diversity: an example from the Burdekin River floodplain, tropical Australia. *River Research and Applications*, *28*(8), 1093–1104.

Pettorelli, N., Barlow, J., Stephens, P. A., Durant, S. M., Connor, B., Schulte to Bühne, H., Sandom, C. J., Wentworth, J., & du Toit, J. T. (2018). Making rewilding fit for policy. *Journal of Applied Ecology*, *55*(3), 1114–1125. https://doi.org/10.1111/1365-2664.13082

Pineda, M.-C., & Johnson, J. E. (2021). *Improving coral reef condition through better-informed resilience-based management: A Synthesis of NESP Tropical Water Quality Hub research. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Pineda, M.-C., & Waterhouse, J. (2021). *Reducing end of catchment fine sediment loads and ecosystem impacts: A synthesis of NESP Tropical Water Quality Hub research. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Pineda, M.-C., Waterhouse, J., & Long, S. (2021). *Restoring ecosystems from catchment to reef: A synthesis of NESP Tropical Water Quality Hub research. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Queensland Government (2016). *Wetlands in the Great Barrier Reef Catchments: Management Strategy 2016-2021*.

Quigley, K., Ramsby, B., Laffy, P., V., M., J., H., & Bay, L. . (2021). *The genetic traits of corals that survived recent bleaching events. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Robson, B. J., Magno-Canto, M. M., McKinna, L. I. W., Logan, M., Lewis, S. E., Collier, C. J., & Fabricius, K. E. (2020). *Benthic Light as an ecologically-validated GBR-wide indicator for water quality: Drivers, thresholds and cumulative risks. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Rogers, A. A., Burton, M. P., Statton, J., Fraser, M., Kendrick, G., Sinclair, E., Gorman, D., Vanderklift, M., Verduin, J., & McLeod, I. M. (2019). *Benefits and costs of alternate seagrass restoration approaches. Report to the National Environmental Science Programme,* Marine Biodiversity Hub (Vol. 4, Issue August).

Ross, B., Waltham, N. J., Schaffer, J., Jaffer, T., Whyte, S., Perry, J., Vanderduys, E., Macdonald, S., Morgan, M., Walsh, T., Huerlimann, R., LePort, A., Burrows, D. W., & Dean, J. (2017). *Improving biodiversity outcomes and carbon reduction through feral pig abatement*. Balkanu Cape York Development Corporation Ltd Pty, Cairns

RRRC (2015). *Reef Rescue Water Quality Research and Development Program. Final Program Report: Overview of research findings and program outcomes, 2011-2015*.

Schultz, M., Hansler, M., Logan, M., Carter, A., Chartrand, K. M., Wells, J., Rasheed, M. A., Costello, P., Thompson, A. A., Davidson, J., Duke, N. C., Mackenzie, J. R., Flint, N., Irving, A., Anastasi, A., Jackson, E. L., Sawynok, S., Sawynok, B., Dunlop, A., … Star., M. (2020). *Gladstone Harbour Report Card 2019 - Technical Report.* F. B. Association. Rockhampton, Gladstone Healthy Harbour Program (GHHP).

Shaver, E. C., Courtney, C. A., West, J. M., Maynard, J., Hein, M., Wagner, C., Philibotte, J., MacGowan, P., McLeod, I., Böstrom-Einarsson, L., Bucchianeri, K., Johnston, L., & Koss, J. (2020). *A Manager's Guide to Coral Reef Restoration Planning and Design.* NOAA Coral Reef Conservation Program. NOAA Technical Memorandum CRCP 36.

Shellberg, J. G., & Brooks, A. P. (2013). *Alluvial gully prevention and rehabilitation options* *for reducing sediment loads in the Normanby catchment and northern Australia.* Griffith University, Australian Rivers Institute, Final Report for the Australian Government's Caring for our Country-Reef R.

Shoo, L. P. (2014). Restoration and the Future Environmental Movement. *BioScience*, *64*(8), 744–745. https://doi.org/10.1093/biosci/biu089

Shoo, L. P., & Catterall, C. P. (2013). Stimulating Natural Regeneration of Tropical Forest on Degraded Land: Approaches, Outcomes, and Information Gaps. *Restoration Ecology*, *21*(6), 670–677. https://doi.org/10.1111/rec.12048

Smart, J. C. R., Hasan, S., Curwen, G., McMahon, J. M., Volders, A., Saint Ange, C., Fleming, C. M., Buck, A., Burford, M. A., Tan, P.-L., Garzon-Garcia, A., Burton, J. M., Dew, P., & Edeson, G. (2020). *Exploring trading in water quality credits as a cost-effective approach for managing water quality in the Great Barrier Reef*. *Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Stewart-Sinclair, P. J., Purandare, J., Bayraktarov, E., Waltham, N. J., Reeves, S., Statton, J., Sinclair, E. A., Brown, B. M., Shribman, Z. I., & Lovelock, C. E. (2020). Blue Restoration – Building Confidence and Overcoming Barriers. *Frontiers in Marine Science*, *7*, 748. https://doi.org/10.3389/fmars.2020.541700

Sweatman, H. P. A., Johns, K. A., Jonker, M. J., Miller, I. R., & Osborne, K. (2015). Final report on coral reef surveys in Torres Strait. In *Final report on coral reef surveys in Torres Strasit. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Tan, Y. M., Dalby, O., Kendrick, G. A., Statton, J., Sinclair, E. A., Fraser, M. W., Macreadie, P. I., Gillies, C. L., Coleman, R. A., Waycott, M., van Dijk, K., Vergés, A., Ross, J. D., Campbell, M. L., Matheson, F. E., Jackson, E. L., Irving, A. D., Govers, L. L., Connolly, R. M., … Sherman, C. D. H. (2020). Seagrass Restoration Is Possible: Insights and Lessons From Australia and New Zealand. *Frontiers in Marine Science*, *7*(August). https://doi.org/10.3389/fmars.2020.00617

Terrain NRM (2015). Wet Tropics Water Quality Improvement Plan: 2015–2020. Innisfail. 232 pp.

Turton, S. M. (2019). Reef-to-ridge ecological perspectives of high-energy storm events in northeast Australia. *Ecosphere*, *10*(1). https://doi.org/10.1002/ecs2.2571

UNEP (2014). *The importance of mangroves to people: A call to action*. 128 pp.

Uthicke, S., Castro-Sanguino, C., Ferrari, R., Fabricius, K., Lawrey, E., Flores, F., Patel, F., Brunner, C., & Negri, A. (2020). *From Exposure to Risk: Novel Experimental Approaches to Analyse Cumulative Impacts and Determine Thresholds in the Great Barrier Reef World Heritage Area (GBRWHA). Report to the National Environmental Science Program*. Reef and Rainforest Research Centre Limited, Cairns

Vanderklift, M. A., Doropoulos, C., Gorman, D., Leal, I., Minne, A. J. P., Statton, J., Steven, A. D. L., & Wernberg, T. (2020). Using Propagules to Restore Coastal Marine Ecosystems. In *Frontiers in Marine Science* (Vol. 7, p. 724). Frontiers Media S.A. https://doi.org/10.3389/fmars.2020.00724

Villamagna, A. M., & Murphy, B. R. (2010). Ecological and socio-economic impacts of invasive water hyacinth (Eichhornia crassipes): a review. *Freshwater Biology*, *55*(2), 282–298.

Wallace, J., Adame, M. F., & Waltham, N. J. (2020). *A treatment wetland near Babinda, north Queensland: a case study of potential water quality benefits in an agricultural tropical catchment (2020) Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Waltham, N. J., Adame, M. F., Karim, F., Abbott, B., & Wallace, J. (2020). *Bund wall removal increases saltwater intrusion and controls invasive aquatic weeds on a coastal floodplain. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Waltham, N. J., Alcott, C., Barbeau, M. A., Cebrian, J., Connolly, R. M., Deegan, L. A., Dodds, K., Gaines, L. A. G., Gilby, B. L., & Henderson, C. J. (2021). Tidal marsh restoration optimism in a changing climate and urbanizing seascape. *Estuaries and Coasts*, 1–10.

Waltham, N. J., Buelow, C. A., & Iles, J. A. (2020). *Evaluating wetland restoration success: feral pig exclusion fencing in the Round Hill Reserve. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Waltham, N. J., Burrows, D. W., Wegscheidl, C., Buelow, C., Ronan, M., Connolly, N., Groves, P., Marie-Audas, D., Creighton, C., & Sheaves, M. (2019). Lost floodplain wetland environments and efforts to restore connectivity, habitat, and water quality settings on the Great Barrier Reef. *Frontiers in Marine Science*, *6*(FEB), 1–14. https://doi.org/10.3389/fmars.2019.00071

Waltham, N. J., & Canning, A. D. (2021). *Exploring the potential of watercourse repair on an agricultural floodplain. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Waltham, N. J., Canning, A., Smart, J. C. R., Hasan, S., Curwen G., Waterhouse, J. (2020). *Scoping land conversion options for high DIN risk, low-lying sugarcane, to alternative use for water quality improvement in Dry Tropics catchments. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Waltham, N. J., Canning, A., Smart, J. C. R., Hasan, S., Curwen, G., & Butler, B. (2021). Financial incentive schemes to fund wetland restoration across the GBR catchment: Learning from the Riversdale-Murray Scheme and other schemes. *Report to the National Environmental Science Program*. Reef and Rainforest Research Centre Limited, Cairns

Waltham, N. J., Coleman, L., Buelow, C., Fry, S., & Burrows, D. W. (2020). Restoring fish habitat values on a tropical agricultural floodplain: Learning from two decades of aquatic invasive plant maintenance efforts. *Ocean & Coastal Management*, *198*(March 2019), 105355. https://doi.org/10.1016/j.ocecoaman.2020.105355

Waltham, N. J., Elliott, M., Lee, S. Y., Lovelock, C., Duarte, C. M., Buelow, C., Simenstad, C., Nagelkerken, I., Claassens, L., Wen, C. K. C., Barletta, M., Connolly, R. M., Gillies, C., Mitsch, W. J., Ogburn, M. B., Purandare, J., Possingham, H. P., & Sheaves, M. (2020). UN Decade on Ecosystem Restoration 2021–2030—What Chance for Success in Restoring Coastal Ecosystems? *Frontiers in Marine Science*, *7*(February 2020), 1–5. https://doi.org/10.3389/fmars.2020.00071

Waltham, N. J., & Fixler, S. (2017). Aerial herbicide spray to control invasive water hyacinth (Eichhornia crassipes): Water quality concerns fronting fish occupying a tropical floodplain wetland. *Tropical Conservation Science*, *10*, 1940082917741592.

Waltham, N. J., Pyott, M., Buelow, C., & Wearne, L. (2020). Mechanical harvester removes invasive aquatic weeds to restore water quality and fish habitat values on the Burdekin floodplain. *Ecological Management & Restoration*, *21*(3), 187–197.

Waltham, N. J., Wegscheidl, C., Smart, J. C. R., Volders, A., Hasan, S., Ledee, E., & Waterhouse, J. (2021). Land use conversion to improve water quality in high DIN risk, low-lying sugarcane areas of the Great Barrier Reef catchments. *Marine Pollution*

Bulletin.

Waltham, N. J., Wegscheidl, C., Smart, J. C. R., Volders, A., Hasan, S., & Waterhouse, J. (2017). *Scoping land conversion options for high DIN risk, low-lying sugarcane, to alternative use for water quality improvement in Wet Tropics catchments. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Waterhouse, J., Brodie, J. E., Tracey, D., Smith, R. A., VanderGragt, M., Collier, C. J., Petus, C., Baird, M. E., Kroon, F. J., Mann, R. M., Sutcliffe, T., Waters, D., & Adame, M. F. (2017). *2017 Scientific Consensus Statement: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 3: The risk from anthropogenic pollutants to Great Barrier Reef coastal and marine ecosystems*. State of Queensland.

Waterhouse, J., Brodie, J., Lewis, S. E., & Audas, D.-M. (2016). Land-sea connectivity, ecohydrology and holistic management of the Great Barrier Reef and its catchments: time for a change. *Ecohydrology & Hydrobiology*, *16*(1), 45–57. https://doi.org/10.1016/j.ecohyd.2015.08.005

Waterhouse, J., & Pineda, M.-C. (2021). *Overcoming barriers to reducing nitrogen losses to the Great Barrier Reef: A synthesis of NESP Tropical Water Quality Hub research. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Waterhouse, J., Schaffelke, B., Bartley, R., Eberhard, R., Brodie, J. E., Star, M., Thorburn, P. J., Rolfe, J., Ronan, M., Taylor, B., & Kroon, F. J. (2017). *2017 Scientific Consensus Statement: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 5: Overview of key findings, management implications and knowledge gaps*. State of Queensland.

Wilkinson, S. N., Bartley, R., Hairsine, P. B., Bui, E. N., Gregory, L. & Henderson, A. E. (2015). *Managing gully erosion as an efficient approach to improving water quality in the Great Barrier Reef lagoon*, CSIRO, Report to the Department of the Environment (Reef Program).

Wilkinson, S. N., Hairsine, P. B., Brooks, A. P., Bartley, R., Hawdon, A. A., Pietsch, T., Shepherd, R., & Austin, J. M. (2019). *Gully and Stream Bank Toolbox. A technical guide for the Reef Trust Gully and Stream Bank Erosion Control Program. 2nd Edition.* (Issue June).

Wilkinson, S. N., Hancock, G. J., Bartley, R., Hawdon, A. A., & Keen, R. J. (2013). Using sediment tracing to assess processes and spatial patterns of erosion in grazed rangelands, Burdekin River basin, Australia. *Agriculture, Ecosystems & Environment*, *180*, 90–102. https://doi.org/10.1016/j.agee.2012.02.002

Wilkinson, S. N., Kinsey-Henderson, A. E., Hawdon, A. A., Hairsine, P. B., Bartley, R., & Baker, B. (2018). Grazing impacts on gully dynamics indicate approaches for gully erosion control in northeast Australia. *Earth Surface Processes and Landforms*, *43*(8), 1711–1725. https://doi.org/10.1002/esp.4339

Williamson, D., Ceccarelli, D. M., Evans, R. D., Jones, G. P., & Russ, G. R. (2014). Habitat dynamics, marine reserve status, and the decline and recovery of coral reef fish communities. *Ecology and Evolution*, *4*(4), 337–354. https://doi.org/10.1002/ece3.934

Williamson, D., Ceccarelli, D., Rossetti, G., Russ, G., & Jones, G. (2016). *Assessing the cumulative impacts of climatic disturbances on coral reefs in the Keppel Islands, Great Barrier Reef Marine Park. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Williamson, D. H., Ceccarelli, D. M., Rossetti, G., Russ, G. R., & Jones, G. P. (2016).

Assessing the cumulative impacts of climatic disturbances on coral reefs in the Keppel Islands, Great Barrier Reef Marine Park. Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns

Wolanski, E., & Duke, N. C. (2002). Chapter Twenty-One Mud threat to the Great Barrier Reef of Australia. In *Proceedings in Marine Science* (Vol. 4, pp. 533–542). Elsevier.

Wolfe, K., Anthony, K. R. N., Babcock, R. C., Bay, L. K., Bourne, D. G., Bradford, T., Burrows, D. W., Byrne, M., Deaker, D. J., Diaz-Pulido, G., Frade, P. R., Gonzalez-Rivero, M., Hoey, A. S., Hoogenboom, M. O., & Mccormick, M. (2019). *Recommendations to maintain functioning of the Great Barrier Reef. Report to the National Environmental Science Programme.* Reef and Rainforest Research Centre Limited, Cairns

Woodley, S. J., Williams, D. M., Harvey, T., & Jones, A. (2006). *World Heritage Research: Making a Difference.* CRC Reef Research, Education and Capacity Building 1999-2006.

APPENDIX 1: RELEVANT NESP TWQ HUB PROJECTS

Table A1. List of NESP TWQ Hub projects and relevant information relevant to the synthesis topic (6.2 *Ecosystem restoration*). 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
Gully and Riparian Restoration				
Dr R Bartley (CSIRO) - Developing an approach to evaluate the effectiveness of investments in riparian management in the GBR catchments *(Project 1.2)*	(Bartley, Goodwin, et al., 2016; Bartley, Philip, et al., 2016)	• Stream-bank erosion rates (or channel change) for the GBR catchments can vary from 0.01 m to 5 m yr^{-1}, with higher erosion rates following flood events, but overall low rates otherwise (0.01- 0.1 yr^{-1}). • The effectiveness of riparian vegetation in reducing erosion rates was assessed in the Fitzroy and Mackay Whitsunday catchments as case studies. • Changes in channel width were mostly measured through historical air photos (~1950-2012), showing no statistically significant differences in channel change between sites with good and poor riparian vegetation. However, this could be an artefact of the technique used and does not prove that riparian vegetation is not effective.	A comparison of tools for monitoring and evaluating channel change (2 terrestrial laser scanning instruments RIEGL VZ400 and Zebedee, and airborne LiDAR) showed that the RIEGL was more accurate than the Zebedee, although the airborne LiDAR could be useful to cover large areas rapidly.	• The need to incorporate a 'lag effect' in the models used to evaluate GBR remediation investment (i.e., Source Catchments models), as the physical water quality benefits 2-18 years after remediation has taken place. • Riparian vegetation is important for stabilising banks, intercepting run-off and ecological function, but it is also important to maintain vegetation upstream. Multiple vegetation metrics should be considered for a given site. • A specific budget should be given to evaluating the effectiveness of on-ground remediation works, including riparian management, on water quality.
Dr R Bartley (CSIRO) - Demonstration and evaluation of gully remediation on downstream water quality and agricultural production in GBR rangelands *(Project 2.1.4)*	(Bartley, Hawdon, et al., 2017; Bartley, Hawdon, et al., 2018; Bartley, Wilkinson, et al., 2018; Wilkinson et al., 2018)	• The Bowen catchment was found to be the major contributor of sediments compared to any other catchment within the GBR area. • Porous check dams constructed from sticks and logs, in combination with stock exclusion fencing, appear to have an impact on the amount of vegetation that stabilises gullies floors, which in turn was linked with an improvement in water quality (i.e., reduced total suspended sediment concentrations and total nitrogen). • Gullies located on black soils (vertosol) were a major sediment and particulate nutrient source and thus require further attention. • The reduction on livestock grazing pressures within and around gullies in hillslope drainage lines could be a primary method of gully erosion control, which could deliver substantial reductions in sediment yield.		• The high variability in estimating sediment supply and cost-effectiveness. Hence, cost-effectiveness is best calculated at the project or program scale (across multiple gullies) to account for inherent spatial and temporal variability at individual sites. • Sites with the following attributes are more cost-effective to treat, when (i) more efficient sediment delivery to the coast; (ii) high proportion of silt and clay; (iii) higher nutrient content. • The reduction on livestock grazing pressures within and around gullies could be a primary method of gully erosion control, which could deliver substantial reductions in sediment yield.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Prof A Brooks (GU) - Achieving maximum reductions of sediment loads to the GBR on the shortest possible timescales: the application and adaptation of mine site rehabilitation approaches to alluvial gully rehabilitation in the Bowen catchment *(Project 2.1.10)*	(Brooks, Pietsch, et al., 2016)	• Large alluvial gully systems are a significant contributor to the sediment load of the GBR catchment rivers and require of rehabilitation efforts in order to significantly reduce sediment and nutrient loads to the GBR and meet reduction targets. • Given the diversity of gully forms, a diverse array of management interventions will be required for their effective treatment, such as hard engineering interventions involving terrain reforming of the whole gully system, or less interventionist measures. • Mine site landscape rehabilitation approaches could be adapted and applied to alluvial gully rehabilitation, cost-effectively. • A stable soil surface needs to be reconstructed. • General principles were proposed as a requirement for successful alluvial gully rehabilitation.	As a result of this project significant progress has been made towards the development of a major collaborative project (with Glencore) that will take this forward into large field trials of the application of mine site rehabilitation strategies for alluvial gully rehabilitation.	Key principles of gully rehabilitation include: • Stock exclusion. • Short term erosion mitigation measures during construction phase (e.g., sediment traps). • When reforming vertical surfaces, determine first appropriate slope for soil. • Hardening of key slope components. • Hydrological reconfiguration and associated drainage management. • Cap unstable subsoils by covering with new soil (imported or built on-site). • Revegetation and ongoing maintenance.
Dr K Paul (CSIRO) - Optimizing the management of riparian zones to improve the health of the Great Barrier Reef *(Project 3.1.4)*	(Paul et al., 2018)	• Sub-optimal rehabilitation: Improved WQ outcomes increased with project age, although remediation projects may not result in full rehabilitation to 'natural' stage (due to persistent erosion, weeds…). • Importance of financial incentives to engage landholders. • Overcoming normalising behaviour and perceived risks by landholders is important to ensure widespread participation in riparian remediation. • Need to prioritise resources to maximise impacts. • Riparian areas play a large role in providing benefits to biodiversity and biosequestration due to their fertile alluvial soils and increased moisture levels.		Recommendations: • To facilitate landholder groups to engage and build local knowledge, including to develop guidelines for recommended management practices that are practical and also provide benefits to agricultural production. • To facilitate alternative incentive schemes (i.e., landholder payments that are directly linked to outcomes of improved water quality, biodiversity and carbon mitigation). • Underpinning research to support riparian remediation.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Prof A Brooks (GU) - Reducing sediment loads to the Great Barrier Reef – developing optimal approaches for treating alluvial gully erosion *(Projects 1.7 / 3.1.7)*	(Brooks et al., 2021)	• Main focus of the project was testing and evaluating cost-effectiveness of different gully rehabilitation approaches within the larger alluvial gully complexes (i.e., Crocodile Station and Strathalbyn). • Results showed that alluvial gullies can be cost-effectively remediated to achieve >95% effectiveness factor, with highest effectiveness at sites that had full reshaping and rock capping, and lower effectiveness at sites treated with organic mulch and other non-rock surface treatments. • Gullies treated with rock capping and soil ameliorants are resilient to major events (e.g., large floods.) • Net increases in dissolved nutrient yields were observed in sites treated with organic ameliorants, which requires ongoing monitoring. • The net end of system fine sediment abatement achieved at the Crocodile and Strathalbyn sites respectively by May 2020 was 0.165 and 4.43 kt/yr, equivalent to reductions of 1.7% and 0.8% of the water quality targets for the Normanby and Bowen catchments, respectively.	The PASS sampler is ideally suited for the cost-effective and rigorous collection of pre- and post-treatment sediment concentration data.	• In order to calculate cost effectiveness of gully remediation, using a 7% discount rate and a 25-year lifetime enables the upfront cost to be converted to its annualised equivalent cost so that it can be compared with annual sediment reduction. • End of system (EOS, (*sensu* Kentula et al., 1992) cost effectiveness could be used as a metric to inform investments in gully remediation across different GBR catchments. • More efforts and resources need to be directed towards baseline sediment and nutrient yield determination to ensure the integrity of estimates of GBR water quality improvement. • In order to meet the 2025 WQ targets for the Normanby and Bowen catchments respectively, 61 and 129 equivalent sites would need to be remediated in each catchment.
Prof A Brooks (GU) - Gully characterisation framework to underpin GBR catchment water quality management *(Project 4.9)*	(Brooks et al., 2019)	In brief, gullies could be classified based on: 1. Climate Zone 2. Gully scale / Gully System Complexity (i.e., simple, composed, complex). 3. Landscape domain: Hillslope (colluvial vs. residual), composite (alluvium to Hillslope, alluvium slopes), and alluvial (Floodplain/terrace, Bank/Slopes, Valley bottom). 4. Gully form: Linear, Dendritic, Open, Amphitheatre, Scarp-front, Variant forms. 5. Gully Catchment: Contributing Catchment Area (CCA) / Distance to Divide (DtD): (i) Minimal, (ii) Moderate, (iii) Extensive 6. Vegetation Cover (In gully / Around gully): (i) bare, (ii) sparse, (iii) dense. 7. Soil materials 8. Erosion Activity	A gully database was developed to facilitate systematic collection of data on gullies, along with purpose-built-Excel-based data entry forms to allow for easy data upload to the centralised database. Available through the NESP TWQ Hub website and eAtlas.	• The identification of different types of gullies in the landscape allows to prioritise management effort and resources so that the appropriate treatments can be applied to different gullies in the most cost-effective manner.

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Dr R Bartley (CSIRO) - Gully remediation effectiveness *(Project 5.9)*	(Bartley, Hawdon, et al., 2020; Bartley, Poesen, et al., 2020)	• High variability of erosion and WQ among gullies, with catchment area being the strongest predictor of sediment yield for linear gullies. TSS concentrations in control sites varied from 60 m/L (Mt Pleasant) to 53,000 m/L (Glen Bowen). Total Nitrogen was not as responsive as sediments to rehabilitation treatment. • Livestock management and revegetation: some improvements in % cover or biomass were observed after treatment, but sites remained in poor condition. • Porous Check Dams (plus fencing) (sites at Virginia Park and Minnievale) resulted in high (>90%) coarse sediment trapping (>63µm). • Hillslope runoff diversion above the gully (Strathbogie) statistically improved the runoff and WQ metrics (~0.95 effectiveness value), but further monitoring is required to assess if the treatment is causing gully initiation elsewhere. • Runoff management within gully (Mt Pleasant) had some success although the property already had good vegetation metrics and in-active gully systems. • Gully reshaping, structural control and revegetation (Mt Wickham) resulted in statistically improved vegetation metrics, TSS and declined sediment loads (effectiveness value of ~0.85).		• Data from this project will be critical for scenario analysis using the Paddock to Reef modelling. • This is a long-term research field, and sites will continue to produce data as sites are exposed to different weather/climate conditions, succession in vegetation, etc. • The qualitative information such as terrain monitoring of gully erosion, photographs of event runoff, vegetation responses and treatment intactness, provides early information to support gully rehabilitation, the appropriateness of the techniques being tested, and the types of responses which can be expected to continue to develop.
Prof A Brooks (GU) - Development and application of automated tools for high-resolution gully mapping and classification from LIDAR data *(Project 5.10)*	(Daley et al., 2021)	• Airborne Light Detection And Ranging (LiDAR) is widely recognised as being the best way to accurately map gullies at a landscape scale at a suitable resolution for management planning. Given the large volume of LiDAR data now becoming available, this project developed and applied automated tools to enable the location of gullies to be extracted from LiDAR Digital Elevation Models (DEMs), along with key attributes of the gullies enabling them to be grouped into classes of similar gully types to aid prioritisation, management and catchment modelling. • Results showed that both alluvial and hillslope gullies can be mapped with a high degree of precision using these approaches and thereby provide the basis for quantifying a range of gully metrics such as: width, depth, area, length, volume, slope, planform shape and cross-sectional shape.	This project refined automated gully mapping approaches currently under development and developed new tools to automate the attribute extraction and assignment of types to the mapped gullies from high-resolution LiDAR DEM data.	• Accurately mapping gullies at high resolution and quantifying their key attributes is the critical first step in the process of prioritising and designing rehabilitation solutions. • Mapping gullies from LiDAR, particularly where coupled with high resolution multi-spectral imagery, provides a far superior product to that which can be obtained via manual and visual mapping from satellite imagery

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Wetland restoration				
Dr N Waltham (JCU) - Scoping options for low-lying, marginal cane land to reduce DIN in priority wet tropics catchments (2.1.2) and Burdekin and Mackay Whitsunday catchments (5. 12) *(Project 2.1.2 / 5.12)*	(Waltham et al., 2017; Waltham, Canning, et al., 2020)	• From a societal perspective land use transition can be a cost-effective option for reducing DIN loss, comparable to existing mechanisms for addressing DIN loss. • Coastal wetland restoration (if sited on poorly performing cane land, with low conversion cost and high ecosystem service delivery) offers the greatest potential for cost-effective DIN reduction ($7-9/kg DIN reduced). • Constructed treatment wetlands and grazing, when placed in appropriate locations (and where conversion costs are low and DIN reductions are high) can offer cost effective DIN reduction in the range of $15-17/kg DIN reduced, which is cheaper than that reported for extension-based approaches (c. $50/kg DIN reduced).	A decision support tool has been developed integrating spatial and economic information to assist with examining options for transitioning low-lying cane land, with a high risk of dissolved inorganic nitrogen (DIN) loss, to lower DIN-risk uses in the Wet Tropics.	• Land use transition could be considered as part of a mix of mechanisms to address DIN loss. It complements other mechanisms, if targeted at the small areas of poorly performing sugarcane land, while best management practice adoption initiatives should focus on the remaining, more productive sugarcane land. • It is recommended that this framework be tested, evaluated and refined via a pilot study. • The limited quantitative information on the DIN removal capacity and conversion costs for wetland restoration or constructed treatment wetlands in the Wet Tropics generates uncertainty around its cost-effectiveness. In general, wetland restoration or constructed treatment wetlands are most cost-effective when conversion costs are low and DIN removal capacity is high. Placing constructed wetlands within an integrated treatment train might further improve water quality, though this needs to be weighed against the additional costs incurred.

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Dr N Waltham (JCU) - Science evaluation of coastal wetland systems repair projects across GBR catchments *(Project 3.3.2)*	(Adame, Arthington, et al., 2019; Adame, Franklin, et al., 2019; Gilby et al., 2020; Stewart-Sinclair et al., 2020; Wallace et al., 2020; Waltham et al., 2019; Waltham, Adame, et al., 2020; Waltham, Buelow, et al., 2020; Waltham, Coleman, et al., 2020; Waltham, Elliott, et al., 2020)	• An exclusion fence (for feral pigs) was constructed in 2016 surrounding the Round Hill Reserve, a coastal wetland in the Baffle catchment. Monitoring (2017-2019) of this and 4 other wetlands, revealed the importance of restoration targeting the threat of feral pigs (and cattle). • Bund wall removal on coastal floodplains to restore the tidal nature of the wetland, resulted in increased saltwater intrusion, controlled invasive aquatic weeds, improvements in water quality, and improvements in connectivity. However, some freshwater values can also be lost. • WQ monitoring of a constructed wetland in Babinda (NQ) indicated that a 10% of the DIN reduction target and 25% of the PN 2025 target could be achieved from 398 ha of wetland with the same mean denitrification properties, which amounts to 1.5% of the total sugarcane area in the Mulgrave-Russell catchment. • Need for long-term maintenance programs facilitated by partnerships to restore coastal floodplains (e.g., aquatic weed removal) while as long as sugarcane production occurs in the area. • Successful GBR wetland ecosystem restoration and management require an understanding of what constitutes “success” and must be underpinned by an understanding of complex cause and effect pathways, with a focus on management of services and values. Suitable, long term, scientific knowledge is necessary to provide government and private companies with the confidence that their investment delivers dividend (environmental) returns.	Fences could result in a functioning and productive coastal wetland system for a much-reduced cost (vs. aerial shooting and bait traps) for feral pig control. Tips to overcome barriers on ‘blue restoration’.	• Maintenance of fences is a challenge and requires long term commitments from state government and other stakeholder groups. • Allowing cattle to enter fenced wetland should cease as this will only continue to impact on the broader value and services of the wetland. • Under a market mechanism scheme (e.g., blue carbon, or water quality markets) these coastal wetlands could become more valuable as part of climate change adaption, and could effectively earn more generated income compared to using these ecosystems for a late dry season cattle feed area. • Financial opportunities for wetland restoration in addition to government-funded schemes include water pollution offsets, payment for ecosystem services, and nitrogen markets • Suitable, long term, scientific knowledge is necessary to provide government and private companies with the confidence that their investment delivers dividend (environmental) returns.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr N Waltham (JCU) - Evaluating the costs and benefits of agricultural land conversion to wetlands *(Project 4.10)*	(Waltham, Canning, et al., 2021)	• Government and private investors are increasingly interested in nitrogen reduction projects, particularly via conversion of land to wetlands. Investing in such projects requires understanding the environmental benefits to be accrued and cost-effectiveness. • This project collected data from previously completed land-wetland conversion sites, on construction and ongoing maintenance costs, and the water quality and biodiversity benefits.		• The outcomes of this project are to maximise the water quality and ecosystem services return for funding invested in wetland projects • Results will direct and inform future government funding schemes to ensure that mistakes made in the past are not repeated.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr N Duke (JCU) - Assessing the Gulf of Carpentaria mangrove dieback *(Project 4.13)*	(Bergstrom et al., 2021; Duke, 2020; Duke, Hutley, Mackenzie, et al., 2021; Duke, Mackenzie, Hutley, et al., 2021; Duke, Mackenzie, Kovacs, et al., 2021; Duke & Larkum, 2019; Harris et al., 2018; Harris et al., 2017)	• Collaboration and information sharing with local TO rangers on both Queensland and NT sides of the Gulf • Partnerships with researchers and managers with CDU, NTG, CSIRO and WAP - including the sourcing of additional funding. • Increased knowledge of the 2015 incident of mangrove mass dieback along 2000 km of coastline - mapped from satellite imagery, and from low-level, aerial surveys in 2017 and 2018. • Compilation of information for 38 major estuary mouths including quantified observations of change indicators and their associated drivers like shoreline erosion and rising sea level. • Detailed archive of photographic imagery covering key features along shorelines of the Gulf. • Field transect data along the Gulf shoreline used to estimate carbon losses with the dieback and for profiling of stand demography. • Mangrove recruitment data had been keeping up with sea level rise until impacted in 2015 event. • Discovery of an equivalent second occurrence of mangrove mass dieback in 1982. • Mass dieback of mangroves was caused by an extreme drop in mean sea level (ca. 40 cm lower for a 6 -mo period). • Combined and cumulative impacts of el Nino, severe tropical cyclones and flooding events.	Impacts of extreme oscillation in mean sea level on shoreline mangroves. Destabilization of protective shoreline vegetation across the Gulf. First major use of green fraction (canopy condition) plots at the landscape scale to describe impacts from various events as well as natural recovery rates Natural recovery processes in mangrove forests are mostly effective and well-resourced but there are limits!	• Future re-occurrences of severely damaging mangrove mass dieback are anticipated across northern Australia. • While human restoration efforts of damaged mangrove shorelines are considered counter-productive, it is recommended to invest in targeted interventions to minimise harm to mangrove stands and to enhance the resilience of wetland ecosystems. • It is recommended to support TO rangers to monitor the condition of shoreline tidal wetlands while also helping manage feral pigs, bush fires and weeds in areas surrounding vulnerable mangrove tidal wetlands • It is also recommended to initiate a program and partnership between researchers, managers and TO rangers to remove the damaging outcomes (now predictable) of desiccation periods associated with extreme low oscillations in mean sea level. This strategy involves selective aerial watering at rare but critical times.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr N Waltham (JCU) - Coastal wetland systems repair across GBR catchments – values based causal framework validation *(Project 5.13)*	(Canning Adame, et al., 2021; Canning, Jarvis, et al., 2021; Waltham & Canning, 2021)	• Invasive plans will require management interventions for as long as sugar production occurs on the Burdekin floodplain and excess nutrients reach the creeks. • Maintaining most creeks on the floodplain in a moderately turbid state is probably important in reducing the threat of eutrophic-driven hypoxia and fish kills. • Installation of recycle pits situated in the lower ends of the farms to capture irrigation water runoff before reaching shallow coastal wetlands, and improved irrigation water delivery efficiency to reinstate the natural wetting and drying cycles of coastal wetlands. • A resurvey of Sheep Station Creek nearly 20 years after commencing the environmental levy (i.e., to ensure weed removal) and maintenance revealed the creek's state is generally better than other places on the floodplain. • The Tedlands wetland complex holds/supports considerable ecosystem services (despite having been created artificially). This has to be considered when assessing interventions such as bund removals to allow seawater inundation.	This case study advocates the need to manage wetland restoration activities for the values and services, and to not focus on the components and processes. Any future proposal to remove bund walls should give full consideration to the existing values.	• Importance to focus on the ecosystem services and converting them to values by engagement of local beneficiaries to ensure long-term maintenance of projects (e.g., weed removal). • Considerable funds to redesign engineered structures are necessary to reinstate fish passage across the floodplain, in addition to ongoing management of the biological and chemical barriers that occur across the floodplain. • Funding for continued maintenance after restoration works is necessary. The funding model in Sheep Station Creek (i.e., environmental levy) should serve as a model for other floodplain systems throughout the GBR.
Seagrass Restoration				
Dr C Collier (JCU) - Light thresholds for seagrasses of the GBR: a synthesis and guiding document for managing seagrass *(Project 3.3)*	(Collier, Chartrand, et al., 2016)	• Synthesis of light thresholds for seagrass species in the GBRWHA, to ensure protection of seagrasses from activities that impact water quality and the light environment, such as coastal and port development (acute management thresholds). Colonising species are the most sensitive to light reduction and have the lowest light thresholds (2 to 6 mol m^{-2} d^{-1}) and shortest time to impact (14-28 days). Opportunistic and Persistent species have higher light thresholds (5-6 mol m^{-2} d^{-1}) and longer times to impact (28-50, and 50 days, respectively). • Thresholds for long-term maintenance of seagrasses were also proposed: 10-13 mol m^{-2} d^{-1} is likely to prevent light limitation for the long-bladed species, although deepwater species require less light.		Guidelines for light are recommended as a management trigger for seagrass meadows at risk from declining water quality. • Acute management thresholds (suited to compliance guidelines for managing short-term impacts): from 2 to 6 mol m^{-2} d^{-1} depending on species. • Long-term thresholds (suited to the setting of water quality guidelines for catchment management): 10-13 mol m^{-2} d^{-1} on average. However, it is essential to determine the desired state at a regional scale beforehand.

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Dr C Collier (JCU) - Developing and refining biological indicators for seagrass condition assessments in an integrated monitoring program *(Project 3.4)*	(Collier, Langlois, et al., 2016)	• The potential bioindicator 'total non-structural carbohydrates' (TNSC) in seagrasses (i.e., storage reserves) responded to cumulative stress and was correlated to seagrass abundance and condition, although specific pressures could not be identified. • TNSC did not respond to changes in light conditions as expected and therefore the study could not support its inclusion as an indicator in monitoring programs such as the MMP. • Above ground biomass was highly correlated to % cover, although canopy height had a strong effect on the calibration values, highlighting the importance of habitat/morphology-specific calibration formulae.	The newly discovered relationship between meadow condition and storage reserve could be used to assess meadow trajectory, through the use of TNSC as an early-warning indicator. However, additional data and validation for other regions and species is still required.	• The inclusion of TNSC as an indicator in monitoring programs such as the MMP was not supported by this study. Additional research is required to address the effects of other pressures and other biological processes and to obtain further data on other species. • Additional work is required to refine calibration formulae to convert %cover to biomass, facilitating integration among seagrass monitoring programs including Queensland Ports Seagrass Monitoring Program and GBR historical baseline data.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Dr C Collier (JCU) - Deriving ecologically relevant load targets to meet desired ecosystem condition for the GBR: a case study for seagrass meadows in the Burdekin region *(Project 3.2.1/5.4)*	(Carter et al., 2018, 2020; Collier et al., 2020; Lambert et al., 2020, 2019)	• 35 years of seagrass spatial point data was compiled and made publicly available. • The potential distribution of seagrass habitat was modelled throughout the entire GBR and adjacent estuaries. • 36 different seagrass communities (containing a mix of species) were identified. • Each of the communities was associated with a unique environmental setting including water temperature, currents, depth, benthic light, mud, salinity and sediment type. • A 'desired state' for seagrass communities in Cleveland Bay (3.2.1) and the whole GBRWHA (5.4) was established as ecological benchmarks. Restoration may be warranted in communities that do not meet desired state. • Catchment inputs of sediments were linked to seagrass desired state based on long-term monitoring data and eReefs. However, seagrass responded over many years, suggesting the use of multi-annual load targets. • A range of estimates for sediment load reduction targets (~31-45%) was proposed by considering multiple indicators of ecological response and stressors over multiple timescales. • The models found stronger correlations between seagrass variables and river flow than sediment load, suggesting that the riverine discharge has other properties that could affect seagrass area and biomass (e.g., organic matter, nutrients).	Community types have been modelled on the GBR for the first time, transitioning from conceptual and descriptive community classification to a quantitative one.	• The compiled data set, potential habitat mapping and community analysis can be applied in a range of applications. These include: -assessing how risk and spatial protection intersect with seagrass communities, -designing a hierarchical seagrass monitoring design, -identified communities where data is deficient, and -identifying potential restoration sites. • Desired state has been defined for seagrass communities filling an identified need in the Long-Term Sustainability Plan. • The seagrass ERTs of 31-45% reduction in anthropogenic fine sediment load from the Burdekin River will have the greatest likelihood of enabling seagrass to achieve desired state or achieve net zero loss. This ERTs were comparable to the existing 2018 WQIP ERT of 30% for the Burdekin River. • Light levels in shallow coastal waters should be thoroughly and accurately characterised, as existing spatial models were inadequate in those habitats. • Long-term data sets on seagrass species, abundance and area should continue to be collected so that management targets can be assessed using ecological data in the future.

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Coral Reef Restoration				
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 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.
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.

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Social aspects of restoration activities				
Dr M Barber (CSIRO) - Building Indigenous livelihood and co-management opportunities in the Northern GBR – ecosystem services and conservation governance for water quality *(Project 2.3.3)*	(Barber et al., 2016, 2017; Barber & Jackson, 2017; Pearse, 2018)	Significant opportunities (and some risks) exist for Indigenous people on Cape York Peninsula (CYP) in the Ecosystem Services (ES) sector (particularly, in water and catchment management). Identifying those opportunities and avoiding potential risks requires a combination of: • Strengthening local and regional Indigenous governance systems; • Development of policy frameworks to support ES valuation; • Building of partnerships with agencies with skills in monitoring and evaluation; • Building relationships with potential future customers; • Identifying commercial opportunities and building revenue streams that support the provision of ES • Building of livelihoods based in Indigenous natural and cultural resource management that can generate substantial social, cultural, political, economic, and health co-benefits. Potential risks to manage include: (i) risk to foundational rights associated with country, and (ii) risks associated with business failure.	Strategic review of drivers and trends in environmental markets and their applications for Australia. Foundations for a strategic business document for an Indigenous country-based management agency, Kalan Enterprises	Indigenous ES represent one crucial pathway to support Indigenous country-based livelihoods in CYP, and to generate desirable outcomes for major environmental assets. These ES must be developed as part of a broader business and enterprise strategy containing mutually supportive elements (e.g., ecotourism, research services, feral animal management and biodiversity protection). Further work is needed to alight commercial development opportunities, build potential markets and generate customers. Future partner support may encompass the underpinning infrastructure that enables Indigenous people to deliver such services; the development and commercialisation of the ES themselves; the creation of commercial products associated with those services; and the lobbying for changes to key national and/or State policies limiting service development and commercialisation.
Dr N Duke (JCU) - Working with traditional owners and local citizens to better manage GBR estuarine wetlands *(Project 2.3.4)*	(Duke et al., 2019a, 2019b; Mackenzie et al., 2016; Mackenzie & Duke, 2019; Schultz et al., 2020)	• Development of a Mangrove Management Plan with TO to provide ongoing estuarine monitoring and repair activity for the maximization of WQ outcomes in southern GBR. • Building of essential capacity amongst the Gidarjil Development Corporation Rangers and the local community to conduct ecological monitoring and assessment of key local estuarine resources. • Evaluation and mapping of mangroves and saltmarsh tidal wetlands for 8 estuarine systems. • Regional impacts related to climate change and sea level rise.	New partnerships between TO, community, scientist and local NRM agencies. Engagement with local stakeholders and end-users through dedicated workshops.	Key project recommendations include: a. Continue supporting Gidarjil Rangers in the monitoring of estuarine shorelines in their region; b. Support on-going shoreline video assessment analyses along with the development of a regional report card on southern Great Barrier Reef estuarine waters.

Image: Justin Stout

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