Tropical Water Quality Hub

National **Environmental Science** Programme

Synthesis Report

Overcoming barriers to reducing nitrogen losses to the Great Barrier 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

Overcoming barriers to reducing nitrogen losses to the Great Barrier Reef

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C_2O Consulting

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Project 6.3 Overcoming barriers to reducing nitrogen losses to the GBR

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

Cover photographs: (front) Farmacist Ayr biomass sampling crew in the Burdekin. Image: Jason Dowie. (back) Sugarcane drain. Image: Nathan Waltham.

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

www.synthesis.nesptropical.edu.au

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

AIMS .... Australian Institute of Marine Science
AMPTO......... Association of Marine Park Tourism Operators
CERF............ Commonwealth Environmental Research Facility
COTS............ Crown-of-thorns starfish
CRC Reef ..... The Cooperative Research Centre for the GBRWHA
CQU............. Central Queensland University
CSIRO .... Commonwealth Scientific and Industrial Research Organization
DIN .... Dissolved inorganic nitrogen
EEF............... Enhanced Efficiency Fertilisers
GBR.............. Great Barrier Reef
GBRMPA...... Great Barrier Reef Marine Park Authority
GBRWHA ..... Great Barrier Reef World Heritage Area
GU .... Griffith University
JCU .... James Cook University
MTSRF .... Marine and Tropical Science Research Facility
N................... Nitrogen
NERP............ National Environment Research Program
NESP............ National Environmental Science Program
TWQ .... Tropical Water Quality
NRM .... Natural Resource Management
RRRC .... Reef and Rainforest Research Centre
STP............... Sewage treatment plant
UQ .... University of Queensland
WQIP .... Water quality improvement plan
6ES............... SIX EASY STEPS™

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EXECUTIVE SUMMARY

The Tropical Water Quality (TWQ) Hub was one of six multi-disciplinary research hubs within the National Environmental Science Program (NESP), focused on delivering innovative research to maintain and improve Great Barrier Reef (GBR) water quality from catchment to reef. The program focused on delivering research outcomes that improved understanding of the impacts on important ecosystems, maximising the resilience of vulnerable species to the increasing pressures, and informing natural resource management improvements.

The GBR is under increasing threat from a range of pressures dominated by a changing climate, but also from increased land-based runoff, coastal development, and to a lesser extent, direct use (e.g. fishing, tourism, recreational use). Land based runoff results in poor water quality, particularly in the inshore GBR, and the adverse impact of runoff to the GBR can be reduced by better catchment management practices. The primary pollutants of concern in runoff are sediments, nutrients and pesticides. These pollutants vary in their extent and severity of impact. The focus of this report is elevated nutrient (and more specifically, nitrogen) runoff, which may cause important ecological impacts including; lower coral diversity, algal blooms (that can also reduce light), enhanced outbreaks of coral-eating crown-of-thorns starfish, increased susceptibility to coral bleaching and some coral diseases.

Several NESP TWQ Hub projects have supported the Reef 2050 Water Quality Improvement Plan aim to reduce the delivery of nutrients from the catchment to the GBR, with a particular focus on nitrogen, the primary driver of algal blooms in the GBR. Research on the ecological impacts of nitrogen losses to the GBR built on previous research investment and focused on the cumulative impacts of multiple stressors to reef ecosystems. The majority of the research focused on investigating solutions associated with on-ground actions for reducing nitrogen losses and developing new instruments for facilitating management changes. The latter is a unique research area for the GBR and its catchments and has proven to be of significant interest to investors and decision makers.

A conceptual framework which identifies four key stages of overcoming barriers to reduce nitrogen losses was used to structure the key findings in this report. The four key stages are: identifying actions, understanding participation, exploring new instruments and evaluating options. Collectively, the NESP TWQ Hub research projects have:

- Combined improved nitrogen fertiliser technology using Enhanced Efficiency Fertilisers with fertiliser nitrogen rate reductions, and assessed the effects of these treatments on sugarcane productivity and nitrogen loss.
- Augmented ‘Internet of Things’ software with irrigation decision support tools and automation so that the right amount of water can be applied at the right time at minimal effort to sugarcane growers in the Lower Burdekin.
- Explored and identified potential cost effective options for land use transition of high DIN risk marginal sugarcane areas to alternative land uses, specifically aiming to reduce nitrogen losses in wet and dry tropic catchments.
- Established a monitoring framework for design and implementation of finer scale water quality monitoring in pollutant generation hotspots in sugarcane. This was used in conjunction with farmer engagement and social research to support building trust in science and facilitating management change. Other approaches to managing off-farm

nitrogen losses were also explored including modifying the catchment's existing farm drainage infrastructure, applying fertilisers after sugarcane harvest earlier than before to avoid coinciding with the 'first flush' rains of the wet season, and experimenting with lower rate applications later in the year.

- Identified barriers and enablers of management change in relation to agricultural run-off to encourage greater uptake of best management practices among land managers.
- Provided guidelines for the development and modification of communication material in the agricultural-environmental sector with the aim of increasing uptake of water quality improvement programs in the GBR catchments.
- Explored the application of a tradeable permit scheme for nitrogen among landholders, and trading in water quality credits between point and non-point sources to facilitate future economic expansion along the GBR coastline without increasing overall nutrient loads.
- Developed a prototype insurance product to mitigate the risk of sugarcane yield reductions arising from reduced nitrogen rates.
- Assessed the cost-effectiveness of nitrogen reduction projects and programs from a program investment perspective, including considerations for site-specific influences (particulary soil) and other policy related issues.
- Identified lessons from previous investment in tender-based environmental funding programs to inform the design of future programs, intended to improve participant satisfaction and ensure program effectiveness.

The highlights are also summarised in Appendix 1.

The NESP TWQ Hub research has been conducted in collaboration with a wide range of stakeholder groups and is of interest to a larger range of audiences. The research findings are significant for the future management of the GBR and its catchments. Extensive program design effort is essential in future programs to 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 stakeholders. This will ensure that the legacy of the program will continue well into the future.

1. INTRODUCTION

1.1 NESP Tropical Water Quality Hub

The Australian Government, through the National Environmental Science Program (NESP), has been funding research in environmental and climate science since 2015, with a budget of $145 million over six years. Specifically, the NESP targeted research in marine, coastal and freshwater ecosystems, sustainable communities and waste, threatened species, climate systems and other key environmental issues. All NESP-funded projects focused on practical and applied research to deliver accessible results and improve decision-making processes.

The program, which builds on its predecessors (the National Environment Research Program [NERP]; the Marine and Tropical Science Research Facility [MTSRF]; and the Australian Climate Change Science Program [ACCSP]) aimed at facilitating delivery of the best available information in order to support better understanding, management and conservation of Australia's environment (Department of Agriculture Water and the Environment 2020). The Tropical Water Quality (TWQ) Hub was one of six multi-disciplinary research hubs within NESP, investing AU$31.98 million on delivering innovative research to maintain and improve tropical water quality from catchment to reef (NESP 2020), mainly in the Great Barrier Reef (GBR) and adjacent tropical waters. It was structured into three main themes:

- Theme 1: Improved understanding of the impacts, including cumulative impacts, and pressures on priority freshwater, coastal and marine ecosystems and species;
- Theme 2: Maximise the resilience of vulnerable species to the impacts of climate change and climate variability by reducing other pressures, including poor water quality; and
- Theme 3: Natural resource management improvements based on sound understanding of the status and long-term trends of priority species and systems.

Research projects within the TWQ Hub covered a wide spectrum of fields, from genes to ecosystems, including Integrated Pest Management of coral-eating crown-of-thorns starfish (COTS), iconic organisms such as dugongs and marine turtles, seagrass, coral reef resilience, water quality (including sources, transport, fate and impacts of sediments, nutrients and pesticides in the marine environment, and management responses), and wetland restoration science that maximises values and services. The TWQ Hub also had an overall strong focus on cumulative impacts and climate resilience, while building Indigenous connections and capacity in management of Queensland land and sea country.

The NESP TWQ Hub was delivered through a collaborative, multi-disciplinary research network composed of six leading Australian universities and research institutions. The institutions were 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), with coordination of the network by the Reef and Rainforest Research Centre (RRRC) and under the guidance of a Steering Committee including a range of 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, NGO's, Indigenous and other community groups. The partners contributed to the success of the Hub through co-funded research programs (e.g. in-kind contributions to specific projects through staff expertise or research facilities and resources), while also fostering partnerships across the other Hubs and with a wide range of relevant stakeholders. Researchers in the NESP TWQ Hub have worked collaboratively with other research organisations, industry bodies, stakeholder groups and landholders. Examples relevant to this report include Canegrowers and Canegrower regional organisations, Sugar Research Australia, Regional Productivity Services and Drainage Boards, Horticulture Australia, Environmental NGOs, Traditional Owner Organisations, Queensland Tourism Industry Association, AMPTO and other Tourism Organisations, Queensland Department of Environment and Science and Queensland Department of Agriculture and Fisheries and many individual sugarcane farmers. This collaboration has been an extremely valuable feature of the research.

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 and 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 and Waterhouse 2021), '**Overcoming barriers to reducing nitrogen losses to the GBR'** (this report; Waterhouse and Pineda 2021), 'Restoring ecosystems from catchment to reef' (Pineda et al. 2021), 'Principles for establishing greater trust between scientist and farmers' (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 (linked through the NESP TWQ Hub website[1]).

1.2 Nutrients and the GBR

1.2.1 Context

The GBR is one of the worlds' greatest natural assets. Its beauty and overall functionality still endure but signs of deterioration are being increasingly observed in several areas (GBRMPA 2019). Despite some positive outcomes obtained in the past years through management initiatives and local actions, the GBR is still facing significant pressures at a larger scale (GBRMPA 2019). The Great Barrier Reef Marine Park Authority (GBRMPA) stated in their most recent Outlook Report (GBRMPA 2019) that 'Australia is caring for a changed and less resilient Reef', and reinforced the need to restore GBR resilience through mitigating climate change and the effective implementation of the Reef 2050 Long-Term Sustainability Plan (Commonwealth of Australia 2020).

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

Threats to the GBR are multiple, cumulative and increasing. The main drivers of change in the region are climate change, coastal development, land-based run off and direct use (GBRMPA 2019; Waltham and Sheaves 2015; Waterhouse et al. 2017). Among them, climate change is the largest long-term threat to coral reefs worldwide, directly linked with sea temperature increases, altered weather patterns, ocean acidification, and sea level rise (GBRMPA 2019). The increasing sea temperatures (i.e. 0.8 degrees Celsius on average since 1910; see Schaffelke et al. 2017) and resulting marine heat waves have caused successive bleaching events in the GBR in 1998, 2002, 2016, 2017 and 2020, followed by widespread coral loss and flow on effects on the overall ecosystem health (Cantin, Klein-Salas, and Frade 2021). The Region's key habitats have a natural resilience against acute physical disturbances, such as tropical cyclones and marine heatwaves. However, climate change is exacerbating both acute and chronic disturbances, reducing recovery windows and limiting resilience capability (GBRMPA 2019). Action(s) at a global and national level to mitigate and adapt to climate change are essential, as is a strong focus on local and regional management actions to maximise GBR ecosystem resilience in the face of a variable and changing climate (Commonwealth of Australia, 2018a).

Poor water quality, mostly due to land-based run-off from the adjacent catchments (i.e. mainly nutrients and fine sediments), is another major driver of change within inshore parts of the GBR (Waterhouse et al. 2017). Annual discharge of nutrients into the GBR has more than doubled since European settlement (McCloskey et al. 2017). More specifically, excessive nutrient inputs in the GBR lagoon may cause important ecological impacts including reduced coral diversity (De'ath and Fabricius 2008), algal blooms (that can also reduce light) (Jompa and McCook 2003), increased growth of macroalgae (Schaffelke et al. 2005), association with enhanced outbreaks of coral-eating COTS (Brodie et al. 2017), increased susceptibility to coral bleaching (Wooldridge 2009) and some coral diseases (e.g. Vega Thurber et al. 2013). While most effects occur in the wet season when a majority of the land-based inputs occur, some effects may continue for many years, for example COTS outbreaks (Brodie et al. 2017). In the GBR, nitrogen loads are considered more important than phosphorus for ecological impact because the GBR is believed to be nitrogen limited (Furnas et al. 2013). Furthermore, dissolved inorganic nitrogen (DIN) is considered most relevant in terms of ecological response as it is immediately available for biological uptake, whereas particulate nutrients are typically bound to sediment particles for a period but may gradually transform to bioavailable forms (Bainbridge et al. 2018). However, new research indicates that the time interval between particulate nutrient delivery and bioavailability may be shorter than was originally thought (Lewis et al. 2020).

Improved nutrient management is an important priority identified in the Reef 2050 Water Quality Improvement Plan 2017-2022 (Reef 2050 WQIP) (Australian and Queensland governments 2018). Several NESP TWQ Hub projects have focussed on the solutions for reducing nutrient inputs to the GBR, while some marine studies have investigated the cumulative impacts of multiple stressors to the GBR, including nutrient runoff.

1.2.2 Current management framework

Managing water quality is an important contributor to increasing the resilience of the GBR to other disturbances such as climate change. While there have been some improvements in catchment water quality on a regional scale due to modest improvements in agricultural land management practices (see for example the Reef Report Card 2019, Australian and Queensland governments, 2019), poor water quality continues to affect inshore and some midshelf areas of the GBR (GBRMPA 2019; Gruber et al. 2020). As a result, the Reef 2050 WQIP (Australian and Queensland governments, 2018), underpinned by the 2017 Scientific Consensus Statement (Waterhouse et al. 2017) and nested within the Reef 2050 Long-Term Sustainability Plan (Commonwealth of Australia 2015, 2020) establishes the guidelines, policies and programs, as well as monitoring and reporting frameworks required to improve the quality of water flowing from the catchments to the GBR.

To meet the desired water quality targets across the GBR catchments (i.e. 60% reduction in nitrogen, 20% reduction in nutrients and 25% reduction in fine sediments loads that reach the end-of-catchment by 2025 at a reef-wide scale; and specific regional and catchment level targets), additional measures such as improvements to governance (i.e. more adaptive, participatory and transdisciplinary approaches), program design and delivery and evaluation systems are also urgently needed (Eberhard et al., 2017). However, the annual Reef water quality report cards, which detail progress against the Reef 2050 WQIP targets, and the annual Marine Monitoring Program reports (Gruber et al., 2020) show that the overall condition of the inshore marine environment (water quality, seagrass and coral) remains poor. Positive progress has been made in some specific targets such as dissolved inorganic nitrogen (i.e. overall annual reduction of 4.3%) and specific examples at the regional/catchment scale (e.g. for fine sediment loads and pesticide targets in the Burnett Mary region)[2] (Australian and Queensland governments, 2020). However, due to the dynamic nature of the interconnected catchment to reef landscape, the influence of external factors and time lags associated with management intervention and water quality response, it will take many years to achieve measurable improvements in GBR marine water quality as a result of land management improvements; however, long term monitoring programs provide the trend analyses required to show improvement over time (Gruber et al., 2020).

To better manage nutrient losses and prioritise remedial actions, it is important to be able to understand and contextualise all of the issues that are involved in reducing nutrient inputs to the GBR, from understanding why this is important to the GBR ecosystems, to exploration of innovative management practices and alternative mechanisms for reducing nutrient runoff. This report summarises the new knowledge generated through the NESP TWQ Hub research and will provide advice on practical on-ground actions for land and sea managers, policy implications and identify remaining gaps for future research and investment into reducing nutrient inputs to the GBR.

1.3 Timeline of GBR nutrient-related research

The National Environmental Science Program[3] (NESP, 2015-2021) built on predecessor national programs: National Environmental Research Program[4] (NERP, 2011-2015), Commonwealth Environmental Research Facilities[5] (CERF, 2005-2011), including the

[2] https://reportcard.reefplan.qld.gov.au/
[3] http://www.environment.gov.au/science/nesp/about
[4] https://webarchive.nla.gov.au/awa/20200605221304/https:/www.environment.gov.au/science/nerp
[5] https://webarchive.nla.gov.au/awa/20200608030458/http:/www.environment.gov.au/topics/science-and-research/national-environmental-research-program/cerf

Marine and Tropical Sciences Research Facility[6] (MTSRF) program, and Reef Rescue R&D[7] (2011-2013), all managed by the Reef and Rainforest Research Centre (RRRC)[8], and programs funded by the Queensland Government (e.g. Reef Water Quality Science Program[9], 2009-present) 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 previous to 2006 was led by The Cooperative Research Centre for the Great Barrier Reef World Heritage Area[10] (CRC Reef 1999-2006) and contributed to creating the basis for topics such as water quality monitoring, COTS and box jellyfish research, impacts of ports and shipping, global warming and climate change effects and Torres Strait marine research. During this period, knowledge of the sources, delivery and fate of nutrients, and DIN in particular, in the GBR has improved considerably. In addition, important findings critical for guiding management actions to reduce end of catchment loads of DIN have been made. Figure 1 summarises the key research findings and associated literature that highlights this progress.

Water quality research funded through the **CRC-Reef** covered issues such as the GBR nutrient budgets, nutrient fluxes to the GBR from a variety of sources including delivery mechanisms such as flood plumes, initial investigations of impacts of nutrients and sediments on coral communities and some of the first samplings in the marine environment for agricultural pesticides. In addition, the 'Catchment to Reef' research program (2002) addressed gaps in knowledge, refocussed some of the research effort to further quantify impacts of sediments, nutrients and pesticides and began to explore links between catchments and the GBR, while providing tools to help improve the quality of water flowing to the GBR (Woodley et al. 2006). Subsequently, the **MTSRF** program contributed to a better understanding of priority areas for pollutant generation (Waterhouse and Brodie 2011), and thresholds of concern were developed for several water quality variables and ecosystem components and were thereafter applied to water quality guidelines for the GBR (reviewed in Devlin and Waterhouse 2010; Waterhouse and Devlin 2011). **Reef Rescue R&D** research (2011-2013) evaluated specific sugarcane water quality management practices for improved water quality outcomes including innovative management practices, advanced drip and optimised furrow irrigation, the influence of legume fallows and factors affecting the adoption of sugarcane management practices (RRRC 2015).

The **NERP** Tropical Ecosystems Hub research on water quality was synthesised in Devlin et al. (2015). Projects had a strong focus on priority pollutants, cumulative pressures on key ecosystems, identification of priority areas or actions for managers and monitoring and evaluation of long-term historical water quality. NERP water quality projects advanced the understanding of both catchment and marine processes that impact on GBR water quality and on the resilience and health of key GBR ecosystems. NERP research generated significant outcomes for informing the design and implementation of water quality monitoring, evaluation and conservation programs. Projects linking catchment changes to the water

[6] https://webarchive.nla.gov.au/awa/20200615034350/https:/www.environment.gov.au/topics/science-and-research/cerf/marine-and-tropical-sciences-research-facility

[7] http://reefrescueresearch.com.au/

[8] https://www.rrrc.org.au/

[9] https://www.qld.gov.au/environment/agriculture/sustainable-farming/reef/reef-program

[10] https://www.rrrc.org.au/crc-reef/

quality condition of the GBR allowed assessment of the main pressures driving change, and also provided information on the resilience of the GBR to withstand change, and our ability to manage and reduce those pressures to provide a pathway to recovery (Devlin et al. 2015).

Programs such as the **Queensland Government Reef Water Quality Science Program** (commenced in 2009) and industry research programs such as those implemented by Sugar Research Australia (SRA) have run in parallel with these Australian Government initiatives and have included a wide range of research aiming to help producers better manage sugarcane growing and grazing lands across the catchments, and minimise their impacts upon the health of the GBR (e.g. Schroeder et al. 2010). This has generated knowledge of improved nutrient management options in sugarcane farming spanning biophysical, social and economic disciplines and including identification of key sources of pollutants, development and refinement of practical on-farm solutions, methods for farmer engagement, monitoring and evaluation techniques and assessment of the cost-effectiveness of practices (Queensland Government 2016). For nitrogen management in particular, research focused on establishing the link between fertiliser applications in a catchment and DIN losses (e.g. Thorburn and Wilkinson 2013; Thorburn, Wilkinson, and Silburn 2013), followed by the emergence of optimising nitrogen use efficiency as a priority (e.g. Bell et al. 2014).

Knowledge gaps were identified in the period leading up to the commencement of the NESP TWQ Hub. Examples in the marine environment included better understanding of cumulative impacts, climate interactions and multi-generational experiments to assess the potential of acclimation and adaptation to cumulative impacts (Devlin et al. 2015). In the catchments, the research gaps were associated with nutrient use efficiency, social and economic aspects of practice change, finer scale prioritisation and exploration of a wider range of policy instruments to support reductions of nitrogen losses from land management at multiple scales. Other research programs have also focused on these topics (e.g. Enhanced Efficiency Fertilisers, e.g. Vilas et al. 2019; Verburg et al. 2019) with a comprehensive synthesis of research as part of the 2017 Scientific Consensus Statement (Eberhard et al. 2017).

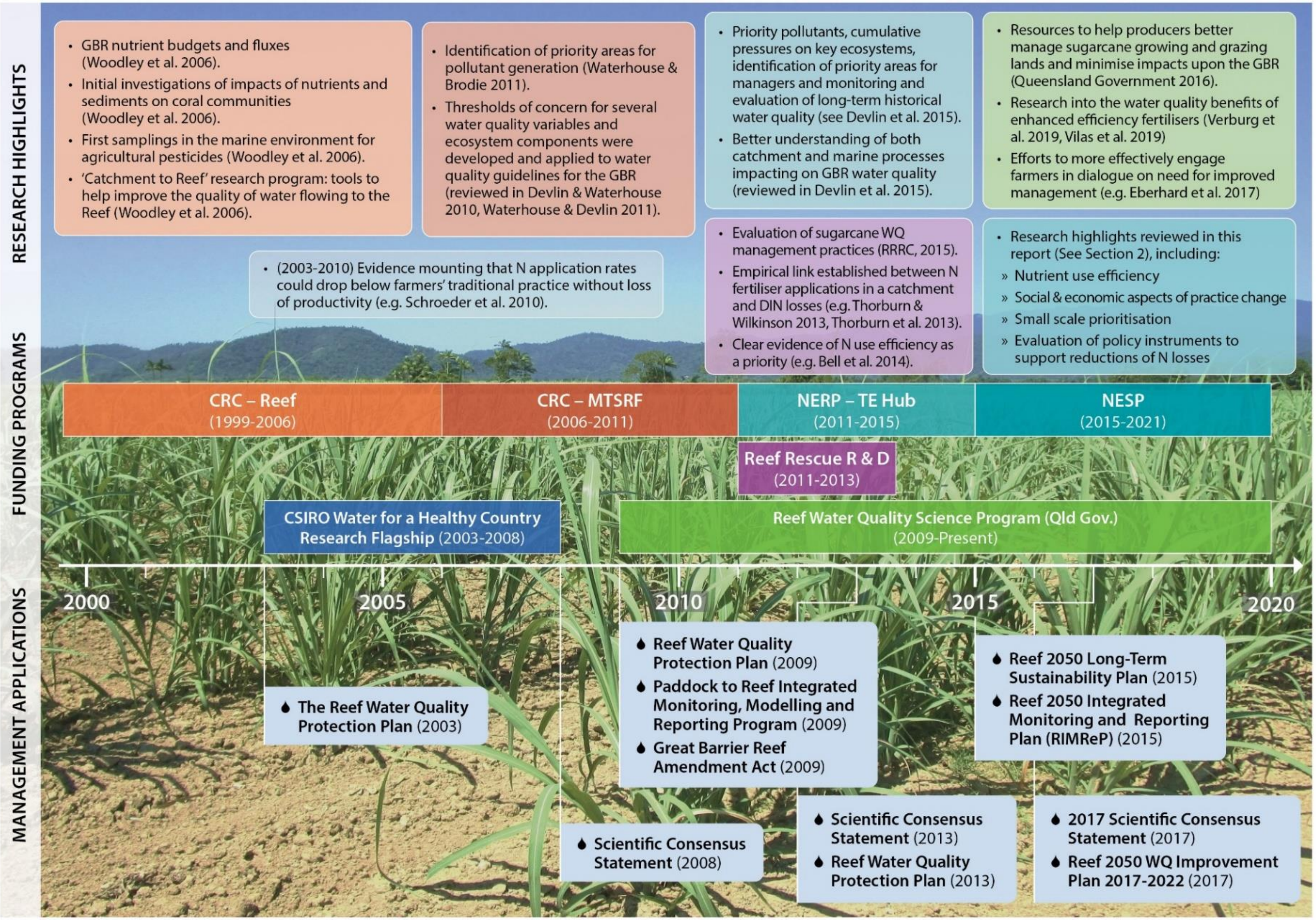

Figure 1. Diagram illustrating the progress of knowledge related to GBR nutrient research.

2. NESP TWQ HUB RESEARCH HIGHLIGHTS: NUTRIENTS, SEA TO SOURCE

As described in Section 1.2, increased nutrient inputs are one of the greatest risks from land-based runoff to the GBR. The scope of NESP TWQ Hub research is illustrated in Figure 2. It has largely focused on understanding how to develop more innovative and efficient ways to reduce nitrogen losses from agricultural land uses in the catchments into the GBR, with some marine studies continuing to assess the risk of nutrients to the GBR. The framework in Figure 3 has been developed to identify where NESP TWQ Hub research contributes knowledge on reducing nitrogen losses to the GBR, highlighting the NESP TWQ Hub catchment related research in stages.

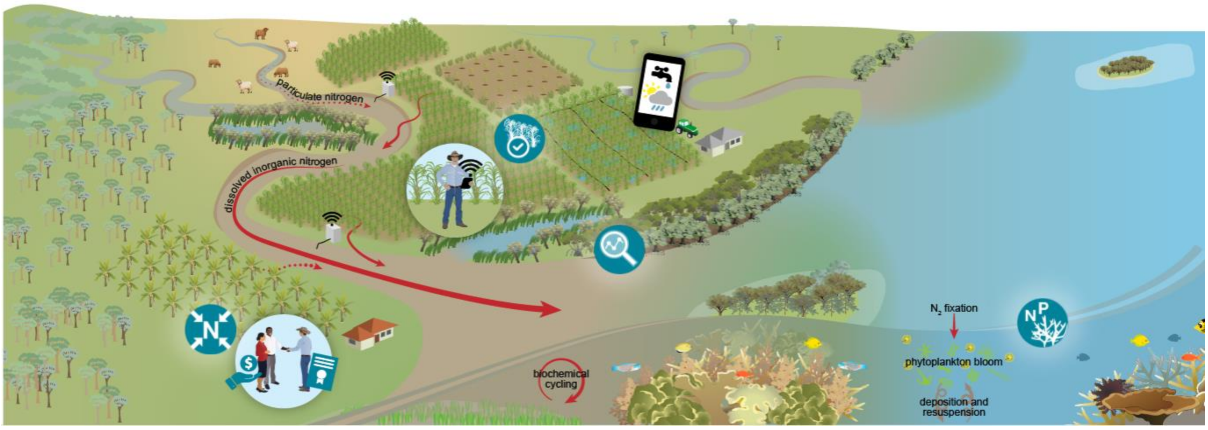

Figure 2. Diagram illustrating the scope of NESP TWQ Hub research associated with nutrient losses and management in the GBR.

In terms of assessing nutrient risk to the GBR (upper part of Figure 3), the research has focused on investigating the interaction between water quality variables, including DIN, increasing temperatures and cumulative impacts of nutrients and other stressors on coral reef ecosystems (Cantin, Baird, et al. 2021; Cantin, Klein-Salas, et al. 2021; Morris et al. 2019; Uthicke et al. 2016, 2020).

In the GBR catchments (lower part of Figure 3), the research can then be broken down into four key stages:

1. **Identifying actions:** On-farm management changes in production systems that reduce losses while maintaining production, and resource changes at the broader landscape level which relate to changes in land allocation and activities designed to reduce losses, where losses in production need to be compensated. This can also include planning actions that support targeted implementation, such as detection of pollutant ‘hot spots’.
2. **Understanding participation**: This involves identifying the barriers to adoption of management changes that would otherwise enable farmers to be more productive / sustainable.
3. **New instruments:** The selection of instruments is specialised and depends on the type of problem being addressed. Several strategies can be adopted including education (awareness, norming), extension, incentives, market-based instruments and regulation.

4. **Evaluating options:** The most important outcomes of policy and program changes are associated with levels of engagement and participation (effects on participation), water quality outcomes, longetivy and total investment with consideration of risks and implementation cost and overall cost effectiveness (costs and cost-effectiveness), the mix of public and private benefits and the mix of tools.

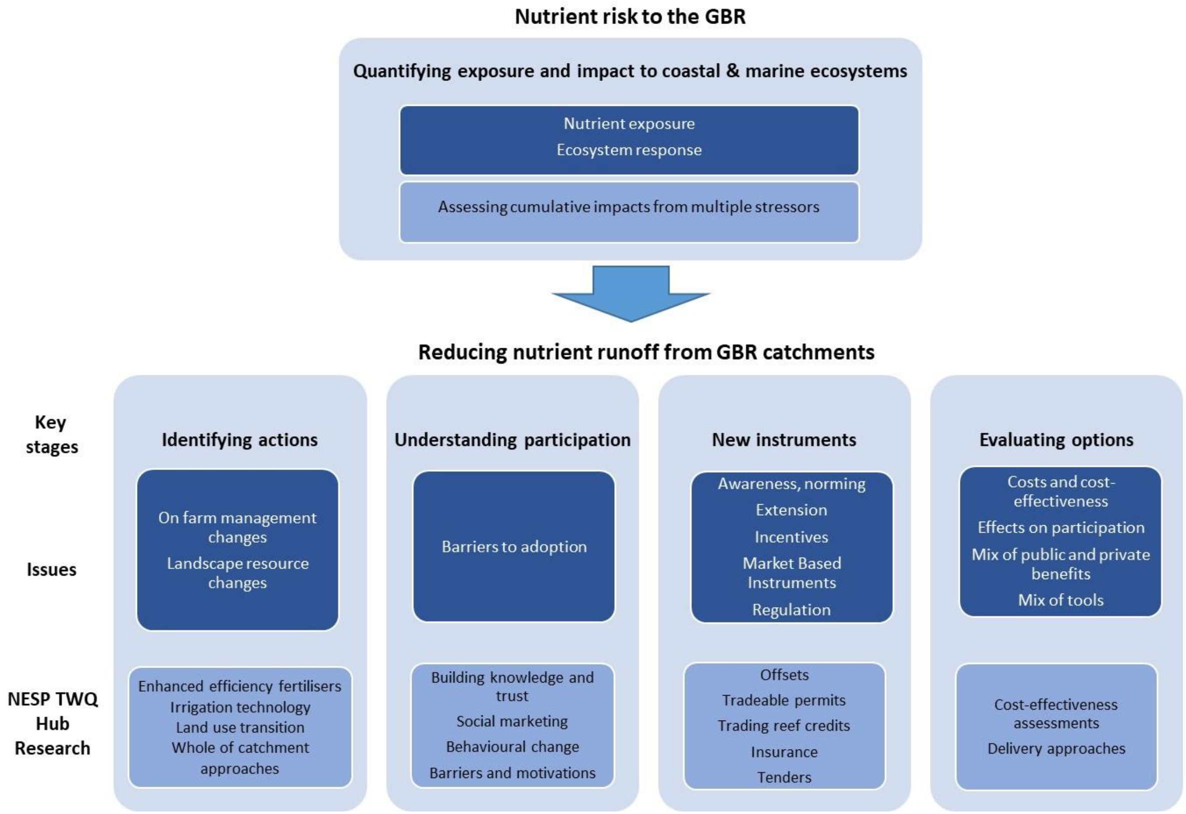

Figure 3. Framework for identifying where NESP TWQ Hub research contributes knowledge on reducing nitrogen losses to the GBR, highlighting the NESP catchment related research in four key stages.

In each of these four stages, NESP TWQ Hub research projects have addressed several areas of research listed below.

Identifying actions:

- Combined improved nitrogen (N) fertiliser technology using Enhanced Efficiency Fertilisers (EEFs) with fertiliser N rate reductions commensurate with productivity at the block/production zone, and assessed the effect on sugarcane productivity and DIN loss (Bell et al. 2021).
- Developed integrated decision support tools to allow scheduling and automation of irrigation practices in a trial in the Lower Burdekin (Wang et al. 2020).
- Explored cost effective options for land use transition in marginal sugarcane areas to reduce N losses (Waltham et al. 2017, 2020, 2021).

- Adopted a formal 'whole of catchment' approach, in recognition that there will be a limit to the nutrient input reduction by the majority of producers and that alternative approaches will have to be embraced (Davis et al. 2021).
- Piloted the mitigation of nitrogen losses by utilising existing drainage networks to enable first flush retention and diversion (Davis et al. 2021).

Understanding Participation:

- Established a real-time monitoring framework for design and implementation of fine scale water quality monitoring to identify pollutant generation hotspots in sugarcane (Davis and Waterhouse 2016) and to provide direct feedback to landholders about nutrient losses in their sub-catchments (Davis et al. 2021). The introduction of real-time monitoring supported extension actions and established a robust 'trust' framework to address concerns by producers regarding the accuracy of the water quality science. The outcomes also demonstrated how the water quality issue can be presented at a local scale, most relevant to farmers (Davis et al. 2021).
- Identified lessons to inform the design of future tender-based environmental funding programs, in order to improve participant satisfaction and ensure program effectiveness (Greiner 2015).
- Identified barriers and enablers of behavioural change in relation to agricultural run-off to encourage best management practice uptake amongst land managers (Hay and Eagle 2019, Rundle-Thiele et al. 2021).
- Provided guidelines for the development and modification of communication material in the agricultural-environmental sector with the aim of increasing uptake of water quality improvement programs in the GBR catchments (Hay et al. 2018).

New Instruments:

- Explored the application of a tradeable permit scheme for nitrogen between sugarcane farms in Wet Tropics catchments to promote nitrogen use efficiency and maintain sugarcane production under theoretical end-of-catchment load caps (Smart et al. 2016).
- Explored trading water quality credits in DIN or sediment between non-point source credit suppliers and point source credit buyers as a mechanism for facilitating cost-effective future economic expansion along the GBR coastline without impacting pollutant loads (Smart et al. 2020).
- Developed a prototype insurance product for insuring against the risk of lower sugarcane yields from reduced N rates (Thorburn et al. 2020).

Evaluating options:

- Assessed the cost-effectiveness of nitrogen reduction projects and programs, including considerations for site-specific influences (particularly soil) and other mechanism-related issues (Rolfe and Windle 2016, Rundle-Thiele et al. 2021). The cost-effectiveness of actions and programs (ratio of outcomes achieved to investment required) and effects on participation are the most useful metrics for evaluation.

A summary of this new evidence follows the structure of this framework in the following sections. The highlights are also summarised in Appendix 1, Table A1.

2.1 Nutrient risk to the GBR

Considerable research was undertaken through MTSRF and NERP to investigate the impacts, ecological thresholds and indicators for land-based nutrient inputs to the GBR. However, there were still significant gaps in our understanding regarding how multiple stressors, including nutrients, overlap in time and space, potentially reducing the overall health and resilience of the reef (Anthony 2016; Mellin et al. 2019). In the first round of NESP TWQ Hub projects, a review based on case studies of cumulative impacts of global and local pressures on coral reef organisms was conducted, showing that some important interactions such as ocean acidification, ocean currents and salinity or ocean acidification and pollution remained relatively poorly understood (Figure 4) (Uthicke et al. 2016). The authors concluded that future work needed to focus on understanding the interactions between 'manageable' pressures, specifically light/turbidity and sediment-bound pollutants (including nutrients), and 'global' pressures such as ocean acidification and ocean warming, with a list of research topics provided to prioritise and guide subsequent projects (Uthicke et al. 2016).

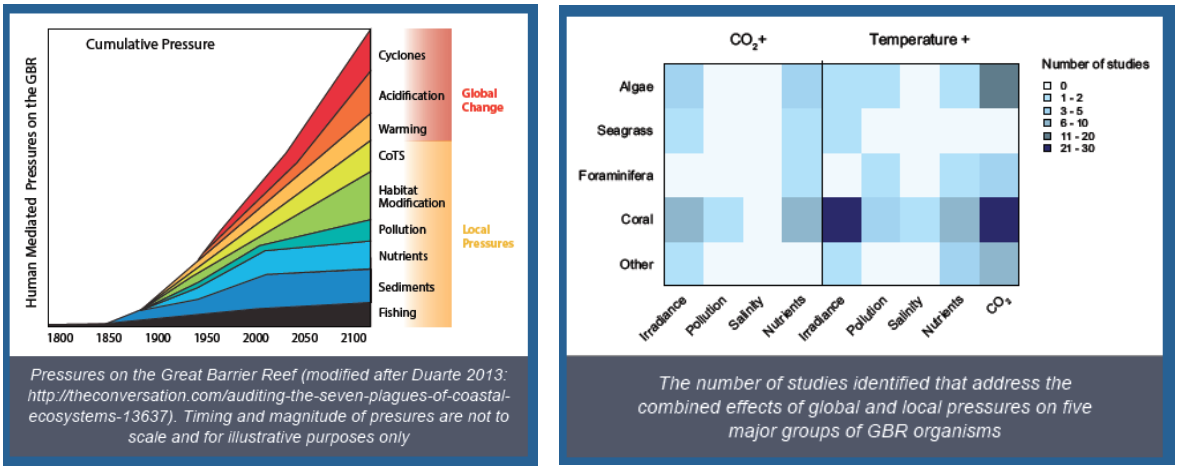

Figure 4. Cumulative pressures on the GBR (left) (modified from Duarte 2014 in The Conversation[11],) and number of studies identified for the combined global versus local pressures on five major groups of GBR organism (right). Source: Uthicke et al. (2016).

To develop effective ecosystems models and management strategies, several NESP TWQ Hub projects focused on developing pressure thresholds and levels of interactions for cumulative impacts affecting the GBR. Experimental assessments of concentration-response relationships were undertaken for selected habitat-builder organisms (i.e. corals, seagrasses, macroalgae and foraminifera) under local stressors (sediments and/or herbicides at a range of concentrations including those detected in the GBR) and different climate scenarios (Uthicke et al. 2020). Although responses depended on the organisms and response variable, the combined stresses created an overall worse outcome for the organisms than when pressures were applied in isolation. For instance, the combined effects of nutrient enrichment and elevated temperature on several life history stages of the coral *Acropora tenuis* showed an impact on fertilisation, thus affecting the overall larval supply and

[11] https://theconversation.com/auditing-the-seven-plagues-of-coastal-ecosystems-13637

recruitment of the species. However, there is a threshold above 32 ºC where temperature effects appear to dominate (Figure 5; Humanes et al. 2016).

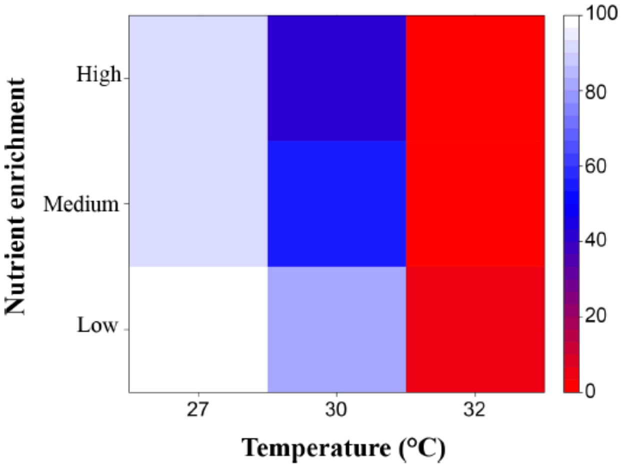

Figure 5. Total effect of nutrient enrichment and temperature on overall recruitment success (0-100%, as indicated in colour legend on the right) of the coral *Acropora tenuis*. Source: Humanes et al. (2016).

The linkages between water quality and the thermal tolerance of GBR coral reefs, and specifically their ability to resist and recover from bleaching events was further explored by Cantin, Baird, et al. (2021). Aquaria experiments at the AIMS National Sea Simulator facility (SeaSim) addressed which water quality parameters (i.e. nutrients, light, turbidity) affected corals' thermal tolerance and how temperature and water quality exposure histories affected coral bleaching and recovery. For instance, inshore corals had a lower bleaching response (i.e. higher tolerance) in experimental conditions, with less than a 50% decline in photosynthetic pigment content at high temperature, whereas the mid-shelf corals lost around 75% of pigments, suggesting a better adaptation of inshore corals to a wider range of temperature and water quality conditions (Cantin, Baird, et al. 2021). A literature review undertaken as part of this research identified that water quality is likely to influence coral health mostly through the cascade effects caused by excess nutrient availability (specifically the forms and ratios of nutrients, such as nitrogen and phosphorus), which causes the shift of symbiont algae from a mutualistic to a parasitic relationship. The study concluded that stable metabolic compatibility between the coral host and algal symbiont could ameliorate bleaching and increase resilience to environmental stress. Furthermore, historical nutrient conditions may influence host-symbiont metabolic capability, and therefore bleaching susceptibility (Morris et al. 2019). However, additional field studies and experimental research, showed that temperature is the major driver of coral bleaching nowadays, and that the effect of different water quality regimes was only evident at lower heat exposures, below the temperature increases experienced during recent bleaching events in 2016 and 2017. It was concluded that if oceans continue to warm, corals will increasingly experience significant heat stress at an intensity that is currently masking acute water quality effects (Cantin, Baird, et al. 2021). These findings were consistent with a previous study by Hughes et al. (2017) where water quality did not play a major role in bleaching response in the severe temperature event of 2016, after accounting for the intensive heat stress experienced during that bleaching event. They reported that results were consistent with the broad-scale pattern of the observed severe bleaching in the GBR which affected hundreds of reefs across inshore-offshore gradients in water quality, and regardless of their zoning (protection) status. This highlights the overwhelming stress of severe high temperature events on coral communities in the GBR, but also emphasises the role of water quality in the less severe events (e.g. lower temperatures or shorter exposures).

In support of making this sort of information on environmental pressures relevant to GBR management more accessible to decision makers, exposure maps for a set of 25 important environmental pressures (e.g. water quality, light, chlorophyll a, temperature, cyclones) in relation to coral cover, were also created and made available through an online interactive tool[12] in eAtlas. Examples of these outputs are shown in Figure 6 (Uthicke et al. 2020).

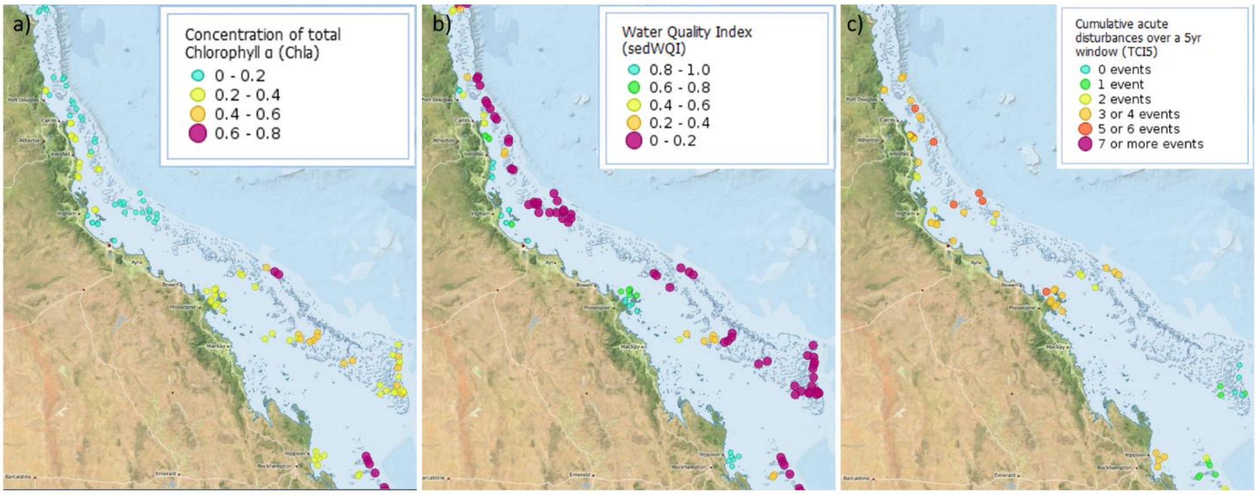

Figure 6. Example maps obtained thorugh the online interactive tool in eAtlas developed within Uthicke et al. (2020). In this case, the tool visualises (a) concentration of total chlorophyll a in mg/m^3 during the wet season (December to April) using eReefs data 2010-2017; (b) a water quality index (frequency of exposure to all river plume types (Primary+Secondary+Tertiary) as per Mathews et al. (2019); and (c) cumulative acute disturbances over a 5-years window using eReefs data 2012-2017.

2.2 Reducing nutrient runoff from GBR catchments

2.2.1 Current management

The main source of excess nutrients and fine sediments from GBR catchments is agriculture, which dominates land use areas. Monitoring and scientific modelling show that sugarcane is the greatest contributor to the DIN that is transported to the GBR, contributing 43% of the total load and 78% of the anthropogenic load (McCloskey et al. 2017). Grazing areas contribute approximately 23% of the total DIN load compared to 4% of the anthropogenic DIN load transported to the GBR, but this mostly originates from low concentrations of DIN over very large areas (Bartley et al. 2017). Other land uses, including urban, mining and industrial areas, contribute relatively small but concentrated pollution loads. For example, urban areas contribute 6% of the total DIN load and 9% of the anthropogenic DIN load. These land uses have a small spatial footprint, so the total load delivered to the GBR is comparatively small relative to the more widespread agricultural land uses. However, these localised sources may have important local impacts depending on the

[12] https://eatlas.org.au/gbr/nesp-twq-5-2-cumulative-impacts

characteristics of the receiving environment (Bartley et al. 2017). A large proportion of the particulate nutrients delivered to the GBR come from grazing areas, although sugarcane land-use dominates contributions in the Wet Tropics and Mackay Whitsunday regions. In sugarcane areas, particulate nutrients are most likely sourced from steeper areas and areas of bare ground between crop cycles. Widespread adoption of Green Cane Trash Blanketing is an effective mechanism for managing soil erosion in these areas. Regional contributions are described further in Bartley et al. (2017) and reported in the technical summary information for the annual Reef report cards[13].

Important new evidence from the NESP TW Hub in the Burdekin basin indicated that DIN can be generated from the terrigenous organic and particulate nitrogen pool from river flood plumes, via ammonium desorption and microbial processing (i.e. bioavailable nutrients) (Lewis et al. 2020). This finding is yet to be translated into formal end of catchment estimates of DIN contributions from different land uses and is a high priority for future work. However, given that the Burdekin Region is already a high priority for DIN reductions from the Lower Burdekin sugarcane area, and the Burdekin basin is a high priority for fine sediment reductions, this finding is unlikely to change the overall priority of pollutant reductions in the Burdekin Region.

This report largely focuses on the losses of DIN from sugarcane areas in the GBR. The export of DIN from sugarcane farms is related to several factors including the location in the landscape (e.g. coastal floodplain areas with high hydrological connectivity to coastal ecosystems, Karim et al. 2012, 2014) and the application of nitrogen (N) fertiliser in excess of the amount taken up by crops with DIN discharges correlated to N fertiliser application rates at all scales, from the field to the basin (Thorburn, Wilkinson, et al. 2013). Applying N fertiliser in excess of crop needs is not uncommon in high value crops, including sugarcane, to minimise the risk of crop growth and yield being limited by the availability of N. Thus, the primary and most well proven path to reducing DIN impacts on the GBR is to encourage farmers to better calibrate N fertiliser application rates to expected maximum sugarcane yields at finer spatial scales, and in relation to soil test results and other N inputs, thereby reduce application rates (Thorburn and Wilkinson 2013).

This has been recognised by Queensland and Australian governments, that have, since 2008, put in place two broad-scale activities to effect that change: (1) periodic regulation of N application rates to not exceed recommendations from SIX EASY STEPS (State of Queensland 2019); and (2) providing training, extension, agronomy services and financial incentives to facilitate voluntary adoption of improved practice through a range of Australian and Queensland government initiatives (e.g. Reef Rescue, Reef Program, Reef Trust and the Queensland Reef Water Quality Program). However, after more than 10 years of these measures and significant expenditure on encouraging sugarcane producers to reduce nitrogen inputs, this has failed to yield corresponding results with many farmers still applying N fertiliser above regulated rates, as shown by management practice adoption rates in successive Reef report cards (Australian and Queensland governments 2020). Alternate approaches to achieving greater DIN reductions will require further exploration within the policy sphere to meet the Reef 2050 WQIP end of catchment DIN targets.

[13] https://www.reefplan.qld.gov.au/tracking-progress/reef-report-card

Changes in land management can be complex to implement, and landholders often require extensive support to move to different triple bottom line management systems which may have different cost:benefit ratios, which in turn requires an understanding of the motives or barriers to change. For example, a move from sugarcane to alternative higher value crops will reduce the available tonnage for the local sugar mills, potentially resulting in mill closures and loss of processing infrastructure. Consequently investors require tools to identify where farmers may be reluctant to change, the reasons for slow adoption, and mechanisms to encourage greater participation and uptake.

Using the framework in Figure 3 the following sections describe the NESP TWQ Hub research commissioned to address these challenges, primarily focused on (i) identifying actions, (ii) understanding participation, (iii) new instruments and (iv) evaluating options.

2.2.2 Identifying actions

Extensive research on the most effective management practices for reducing N losses in sugarcane has continued in the GBR catchments for many years. The 2013 Scientific Consensus Statement provided a comprehensive review of the relevant literature (Thorburn, Rolfe, et al. 2013), building on the synthesis of Thorburn and Wilkinson (2013), and the 2017 Scientific Consensus Statement updated that knowledge (Eberhard et al. 2017). At this time, key practices such as a rationalisation of N application rates depending on factors such as soil types and local conditions, were highlighted as the most effective practices for reducing N losses in sugarcane. These priority practices have been adopted in the Paddock to Reef Sugarcane Water Quality Risk Framework and are promoted in the Queensland government Reef Protection Regulations[14] and current water quality investment programs such as the Queensland Reef Water Quality Program and the Australian Government's Reef Trust Partnership.

NESP TWQ Hub research has built on this knowledge with several targeted studies.

Improving N use efficiency

Minimising losses of fertiliser DIN to the GBR from sugarcane farming requires a combination of management strategies that collectively maximise crop recovery of applied N while minimising the risk of loss in runoff or via deep drainage. The large N requirement of sugarcane, coupled with an extended period of crop N uptake that can coincide with the monsoonal wet-season in northern Australia, makes this challenging. A five year NESP TWQ Hub research project (Bell et al. 2019, 2021) assessed whether a number of inter-related strategies could be used to maintain sugarcane productivity while improving fertiliser N use efficiency and minimising DIN loss in runoff and deep drainage.

The studies combined improved N fertiliser technology using Enhanced Efficiency Fertilisers (EEFs) with fertiliser N rate reductions that are intended to better match the crop demand in a productivity zone which can range in scale from intra-block, several blocks or whole farm. The trials included laboratory and field experiments. The laboratory experiments were

[14] https://www.qld.gov.au/environment/agriculture/sustainable-farming/reef/reef-regulations

conducted to better understand whether the performance of different EEF technologies was affected by application rate in concentrated sub-surface fertiliser bands typical of those used in the sugar industry. Field trials were undertaken in eight field sites from Mackay to Cairns using fertiliser N application rates that matched the productivity zone yield potential of the blocks in which they were tested and applied as urea or a blend of commercial EEF products. These practices were benchmarked against urea applied at rates calculated using the district yield potentials defined in the SIX EASY STEPSTM (6ES) nutrient management program (which represents current industry best management practice), and all sites hosted a treatment that received no fertiliser N. Traditional crop performance indicators were collected (sugarcane yield, Commercial Cane Sugar and sugar yield), in addition to crop biomass samplings and analyses that allowed quantification of apparent fertiliser N recovery and the efficiency of fertiliser N use. Runoff losses were quantified at sites at Freshwater and Silkwood, in the wet tropics, while the concentrations of DIN measured in deep drainage were also collected at Silkwood.

The results indicated that:

- Reducing fertiliser N rates applied as urea below those determined using the 6ES-district yield potential calculation by substituting yield potential derived from block records resulted in small and not statistically significant decreases in cane yields (3-8%) averaged over 3-4 consecutive ratoon crops. These yield reductions were consistent with a reduction in the amount of fertiliser N taken up by the crop. A 3-8% yield loss represented a profit loss in all instances, which could be considered unacceptable by industry. Changing from urea to EEFs offers a way to reduce N rates without any increased risk of yield loss, but EEF blend used in these studies cost more per kg of N applied, with the additional costs not able to be negated by the reduced rates applied. While this represents a cost to growers, further refinement of the EEF products and blends used (such as that being tested in EEF60) offers the possibility that cost-effective EEF products that de-risk productivity losses will become available in the future.
- Use of EEFs may allow reductions in N rates without significant risk to production, and this may lead to reduced DIN losses. However, effects will be site and season-specific and rely on the crop being able to capture the available N. Runoff varied between sites, seasons and treatments, with the EEF treatment resulting in Total N reductions in surface runoff and DIN loss in deep drainage varying between 30-80% and up to 90%, respectively, of that from urea at 6ES rates. It should be noted that DIN was not measured at all sites so Total N is reported. These water quality benefits were lessened or reversed if EEFs were used at the higher district yield potential rate, as the extra N retained in the soil could not be recovered by the crop during the wet season.

In addition to this work, NESP TWQ Hub research supported trials using concentrated bands of urea with and without coatings or inhibitors. Results showed that the band environment could potentially impact the efficacy of these products compared to when broadcast or incorporated sub-surface (Janke et al. 2019, 2020, 2021). The application of fertiliser N in highly concentrated bands typical of those used in the sugarcane industry changed the dynamics of N transformations in soil, and hence increased the window for crop N acquisition or environmental loss. The band environment increased the duration of nitrification inhibition and slowed the rate of N release from coated EEF products, both of which can influence the timing of N availability to the crop or prolong the period of vulnerability to environmental loss. These effects were accentuated under drier conditions and in heavier textured soils. The work also showed that the development of biodegradable materials to replace polymer coated EEFs will reduce the risk of introducing persistent bioplastics into the environment, but improvements in coat integrity are needed before reliable performance is assured. In summary, the interacting effects of application method, fertiliser product and environmental conditions mean that the relative efficacy of standard urea and the EEF products will vary, and so potential agronomic or environmental benefits will likely be site and season specific.

While the use of EEF technologies on their own did not provide substantial benefits in runoff water quality and could actually cause greater N runoff losses than urea when applied at high rates, their use did allow a reduction in application rates with a lower productivity risk. These project findings, albeit from a limited number of sites and seasonal conditions, were consistent with preliminary results emerging from a broader evaluation of these approaches in the Reef Trust Phase IV EEF60 project, which is very encouraging. More specifically, the EEF60 projected (funded by the Australian and Queensland governments, and managed by CANEGROWERS and SRA) comprised 60 trial sites, with results for three crop cycles indicating no yield loss with EEFs at 20% below 6ES rates (and comparable prices for the Nitrification Inhibitor EEFs applied at 80% of 6ES rates compared to urea at 100%)[15]. The study also provides water quality monitoring data at six sites, showing environmental losses related to the rate of fertiliser applied. The latter project is an example of the broader evaluation that is needed before this combination of management approaches can be confidently promoted to stakeholders as a reliable and low risk approach to the win-win of maintaining productivity and improving water quality through improved fertiliser nutrient use efficiency.

Further testing is needed to provide clearer guidelines to fertiliser manufacturers, industry and Natural Resource Management (NRM) bodies on which EEF technologies are most effective, which soil types and application times are most likely to deliver benefits from EEF use, the likely size of water quality benefits (an urgent requirement due to the variability between sites and conditions) and the extent to which fertiliser application rates can be reduced. Given the additional cost/kg fertiliser N applied as EEFs, more extensive testing of agronomic and environmental impacts of different combinations of EEF technologies and fertiliser application strategies (locations, rates and timing) will be needed before widespread government or industry investment in these approaches can be justified.

Decision support systems for improved irrigation management practices

Irrigation of sugarcane is a dominant practice in the Lower Burdekin sugarcane area, and is used to a lesser extent in the Mackay Whitsunday and Burnett Mary sugarcane growing areas. Because of the strong linkage between irrigation management and DIN losses (see for example, Waterhouse et al. 2018), managing DIN loss from these sugarcane areas must involve improved irrigation management and scheduling. Current adoption of low risk irrigation management practices is relatively low (see Reef Report Card 2019, Australian and Queensland governments 2020), and flood irrigation is the dominant practice. The challenge

[15] https://sugarresearch.com.au/wp-content/uploads/2020/08/CaneConnection-Spring-2020_F_web.pdf

is how to improve practices in a way that is both practical and profitable for farmers and accrues environmental benefits. Smart technologies like automated irrigation systems can offer a solution to this problem and refine farmer's knowledge and capacity to manage their system more efficiently.

IrrigWeb[16] is an example of a decision support tool that is used in the Lower Burdekin to support farmers in irrigation scheduling. It **combines crop water use estimates with user-defined irrigation system constraints and crop cycle inputs to schedule future irrigation events**. However, cropping irrigation systems are dynamic which means that IrrigWeb requires frequent updating to obtain precise irrigation scheduling. Farmers typically have more than 20 irrigation management units or fields, each requiring multiple irrigations for most surface irrigated fields (between 10 and 20 in the Burdekin region), to more than 100 irrigations for subsurface drip irrigation each year. As such, the time commitment to continuously update the information is a significant hurdle to ongoing use and ultimately leads to failed adoption practices because farmers do not have the time to do this.

WiSA[17] is an irrigation technology system that can **provide automation, monitoring and real time analysis**. It uses real-time weather, soil and environmental data from the farm to support automatic scheduling and can save farmers a significant amount of time by remotely turning on and off pumps and valves.

Unfortunately, neither of these systems on their own can ensure the amount and timing of irrigation required by the crop is appropriate to the crop needs. or how irrigation schedules should change with soil type, farm management and climate. Therefore another tool is required to integrate these capabilities. NESP TWQ Hub researchers investigated if the Internet of Things could make the two technologies of WiSA and IrrigWeb share data and work together as one tool, working with several sugarcane farms in the Lower Burdekin region (Wang et al. 2020). To do this a two-way communication channel was generated between the tools.

An **Uplink program** was developed to automatically upload the irrigation and rainfall data to IrrigWeb from the WiSA irrigation system. The results showed that a significant amount of time was saved via this process. Another benefit is that the farmer can co-learn from the decision support tool by observing the exact amount of water applied to each paddock, while comparing to the expected crop water use. The system also allows the farmer to make modifications to the irrigation management if required. Moreover, automating the data transfer from WiSA to IrrigWeb makes it easier for farmers, and thus, can motivate more farmers to adopt these types of technologies and accrue water quality benefits.

A **Downlink program** was then developed to connect IrrigWeb to WiSA, which can download, extract, calculate and apply irrigation schedules automatically. This step also saves the farmer time and successfully mimicked the IrrigWeb generated soil-water deficit for all fields. The simulation results demonstrated the Downlink program improved the scheduling by incorporating practical limitations, such as energy and irrigation system

[16] www.irrigweb.com

[17] https://www.irrigatewisa.com.au/

constraints, pumping capacity or pumping time constraints, irrigation priorities at a different time of the year and farmer irrigation preference.

Finally, an **Internet of Things-based irrigation monitoring system** was designed to monitor the implementation of the *smarter* irrigation system. In this stage, detailed information about the recorded irrigation event and rainfall data were collected. Moisture probe values and flow rate data were also collected as a quality control procedure to ensure the irrigation water applied by WiSA, matches the irrigation schedule suggested by IrrigWeb together with the adjustments which allow for practical on-farm constraints.

A real-farm trial was carried out for more than a year on the drip irrigation blocks, demonstrating that this *smarter* irrigation management system could reliably manage irrigation scheduling on a real farm. To the best of the knowledge of the research team, this is the first time an experiment of this type has been performed for any sugarcane system, anywhere in the world. The project demonstrated that s*marter* irrigation systems represent a solution to saving energy and improving water quality by transferring more farmers to low risk irrigation management practices[18]. It will save farmers time and money and allows farmers to automate record keeping of irrigation events thus enabling them to assess their improved irrigation performance. There is also the safety factor as the staff do not have to drive around the farm at odd hours turning pumps on and off. Despite these benefits barriers exist to wider adoption. Besides trusting and learning how to interpret new technologies, another major barrier is the capital outlay to purchase the infrastructure for automation. However, these studies indicated that there are large potential social and economic benefits that can recover these costs in a relatively short period (Wang et al. 2020).

The predicted water quality benefits of adopting the smarter irrigation practices included in this research were calculated using the [Paddock to Reef Projector Tool][19]. Using a range of scenarios, the estimated range of DIN improvements was from 4.8 kg N/ha/year up to 28 kg N/ha/year (end of paddock). With approximately 80,000 ha under sugarcane production in the Lower Burdekin area, the Projector estimated annual potential benefits of between 384 to 2,240 tonnes of N at the end of paddock. While an end of catchment outcome would not be as significant, this still indicates that smarter irrigation practices could make significant inroads to meeting the Burdekin sugarcane region's estimated DIN reduction target of 720 t/year (Waterhouse et al. 2018, noting that this excludes the DIN delivery from other land uses). The cost of these changes was not examined in this project but would largely be associated with the irrigation automation system and if applicable, installation of drip irrigation. These costs vary depending on the system and the location, but average around $1,000/ha if drip irrigation is already in place (Everingham, pers. comm.). These aspects will be assessed further in the additional work to be undertaken as part of the Reef Trust Partnership Water Quality Innovation Program, and opportunities for incentive programs to make this transition easier and less risky for producers should be explored.

[18] https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0036/78867/sugarcane-water-quality-risk-framework-2017-22.pdf
[19] https://p2rprojector.net.au/

Landscape scale actions

Management actions are required at a range of scales, and in addition to the studies identified above that are most relevant at a paddock scale, landscape scale actions such as land retirement, land use conversion or where possible, landscape restoration, are also necessary to achieve the Reef 2050 WQIP water quality targets. In a more novel approach to minimising DIN from reaching the GBR lagoon, Waltham et al. (2017) explored the most cost-effective options for retiring lower yielding, high DIN loss sugarcane areas in the Wet Tropics using a combination of spatial analysis and economic analysis.

The land use transition options considered included grazing (grass-fed beef fattening), tree crops, construction of wetlands to provide water treatment in runoff before discharge to receiving waters, and restoration of wetlands to provide services for aquatic ecosystems (such as fish habitat extension, or carbon sequestration).

In general, wetland restoration was assessed as being the most cost-effective when conversion costs were low (purchase and construction) and DIN removal capacity was high ($7-9/kg DIN reduced). Wetland restoration also had additional important ecosystem benefits, such as potentially carbon additionality opportunities or extended habitat for fish. An important assumption in these calculations, however, is that the intital costs to set up the wetland (for example, for water treatment) needs to be low for this action to more quickly return profit to landholders (Waltham et al. 2020).

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).

The key to cost-effective DIN reduction from transitioning to wetlands is to identify locations which offer a favourable combination of conversion cost and DIN removal rate. These locations will have to be identified at a site-specific level using appropriate local knowledge, for example understanding local hydrology (Wallace et al. 2020). Location is somewhat less critical to the cost-effectiveness of transitioning to grazing, but it will be much more cost-effective to convert to grazing on the soils that are 'leakier' with low sugarcane productivity. 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 et al. 2019), and end users need to be cognisant of the assumptions used in the framework when interpreting the results (Waltham et al. 2020).

Extension of this work into the Lower Burdekin and Mackay Whitsunday sugarcane areas showed that opportunities for reducing DIN losses through land use transition also exist in these regions (Waltham 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, which is another potential mechanism to provide more direct incentives for landholders. Revenues from sale of water quality credits could be used to offset some of the opportunity costs of land transition (Smart et al. 2020).

2.2.3 Understanding participation

The primary barriers to adoption of management changes in sugarcane areas have been studied in the past identifying important factors such as cost, lack of trust, fear of the loss of productivity, the need for greater knowledge capacity and technological limitations can influence the farmer's take-up of different management practices. Global experiences suggest that spatially identifying and prioritising landscape 'hotspots' of pollutant generation for management intervention, and small catchment-scale water quality monitoring in collaboration with landholders, are among the most promising strategies for reducing diffuse water quality pollution.

Building knowledge and trust

These factors were considered in the commissioning of NESP TWQ Hub research, resulting in a project specifically designed to addressed factors associated with lack of trust and building capacity for greater water quality outcomes. 'Project 25' adopted a combination of small scale monitoring and farmer participation and engagement techniques to influence management practice choices. The project was commissioned in response to a request by local farmers in the Russell Mulgrave catchments in the Wet Tropics region.

As a first step, **a robust framework was developed for the design and implementation of a sub-catchment scale monitoring, modelling and extension program in GBR sugarcane areas** (Davis and Waterhouse 2016). This framework highlighted the key features of successful smaller scale monitoring programs, referring to several case studies of local monitoring programs including Sandy Creek (Plane basin), the Herbert River catchment and the Lower Burdekin irrigation area (spanning the Haughton, Burdekin and Don basins). It identified minimum requirements for monitoring design depending on the program objectives and therefore standard required – termed as 'gold, silver and bronze' standards.

The necessity for integrating program outcomes into broader, concurrent water quality monitoring and modelling programs was emphasised and included examples of important aspects for doing this such as the value of expanding beyond concentration data to include flow (calculating loads), concurrent collection of agronomic data, appropriateness of design to meet objectives and mechanisms for industry engagement. The significant levels of time and local capacity investments and the resources required to implement these small scale programs were highlighted.

Building on these learnings, 'Project 25' was based around fine-scale, sub-catchment water quality monitoring in the Russell Mulgrave sugarcane growing area, and **utilised a 'bottom-up' approach to integrate sub-catchment monitoring and intervention to identify 'hot spot' sub-catchments through localised water quality monitoring** (Davis et al. 2019, 2021). The project emphasised industry ownership, and enabled growers to participate directly in the water quality monitoring design, overall management, delivery of locally targeted water quality data and extension effort. The ultimate goal was to facilitate improved practice changes within the sugarcane industry. The use of traditional, as well as emerging water quality monitoring approaches, and social research to identify mechanisms to maximise grower engagement with science, was intended to enable farmers to directly link their activities with catchment water quality conditions, while enhancing the capacity of some growers to act as leaders of change within their local farming community and networks.

A total of nine sites were initially selected for the monitoring program through the period 2016-2019, measuring a range of nutrient and sediment parameters. A combination of traditional monitoring approaches used in the GBR catchment (discrete sample collection for subsequent laboratory analysis during the dry season and in event flows), and emerging real-time (sensor-based) and continuous water quality monitoring approaches were used. The development of real-time information and feedback on local water quality dynamics was employed as a relatively novel approach to landholder engagement that was not fully explored elsewhere.

Project 25 addressed water quality science-farm management communication challenges through a collaborative model by:

- Collecting and presenting locally relevant data on agricultural impacts on water quality;
- Communicating data at appropriate spatial and temporal scales; and
- Developing local trust in the science and monitoring measuring water quality runoff and linking this to farming practices.

Participant feedback highlighted that having near real-time and visual evidence in the 'data' (e.g. DIN readings, rainfall data and river height at various points in the catchment), in particular, led to the articulation of farmer trust and confidence in the water quality science as partners in the Project 25 experiment. This confidence in interpretation of 'trustworthy' scientific information created the opportunity for growers to share and discuss experiences with neighbours, enabling peer-to-peer leadership. While provision of real-time water quality data was generally well received by the growers in a researcher-supported setting, the exercise revealed considerable variation in digital literacy and accessibility amongst growers. If such a tool was to be part of a future scaling strategy for the project model these capacity issues would need to be carefully assessed and considered.

An early indication of the engagement success of Project 25 was the willingness of participating stakeholders (particularly in industry) to support additional research into the sociological basis and outcomes from Project 25. An important evolution of the program was the addition of a major social science component in 2018 to better understand the human behaviour components to design, implement, and evaluate industry wide programs to understand the day-to-day challenges facing sugarcane farmers and to recognise, value and accelerate their efforts to adopt farming practices that help improve water quality. In addition, the 1622WQ™ app (Vilas et al. 2020) developed in the CSIRO Digiscape Future Science Platform initiative was used to help communicate water quality information to farmers.

The project generated many important findings for future practice change programs. In particular, the **grower participation outcomes** highlighted that:

- Establishing robust trust frameworks is important in delivering desired program outcomes and is important for dialogue between growers and scientists on a contentious topic.
- Improved communication, an improved trust environment with more direct oversight of monitoring data, and ‘space’ to learn and experiment were contributing factors to grower engagement in the project. The presence of meaningful and ongoing two-way communication between science and industry stakeholders, and two-way trust and recognition of the value of bridging on-farm knowledge with water quality monitoring data as critical to engagement was highly valued by participants.
- Direct involvement of growers enhanced the capacity of some grower participants to act as leaders and influencers within their local farming community and networks. Members of the project Steering Committee regularly advocate the rationale and benefit of the project in public and particularly in industry forums, where the project is framed as a means to demonstrate social and environmental responsibility of the local industry to the public; and to contribute to local self-regulation.
- There was clear evidence of progress of change in participant’s behaviour - from early stages of agenda building and collaboration; to the co-production and assimilation of new knowledge about consequences of nutrient management; to modifying practices on their own farms; to farmer participants advocating for and setting standards of behaviour amongst their peers.
- There was evidence of change in the collective thinking or group norms within the broader farming network associated with the implementation of Project 25. Farmers shared their learning with their farming peers and were developing greater levels of trust in the water quality science outputs. Extension advisors and farmers involved with the project also articulated evidence of change in that they felt confident about taking water quality data and learnings more broadly to the industry.
- It was emphasised that establishing these collaborative relationships and frameworks for behaviour change takes time, is resource intensive and multi-disciplinary (expertise in water quality, sensor-telemetry, IT, user experience etc.). Broad program results align with growing calls for recognising the input of various stakeholders and forms of research within the process of research and development.
- The interpretive materials from the 1622WQ™ app (Vilas et al. 2020) helped growers understand links between runoff following events and N in local waterways.

The project also generated several notable technical, biophysical or program design outcomes relevant to future water quality management programs. For example, monitoring of sub-catchment Nitrate-N loss dynamics reiterated that some of the highest nitrate-N concentrations, and a significant proportion of annual nitrate load losses from sugarcane-dominated catchments, can often occur in the first 3-4 significant rainfall-runoff events of the year (usually between October-December in wet-tropical catchments of north Queensland, such as the Russell Mulgrave) (Figure 7). The results suggest that, the **first flush** phenomenon can occur in agriculturally dominated catchments and depending on the timing of fertiliser application and size of the runoff event, the concentrated initial load loss process may provide an important potential intervention point for the management of diffuse pollution. For example, such (relatively small) flushes could be held within the drainage system (e.g. in agricultural ditches, which are prevalent across the GBR catchment area) or associated wetland systems that provide sufficient time for biochemical transformation or uptake of nitrogen, prior to the larger, major wet season runoff events. Similar concepts are being implemented worldwide (Kröger et al. 2014, Mander et al. 2017, Tournebize et al. 2017). However, additional research is required on the ability of different wetland and drainage systems to trap pollutants in the hydrological and climatic conditions of the GBR catchment (i.e. with extreme rainfall volumes and rapid catchment transit times).

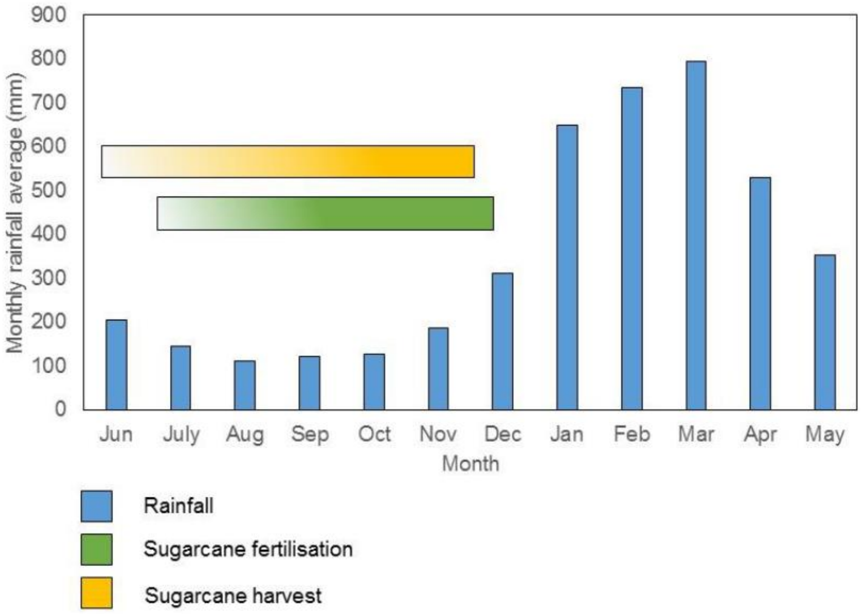

Figure 7. Temporal distribution of key sugarcane farming activities in relation to monthly rainfall averages under typical harvesting and weather conditions. Source: Davies et al. (2021)

In addition to providing a mechanism for generating specifically relevant evidence and information about runoff at various scales, smaller scale monitoring programs support definition of pollution generation 'hotspots' and to help maximise intervention efficiency. The water quality monitoring program provided clear capacity for DIN 'hotspot' identification in the broader Russell-Mulgrave catchment, and sub-catchment areas consistently responsible for generating relatively high nutrient losses emerged with ~3 years of monitoring effort. These are focus areas for additional fine scale monitoring, extension and engagement effort from industry support programs.

The core elements or principles of the Project 25 design are transferable to other groups of growers or locations in the GBR catchments. Importantly, the Steering Committee farmers took time to begin to share their new knowledge with other farmers in the region. This was part of the process of building trust with the researchers and advisors involved during the project and simultaneously building enough confidence in what the water quality data was showing. There was also evidence of a pattern of farmers participating in Project 25 to identify strongly with the range of benefits of the project, and with the possible benefits from wider application of the project model to other districts.

The project showed that **demonstration of locally relevant farm-scale impacts on the environment, loss of nutrients (itself a dominant economic input cost for many agricultural commodities) and capacity for active management, may provide powerful landholder motivations for practice change.** The capacity for farmers to monitor, adaptively trial and develop their own innovative and locally specific farming practices could provide much of this empowerment and confidence in adopting meaningful practice change. Translating this new quantum of data and information into forms that are accessible, coherent and understandable to target stakeholders such as farmers also presents a significant challenge, and requires substantial collaboration between water quality scientists, farmers, information systems experts and extension staff now and into the future.

The role of social marketing and behaviour change

NESP TWQ Hub projects investigated the role of **social marketing and behaviour change in improving GBR water quality** (Hay et al. 2018, Hay and Eagle 2019). More specifically, the projects aimed to inform the design of marketing and engagement approaches associated with water quality improvement strategies so that they better match the motivations, values and other social characteristics of land managers in the GBR. The project also sought to identify barriers to, and potential enablers of behavioural change in relation to agricultural run-off and thus to encourage best management practices uptake amongst land managers.

Key **barriers** identified included (Hay and Eagle 2019):

- Conflicting information and changing advice over time;
- Distrust of government agencies and certain denial on the link between their activity and environmental impacts (Figure 8);
- Lack of tailored communications for different personalities (Figure 9);
- Resistance of some extension officers to change;
- Uneven coverage of land manager properties by extension officers; and
- Complexity of applications and perceived unfairness of funding initiatives.

Key '**enablers'** (i.e. factors that may encourage uptake) included (Hay and Eagle 2019):

- Discussion of research findings by someone within the community;
- Upskill extension officers in social marketing;
- Ensure communications send consistent and integrated messages and preferably from trusted sources;
- Develop systems for monitoring and analysing messages and minimising conflicting messages;
- Tailor information strategies according to land managers preferences (Figure 9);
- Incorporate long-term relationship management strategies; and
- Develop specific strategies for engaging those who are less committed to adopting recommended best land management practices.

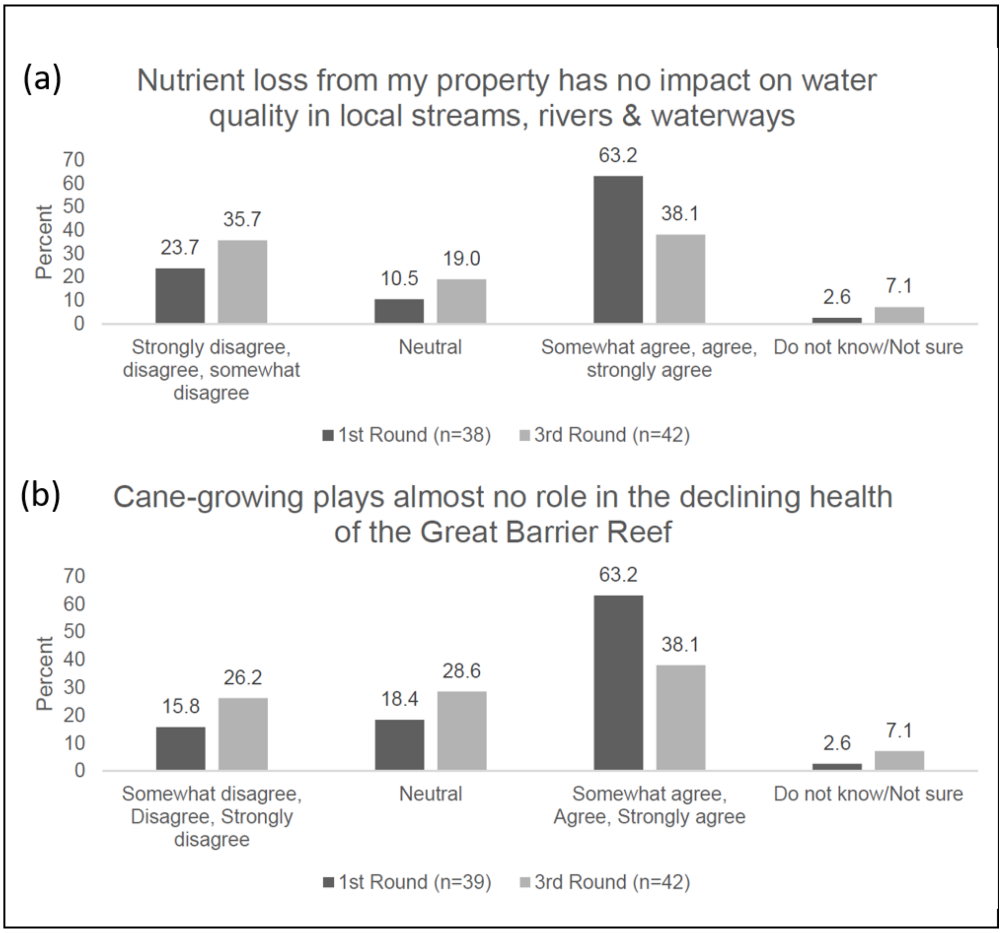

Figure 8. Examples of responses from Burdekin sugarcane land managers about (a) nutrient loss from their property impacting local streams, rivers and waterways, (b) the role sugarcane growing plays in the declining health of the GBR. Source: Hay and Eagle (2019)

This project additionally provided **guidelines for the development and modification of communication material in the agricultural-environmental sector**. Main issues identified included complex language, message tone and unintended effects of certain visual imagery. Recommendations included:

- To use a two-way communication strategy;
- To use social marketing tools;
- To write material at no more than grade 9 school level;
- To identify and work around prevailing social norms; and
- To follow certain principles of design (e.g. updated content, credibility of spokesperson, useful visual imagery).

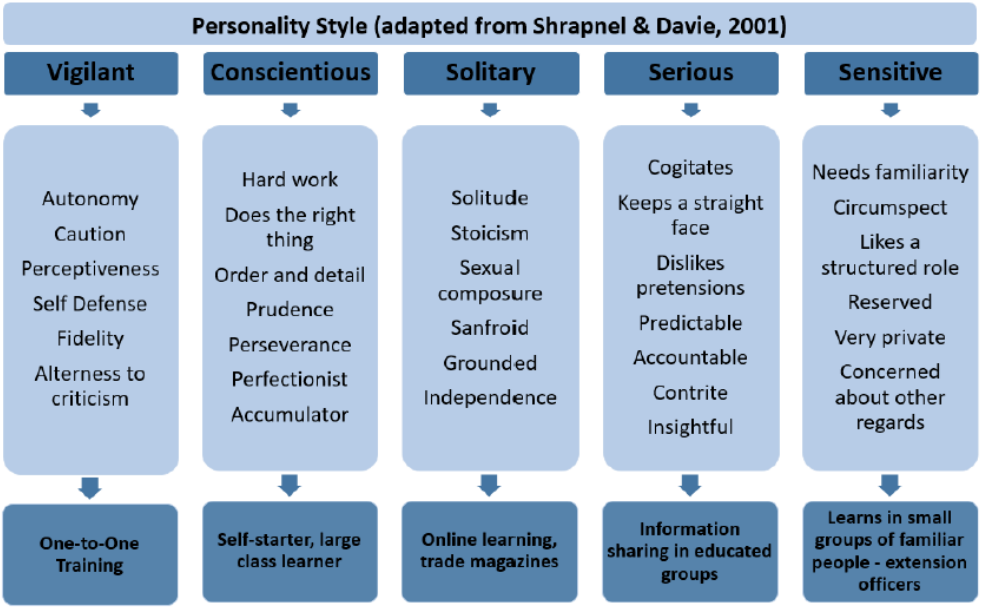

Figure 9. Farmer typologies and learning preferences. Source Hay and Eagle (2019)

The project concluded that improving the way projects communicate and get buy-in from land managers can help to ensure greater project uptake, associated positive results and lasting behaviour change (Hay et al. 2018).

Rundle-Thiele et al. (2021) additionally explored **enablers and barriers to farming practice change adoption**, including a range of demographic, psychographic, financial, information and communication, extension support, training, and farm management factors (Table 1). Researchers suggested a list of recommendationis to enhance efficience of funding programs in the sugarcane industry, such as:

- Fostering shared responsibility: Localised evidence is needed so that all stakeholders involved feel ownership of the problem.
- Upskilling extension support services: Stakeholders identified the need for advisors to provide consistent advice with guidance focused on optimising change outcomes and farming practices. A quote from the workshop emphasised the need for better trained advisors: "*We need an army of trained, trustworthy, available, agronomic advisors, who are able to offer ongoing service and support, as well as offering consistent advice*". Moving forward, extension support officers need training to build a skill set in identifying farmer needs and they will need to be able to deliver **tailored** support (Figure 9). Upskilling could involve workshops, seminars and training sessions that are focussed on farmer orientation (seeing it through their eyes to understand what message needs to be delivered), enhancing **communication effectiveness** (ensuring messages are tailored to farmers and emphasise the benefits (e.g. improved profit of recommended changes), and ensuring a positive farmer experience (e.g. monitor farmer awareness of key issues, measure farmers satisfaction with services provided) (in accordance with Hay et al. 2018 and Hay and Eagle 2019).
- Change communication practices: There is a need for positive stories, which can deliver hope and inspiration for others; and more simplified information (i.e. translate

scientific papers and dense reports into accessible forms that ensure the message is received), as also suggested by Hay et al. (2018).

- Change industry leadership practices: Strong advocacy from leaders in industry is needed to acknowledge that pesticide and nutrient reduction is a necessity and that industry is taking ownership and is part of the solution.
- Change evaluation practice, from a ‘prove’ mindset towards an ‘improve’ mindset, focusing on learning from experiences gained to understand which improvements are needed to extend program success. Evaluations should be undertaken throughout the project, not just at the end, to avoid costly mistakes through early identification of approaches that are not working. Recognise all stakeholders shared responsibility using mapping methods such as ‘Creating Collective Solutions’. . Use of ‘dynamic approaches’ for outcome evaluation (i.e. identifying rates of change and drivers of positive and undesired change). Coordinated evaluations (farmer-focused, not project focused) led by an independent third party which no involvement in the sugar sugarcane sector are recommended) (Rundle-Thiele et al. 2021).

Table 1. Summary table of the barriers and enablers of lasting behavioural change in the sugarcane industry. Within each theme, specific barriers/enablers are ranked by importance based on the proportion of project outputs indicating the factor. Modified from Table 3 in Rundle-Thiele et al. (2021).

Theme	Definition	Barriers	Enablers
Financial support & Market forces	Financial outputs and inputs	• Lack of money • Lack of government funding • Misplaced resources • High up-front costs • Access to cash	• Improved financial returns • Financial support • Diversified income • Market forces: Commodity pricing • Branding and image • Household income
Information dissemination	How the information is communicated	• Low/no communication between stakeholders • Failure to deliver communication that farmers need and value	• Bridging science and practice delivering access to scientists • Clear communication • Significant amount of data and knowledge on the GBR
Farmer & Farm characteristics	Farmer’s demographic and farmland’s geographic characteristics	• Lack of resources	• Natural resources • Farmland characteristics • Farmer demographics • Land/stock ownership
Institutional setting & Regulations	Government regulations and institutions interests/ agenda	• Lack of repercussion	• Regulation and policy • Institutional structure
Stakeholder interactions	Interactions and relationships between two or more stakeholders	• Industry influence • Lack of holistic approach • Stakeholders’ competing interests • Lack of leadership	• Collaboration • Peers • Training and education • Community led • Social norms
Farming practice	Factors related to the farming operation and management	• Time • Lack of innovation • Lack of leadership	• Business management • Technical aspects • Labour availability
Beliefs Attitudes and Individual Capabilities	People’s awareness, knowledge, capabilities, what people think, feel, believe and can already confidently do	• Preferences • Resistance	• Trust • Knowledge • Skillset • Perceptions • Motivation and interest • Outcome expectations • Experience with the promoted practice

2.2.4 New instruments

The selection of instruments for water quality management in the GBR catchments is specialised and depends on the type of problem being addressed. Several strategies can be adopted including education, extension, incentives, market-based instruments and regulation. In the past, investment programs in the GBR have largely been focused on incentive programs (in the form of landholder grants), supported by extension, training and education programs (see Eberhard et al. 2017). The current Queensland government Reef protection regulations (State of Queensland 2019) started on 1 December 2019[20]. For sugarcane, this includes requirements for record keeping to demonstrate that activities on the property are being undertaken in accordance with the minimum practice agricultural standards and all uses of fertiliser and agricultural chemicals on agricultural land.. Minimum standards are associated with the amount and methods of fertiliser application, soil testing, and maps of soil types to define and apply N according to management zones. By 1 December 2021, all sugarcane producers in the Wet Tropics, Burdekin and Mackay Whitsunday regions must have a farm nitrogen and phosphorus budget, and in the Fitzroy and Burnett Mary regions by 1 December 2022. An environmental authority permit is also required if commencing new or expanded commercial cropping activities on five hectares or more from 1 June 2021. Permits are required for any commercial crop which is cultivated, harvested and sold off-farm for a fee or reward, including crops, sugarcane, horticulture, biofuels, fodder and pasture seed.

While investment in incentives, extension and education programs continues in the GBR catchments, market-based approaches are also becoming more attractive to investors. Market-based approaches also have the potential to help alleviate landholders' resistance to change because they could provide farmers with a source of income to offset the possible losses in profits from reducing N fertiliser rates (Thorburn et al. 2020). One approach trialled, "reverse auctions" (referred to as the **Reef Trust Tenders**) that helped to fund farmers' changes in N fertiliser management by having the government "purchase" reduced N fertiliser rates over a period of time (e.g. 3 years). The assumption is that this period of reduced N rate trialling by the farmer will demonstrate that the practice is sustainable in terms of maintaining yield (with appropriate management practices in place) and will therefore continue after the payments have stopped. There is evidence that some farmers involved in the tenders have adopted the lower rates over larger areas of their farms than contracted, supporting this proposition (Greiner 2015; see also Section 2.2.5). The scheme is also competitive between farmers, with only the most cost effective bids accepted and farmers choose their own strategies to ensure yields are maintained. However, paying for management changes through the provision of public funds, whether through reverse auctions or other means, may not be attractive in the long-term. As another example, the success of Reef Trust N Tenders with innovative farmers has led to the development of a similar commercial scheme, the Reef Credit Scheme[21]. Approved methodologies include N reduction in sugarcane by developing and monitoring farm budgets for N and P, and gully rehabilitation. To date, two investors in Reef Credits are Queensland Government and the overseas bank HSBC. Given the large variety in farmers' interests, catchment characteristics

[20] See https://www.qld.gov.au/environment/agriculture/sustainable-farming/reef/reef-regulations/producers/sugarcane
[21] https://www.reefcredit.org

(both physically and culturally) and political interest, there is a need for additional approaches.

NESP TWQ Hub research has explored several approaches that could be considered by investors in the future for facilitating water quality improvement in the GBR catchments.

Offsets

Biodiversity offsetting provides a mechanism by which the permitted environmental impacts of certain projects or practices are compensated through conservation activities that yield a gain at least equivalent to the impact. NESP TWQ Hub research designed a **draft calculator to determine the amount of money that proponents would pay when voluntarily using the Reef Trust as an offset provider** (Maron et al. 2016). The prototype calculator is a transparent and easy-to-use spreadsheet style tool that considers (i) surrogates (matters of national environmental significance that are likely to be impacted by proposed projects); (ii) surrogate condition factors (accounting for the ability of habitats/species to respond to conservation actions); (iii) implementation costs; (iv) time delay (time difference between impact and benefit from offset activity); and (v) administration fees. This new approach was adapted to the GBR context and could significantly increase the likelihood that marine biodiversity offsets are successful (Maron et al. 2016). While not specifically relevant to nutrients, this calculator could be applied for future offset projects.

Nitrogen trading

Trading nitrogen at a farm scale through a permit scheme is potentially an innovative way to increase sugarcane production under a fixed cap on the total amount of N emissions, via a tradeable allocation of emission permits among polluters. Key elements of any successful water quality-trading scheme are the establishment of a regulatory cap, clear identification of the pollutants to be traded and geographic trading area, development of trading rules and supportive institutional structures. A trading approach between sugarcane producers was explored as a potential mechanism for N management in sugarcane under an end of catchment DIN load cap in the Tully catchment (Smart et al. 2016).

A spatially explicit model of DIN permit trading was constructed under the regulations that were in place at the time the study was conducted (2015 - 2016). The model of DIN permit trading between sugarcane farmers was driven by variation in DIN losses and gross margins on different soil types under different N application rates. In this model, sugarcane farmers were given a uniform per-hectare allocation of DIN permits, such that the sum of these initial allocations matched an end of catchment total DIN load cap. Sugarcane farmers could bid to buy extra permits if they knew their gross margin would increase if they were able to apply more N. However, those permits would have to be offered for sale by another sugarcane farmer who was willing to reduce their DIN emissions below their initial allowance (either by reducing fertiliser applications, or by converting some sugarcane land to nitrogen treatment wetland). Trading would only take place if the price a buyer was willing to pay for additional DIN permits exceeded a supplier’s asking price for selling DIN permits. Buying and selling N was managed through a ‘smart market’ to coordinate trading across the catchment and maintain the overall DIN load cap by ensuring that the total of DIN buy:sell trades ‘balanced’ at end-of-catchment.

The results showed that, using the soil-type specific DIN losses and gross margins published by van Grieken et al. (2014), there was sufficient variability in gross margins and per hectare DIN loss across sugarcane farms in the Tully catchment to drive an active trading market, with more than half of the participants buying or selling N-permits in a range of simulations. It also showed that gross margins were increased through trading.

The spatial modelling also indicated that a N trading market could deliver improved targeting of management and resource changes. The trading price for N-permits incentivised sales of permits from locations where they produced more DIN losses – and typically generated lower sugarcane yields – to locations where they produced lower DIN losses – and typically generated higher sugarcane yields. Consequently, (for a given end-of-catchment DIN cap) as a result of N-permit trading nitrogen use efficiency increased, and the gross margins realised by sugarcane farmers increased - allowing for the payments that changed hands as N-permits were bought and sold. Since market action, under a given DIN load cap, produced a spatial redistribution of DIN losses away from lower yielding land, it is likely that total sugarcane production would also increase due to market action – although this outcome was not evaluated in the study. Market simulations were run with different overall DIN caps for the catchment to investigate performance under a different scenarios. If a trading scheme was introduced, the market price for N would increase as the cap tightens, so conversion of marginally productive sugarcane land in key locations to wetlands would become more economically viable. This approach could reward growers who can most effectively reduce their N pollution and maximise production on better soils. It could help incentivise innovation and implementation of existing best management practice and new approaches. While NESP TWQ Hub research proved that the concept of N trading between sugarcane farmers could work, further research would be required to fully understand farmers' capacity and interest to participate in such a scheme. This research was completed in 2016 and subsequent revisions to the Reef protection regulations (State of Queensland 2019) do not currently allow growers to apply N applications in excess of prescribed best practice, thus removing potential demand for purchase of N permits by other farmers. This does not, however, preclude purchase of DIN reductions via other crediting mechanisms such as the Reef Credit Scheme.

Further research in this area went on to examine **the potential for point to non-point trading of N in key catchments and among urban, industrial and agricultural sectors** (Smart et al. 2020). It specifically investigated how trading in water quality credits could help facilitate future economic expansion in the GBR catchments, without jeopardising improvements in GBR water quality.

The study considered potential supply of DIN credits by agricultural landholders through voluntarily undertaking (i) improvements in fertiliser management practice in sugarcane production, (ii) setting aside less productive sugarcane land, (iii) constructed nitrogen treatment systems (i.e. landscape and constructed treatment wetlands and bioreactors), and (iv) reducing bioavailable nitrogen via reductions of fine sediment loads.

Using catchments in the Wet Tropics as an example, fine spatial scale predictions of reductions in DIN loss showed that full adoption of the Reef protection regulations (described above involving widespread adoption of 'Minimum Standard' i.e. P2R Moderate risk (C class) nutrient management practice) could deliver considerable reductions in end of catchment DIN loads. The next step of sugarcane practice change from 'Minimum Standard' to 'Best Practice' (i.e. P2R Moderate-Low risk (B Class) could provide further DIN reductions at costs of $8 - $50/kg DIN (at end of catchment). Initial cost data from N treatment systems constructed under the Wet Tropics Major Integrated Project, together with representative average DIN removal rates from the literature, suggest that constructed and landscape N treatment wetlands in the Wet Tropics are potentially able to supply DIN reductions at a cost of ~40 – 60 $/kg DIN, with 1ha of wetland potentially supplying 550 - 750 kg of DIN credits annually[22]. Although there is still large uncertainty about the cost-effectiveness of wetlands, these estimates were also supported by work undertaken by Waltham et al. (2017). Therefore in sugarcane catchments, in the future it appears likely that, post-adoption of ‘’Moderate-Low Risk’ (B class) nutrient practice, constructed and landscape treatment wetlands could provide a low cost source of N reduction and thus a low cost source of nitrogen credits.

Sewage Treatment Plants (STPs) and aquaculture facilities are licensed point source N emitters and potential buyers of DIN credits sourced by agricultural landholders. Assessment of the demand for N credits from these point sources indicated that if older-specification STPs sought to purchase DIN credits to avoid the need for upgrading to a de facto discharge standard of 5 mg N/L, this could generate sizeable (up to 260 tonnes) annual DIN credit demands at prices in the range $45 – 100 /kg DIN from STPs as far south as Rockhampton, and up to 25 tonnes of demand at $150 – 500 /kg DIN from Bundaberg. STPs that already deliver 5 mg N/L discharge performance but are approaching their capacity limits due to population growth may also seek to buy N credits as a temporary measure to defer the cost of capacity augmentation. Given that prices for credit demand could exceed prices for credit supply, there is potential for an N-trading market between point source buyers and diffuse source suppliers of N-credits.

An important consideration for decision makers in the adoption of a trading scheme is **whether DIN credit trading can help deliver DIN load reductions, ideally at relatively low cost**. The study showed that this depends on who buys the credits. For example, if the DIN credits are bought by 'emitting buyers’ because they provide a cost-effective way of offsetting un-mitigated emissions that would otherwise be in excess of licensed or regulated discharge limits (e.g. aquaculture, STPs, urban development), then trading will not significantly reduce total DIN loads. In this instance, offsetting excess emissions via DIN credit purchases simply reduces the cost of maintaining catchment DIN loads by offsetting emissions which would otherwise push the total end of catchment DIN load above its current level. This is a very important outcome for the longer-term application of a trading scheme, and in the context of future expansion assuming that the current targets could be met. However, if the DIN credits are purchased by 'non-emitting buyers' who do not emit DIN load into catchments that drain into the GBR lagoon, then these DIN credit purchases will deliver overall DIN load reductions in-catchment provided that robust and sufficient monitoring and reporting is in place. This is the market opportunity currently being developed by the Reef Credits scheme. Presently, there is limited knowledge of how much these non-emitting

[22] Peer-reviewed esimates of DIN removal rates and corresponding cost-effectiveness results for treatment wetlands along the GBR coast willbe available during the final quarter of 2021 or early 2022.

buyers are willing to pay for DIN credits. If the amount is in the order of $10 – 50 /kg DIN or higher then Smart et al. (2020) consider that this market could stimulate supply of substantial quantities of DIN credits (i.e. DIN reductions) via the ‘Minimum Standard’ (Moderate Risk, C Class) to ‘Best Practice’ (Moderate-Low Risk, B Class) step in sugarcane nutrient practice, and/or from appropriately located farm-scale constructed treatment wetlands.

The study also examined the factors to be considered in implementation of a trading scheme under current legislation and highlighted the potential challenges from the perspective of credit buyers and suppliers. A suggested market configuration was proposed, building on the framework of the existing offset schemes and identifying the roles of all levels of government, regulators, buyers and suppliers. Additional requirements were also identified including improved finer scale quantification of N losses from different land uses (transport pathways from paddock to reef especially via drainage, delivery ratio, equivalency ratio and environmental integrity), launching a scheme at scale and options for in-catchment monitoring technology. Overall, **it was concluded that water quality credit trading in N offsets has the potential to be an important facilitator of cost-effective future economic expansion along GBR coast, with no net decline in water quality, noting that substantial investment would be required to establish a trading scheme**.

Underwriting risk

As described above, the export of DIN from sugarcane farms is related to the application of N fertiliser in excess of the amount taken up by crops. This overapplication above predicted crop uptake is a justified response, as demonstrated in the studies conducted by Bell et al. (2021), where reducing N application below the rates recommended in Six Easy Steps resulted in reductions in crop yield in some locations. **Insurance is an instrument commonly used to mitigate risk**, and Thorburn et al. (2020) examined whether insurance could be an enduring instrument, that does not depend on public funding, **to help farmers manage the risk of reducing N applications below current rates**.

The opportunity for insurance exists because most farmers over-estimate the risk of yield loss compared with the real risk and the money saved by the farmer on reduced N fertiliser effectively subsidises the premiums. Further, as N fertiliser management of sugarcane is now regulated in the GBR catchments there is now some pressure for farmers to reduce N fertiliser application rates to meet the regulated standard and explore new risk-management strategies.

In this research, **a prototype insurance product was developed for insuring the risk to sugarcane yield from reduced N fertiliser application rates**. This followed review of existing crop insurance products to gauge their suitability for this application. Products existed for specific perils to crops (e.g. hail, or fire), adverse weather (e.g. inadequate rain), low crop yields and low farm income but none of these were suitable for the problem of N insurance.

To create an insurance product, it is necessary to be able to quantify the risk of loss (in this case the size and frequency of sugarcane yield loss due to N reduction), develop a technique for assessing the size and value of the loss, and estimate the variability in total losses and thus claims likely to be paid out. A range of products were investigated. A parametric product was selected to overcome some of the critical problems associated with more traditional crop insurance products and because it is efficient to administer and deliver. The essence of a parametric approach is having both the risk of loss and the assessment of loss linked to an "index" that cannot be affected by the insurer or insured. To support this feature, a *Weather Derivative Index* was developed, where yield loss from reduced N fertiliser is simulated with the APSIM cropping systems model for specified biophysical and crop management attributes (other than N rates) using weather as an input. In an effort to provide more practical examples and better communicate to farmers , empirical approaches to quantifying risk were also investigated but proved to be impractical. The conceptually complex parametric approach, requires additional effort in ensuring understanding and trust is built amongst the providers and sugarcane farmers. To assist with this potential challenge, sugarcane farmers, Canegrowers and insurance companies collaborated in the development of this prototype product, providing a solid base for its development.

It was estimated that if insurance facilitated a 30 kg ha^{-1} reduction in N applied to 180,000 ha of sugarcane (~50% of the area under sugarcane in GBR catchments) it would result in a reduction in DIN discharge of ~1,000 t yr^{-1} (assuming a delivery ratio of 0.2).. In addition, indicative pricing showed that there were many situations where premiums were less than money saved on fertiliser.

The product was tested with farmers via participatory rural appraisal processes, with positive responses including comments from farmers. **Feedback from international crop insurance companies indicate that the prototype product is conceptually sound and could potentially be developed to commercial reality, however questions about pricing and demand require further consideration**. Establishing commercial viability of this prototype product will require considerable effort to build understanding of, and trust in the product amongst farmers to ensure a large enough pool are willing to participate. From a commercial perspective, there are many barriers to establishing new agricultural parametric insurance products, including unknown demand and high setup costs. Further, if a new product is successful, it may be easily replicated by other companies making it hard for the originator to recoup costs. Compounding these problems is the small potential revenue, by global standards, of sugarcane N insurance in GBR catchments. Thus, while insurance is potentially a very useful tool for helping reduce N rates and protect the GBR there are substantial barriers to companies creating the product by themselves. These barriers warrant further investigation as this insurance product could provide an enduring market-based risk management tool that supports sugarcane farmer behaviour change and water quality improvement. Further funding through the Reef Trust Partnership Water Quality Innovation Program[23] will assist to progress assessment of this product for N reduction in the GBR catchments.

2.2.5 Evaluating options

Evaluating the best available management options and approaches for reducing N losses to the GBR requires considerable knowledge and effort. Some of the most important outcomes of policy and program changes are associated with levels of engagement and participation, water quality outcomes, total investment, risks, and transaction and administration costs.

[23] https://www.barrierreef.org/what-we-do/reef-trust-partnership/water-quality-improvement/innovation-and-systems-change

The **cost-effectiveness** of actions and programs (ratio of outcomes achieved to investment required) and effects on **participation** are the most useful metrics for evaluation of different management options.

Evaluation of overall program cost-effectiveness

One of the early NESP TWQ Hub research projects involved an **assessment of the cost-effectiveness of a range of government programs and initiatives aimed at reducing end of catchment pollutant loads** (Rolfe and Windle 2016). Cost-effectiveness is the ratio of water quality improvements (such as reductions in sediment or nutrient loads) to the costs of achieving the change. This varies widely between projects and is influenced by factors such as the amount of pollutant reductions, construction costs, maintenance costs, administration costs, the time lags to be effective, the risks of failure, and the number of years that projects are effective.

Rolfe and Windle (2016) **evaluated average costs of different pollutant reductions across various programs**, compared those to the predicted costs from regional Water Quality Improvement Plans (WQIPs) prepared in 2014 to 2016 and evaluated costs of Reef Rescue grants by comparing to Paddock to Reef modelling outcomes. While there is increasing data on the cost-effectiveness of various government programs, there was very limited consistent data available on cost-effectiveness of the Reef Rescue grant programs (2008-2013) evaluated in this study. In part this is because modelling information to predict pollutant reduction has been limited for NRM groups when allocating project funds. In total, 530 Reef Rescue sugarcane grants for 2013-14 and 2014-15 were assessed.

The results showed **substantial variation and heterogeneity in cost estimates for management practices**, even after allowing for systematic differences in the estimation of both costs and emissions. In addition, the predictions of future costs in WQIPs were much lower than average historic costs. The evaluation of the Reef Rescue grants showed that the first 50% of projects generated 95% of the DIN reduction at an average cost of $2.92/kg while the second 50% of projects generated only 5% of the benefit at an average cost of $87/kg (Rolfe et al. 2018). These findings also supported the additional work undertaken in 2015 to develop marginal abatement cost curves for DIN and sediment (Whitten et al. 2015) in support of the GBR Water Science Taskforce. This work also highlighted large variations in costs between projects (up to 1,000 times difference) with some actions that are low cost with a high water quality outcome, and typically, actions that are more expensive as a pollutant reduction target is approached. These findings confirm that cost-effectiveness should be a key criterion for project prioritisation and funding evaluation and that large benefits are available from targeting investment both in terms of spatial priorities but also specific practice shifts in specific catchments.

Rolfe and Windle (2016) recommended that **benchmarks for cost-effectiveness be used as a mechanism to set thresholds or caps for funding**. Approximate cost-effectiveness thresholds can be set at the average of achieved and predicted costs for end-of-catchment loads. Examples derived in this research were: Sediment: $259/tonne and Nitrogen (DIN): $150/kg.

Finally, it was recommended that **data on cost-effectiveness should be automatically collated at the project level when predictions of improvements are made and funding is allocated**, and there is an urgent need for **consistency of cost-effectiveness measures for each pollutant**. Understanding of the drivers of large variations in some factors is limited and requires further work.

Example: Evaluation of the cost-effectiveness of the Reef Trust Reverse Tender programme

Further to this research, Rundle-Thiele et al. (2021) analysed the cost-effectiveness of the **Reef Trust Reverse Tender** programme in reducing nitrogen applications to sugarcane in the Wet Tropics and Burdekin regions. Comparison with the literature indicated that **the Reef Trust Reverse Tenders were extremely cost-effective** (at an average of $7.74/kgDIN at end-of-catchment in 2018 -i.e. ranging from $0.80- $35.60/kgDIN at end-of-catchment).

The Reverse Tenders gave sugarcane farmers the opportunity to obtain funding of up to $500,000 to reduce fertiliser application rates within limits set to prevent undesirable reductions in sugarcane yield. Reduced fertiliser application rates were expected to deliver positive outcomes for GBR water quality by reducing runoff of DIN via surface runoff and reducing DIN leaching via deep drainage. Cost-effectiveness was assessed by a metric (expressed in $/kgN reduction) derived from the ratio of the total cost incurred to the total contracted reduction in nitrogen application. However, researchers also highlighted that the ratio between reduced nitrogen applications to sugarcane fields and DIN reduction at end-of-catchment clearly varies with factors such as fertiliser application rate, soil type, soil permeability, rainfall timing and intensity, and DIN transport pathways from the field to end-of-catchment, therefore making it very difficult to compare cost-effectiveness results quoted in terms of reductions in nitrogen applications with those quoted in terms of DIN reductions at end-of-catchment (Rundle-Thiele et al. 2021).

Researchers additionally noted the importance to consider site-specific influences and other mechanisms-related factors when evaluating the effectiveness of programs supporting farming practice change (Rundle-Thiele et al. 2021).

Site-specific influences

DIN loss from sugarcane varies considerably by catchment, soil type and the level of fertiliser management practice (Figure 10). As a result, the reduction in DIN loss that follows from a given change in fertiliser practice may differ considerably between management units. This confirmed that spatial targeting (particularly by soil type) has the potential to considerably increase the level of DIN reduction delivered at the sugarcane field. Other important factors to consider are the connectivity between field and end of catchment (i.e. surface waters versus deep drainage and location-specific transport coefficients for both pathways), farm size (which impacts on the per-hectare cost through the farm-level fixed costs, such as the transition and transaction costs – i.e. purchase of new machinery and equipment, resources and time required to learn new skills, etc.) (Rundle-Thiele et al. 2021).

Mechanism-related issues

It is also difficult to compare the cost-effectiveness of different mechanisms, such as Reverse Tenders and Reef Credits versus grant- and extension-based programs, due to intrinsic differences in their design and expected outcomes. In the first group (Reverse Tenders and Reef Credits), it seemed appropriate to evaluate the cost-effectiveness solely within the scheme's duration, in terms of the costs incurred relative to the end-of-catchment DIN reductions delivered, where incurred costs should ideally include the costs of scheme administration as well as direct payments to farmers. In contrast, grant- and extension-based programs can potentially be evaluated in terms of the cost-effectiveness of each program overall ($ spent per total DIN reduction delivered), or the cost-effectiveness of individual interventions within programs ($ spent per farm per DIN reduction delivered from that farm). However, grant- and extension-based programs seek to encourage practice change through diffusion (i.e. practice change inspired by the program), which is notoriously difficult to quantify. Thus, when the cost-effectiveness of these types of scheme is evaluated solely in terms of outcomes delivered by scheme participants within the duration of the scheme, it is very likely that the cost-effectiveness achieved by these types of scheme will be lower than that of contracted 'payment for delivery' schemes like the Reverse Tenders (Rundle-Thiele et al. 2021).

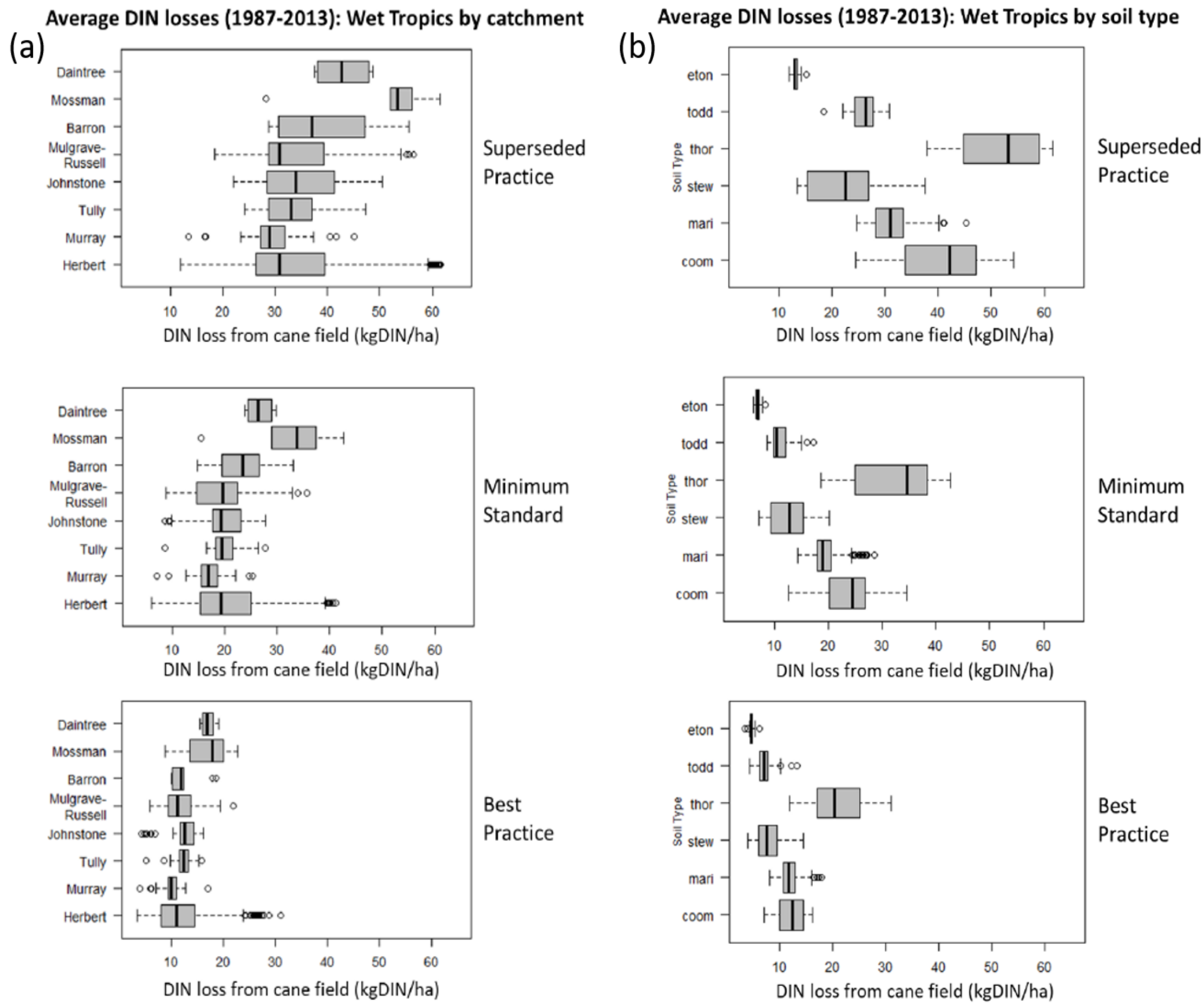

Figure 10. Average annual DIN losses (1987-2013) predicted by Paddock to Reef APSIM modelling for 563 sugarcane land management units in the Wet Tropics, for Superseded, Minimum Standard and Best Practice fertiliser management, grouped by (a) catchment and (b) soil type. Source: Rundle-Thiele et al. (2021)

Example: Evaluation of the design of water quality tenders

On a constructive evaluation of **water quality tender processes** undertaken in the GBR catchments, NESP TWQ Hub research focused on providing the evidence of where the 2008 Lower Burdekin Water Quality Tender had worked and where it failed in delivering its objectives, in order to inform the design of future tender-based environmental funding programs (Greiner 2015). More specifically, research provided evidence that the Tender:

- Satisfactorily engaged with participants through its information and communication strategy during the Tender implementation process (although satisfaction in transparency and communication decreased once funding decisions were made);
- Incentivised the participation of many farmers who were not previously engaged in water quality improvements;
- Contributed to increase knowledge on the impacts of agriculture on water quality, generating intrinsic motivation for many participants to do more about improving water quality;
- Sparked subsequent investments into water quality improvements (funded by farmers or other programs); and
- Facilitated farming-systems change to more environmentally benign practices in some instances.

However, the Tender failed in achieving its anticipated pollution reduction, as some major projects did not proceed due to cost under-estimation during proposal preparation. This research showed the importance of educating landholders about the conservation issues, which can contribute to intrinsic motivation and behaviour change, but also the need to maximise transparency of processes and communication of decisions to increase trust. In this specific case it was also obvious that additional technical advice for bid development would have been required to maximise accuracy of costing assumptions (and minimise the risk of under-estimating projects), and additional assistance could have contributed to overcome impediments to project implementation. Overall, this research highlighted the need to engage with industry at a grass-roots level in the design of new policies and programs, to maximise industry acceptance and collaborations (Greiner 2015).

These projects provide useful insights into program design that can be applied to guide the development and implementation of more efficient water quality management programs in the future.

2.3 Innovations in methodology and delivery

One of the most significant innovations of NESP TWQ Hub was the development of decision support systems and tools for policy makers and farmers, which not only provide more objective and reliable systems for decision-making by integrating large volumes of high definition data, but also open accessibility to all stakeholders and interested citizens. More specifically, these tools provide access to much finer scale data and information than has been available for prioritisation in the past. This has been supported by advances in water quality monitoring approaches and integration of technology platforms that will become more accessible and affordable over time.

Regular and meaningful communication between researchers and stakeholders has also enabled the trial or piloting of policy instruments, or novel approaches to farmer engagement.

Some examples of innovations in the research methodology and delivery related to the suite of projects discussed in this report include (information summarised in Table A1.1):

- Development of a new dynamic mechanistic model that enables predictions of cumulative risk in space and time for complex environmental scenarios to generate Cumulative Impact Risk maps for GBR receiving waters (Uthicke et al. 2016).
- Definition of climate adjusted thresholds for water quality guidelines including a set of 25 important environmental pressures that were combined into exposure maps and available through the eAtlas and the Online interactive tool[24].
- Integration of two irrigation decision support tools, IrrigWeb and WiSA (automatic irrigation scheduling) to develop a full decision support tool and further supported by the Internet of Things output by connecting them and developing a system to monitor the implementation of the smarter irrigation system (Wang et al. 2020).
- Development of a decision support tool integrating spatial and economic information to assist with examining options for transitioning low-lying sugarcane 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 et al. 2020).
- Mapping generated from land use transitioning projects (Waltham et al. 2017, 2020) has been used by regional NRM groups, Traditional Owner 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).
- Inclusion of Real Time Water Quality Monitoring instrumentation for measuring nutrient losses at a farm scale (Davis et al. 2019, 2021).
- Incorporation of the Digiscape Future Science Platform as an alternative way to produce interpretive materials for on-farm decision making (Davis et al. 2019, 2021).
- Adoption of a very deliberate combined approach of water quality monitoring with strong elements of social science to build grower trust and facilitate land management change (Davis et al. 2019, 2021).
- Evidence showed that focus on information, education, and one-on-one engagement with participants during Tender processes generated high levels of participant satisfaction during Tender preparation (although this transparency and communication should have been extended after project selection) (Greiner 2015).
- Preparation of 'Best Practice Guide for development and modification of programme communicatioin material' in the agricultural environment sector with the aim of increasing uptake of water quality improvement programs in the GBR catchments (Hay et al. 2018).
- Exploration of trading nitrogen application allowances as an innovative way to apply and manage an end of catchment N load cap (Smart et al. 2020).
- Development of a world-first prototype insurance product for insuring the risk to sugarcane yield from reduced N rates (Thorburn et al. 2020).

[24] https://eatlas.org.au/gbr/nesp-twq-5-2-cumulative-impacts

- Establishment of benchmarks for guiding cost-effectiveness assessment in the prioritisation of projects (Rolfe and Windle 2016).
- Development of methodologies for assessing cost-effectiveness and for identifying key drivers of variation in cost-effectiveness in data-challenging situations (Rundle-Thiele et al. 2021).

3. RESEARCH INFORMING MANAGEMENT

NESP TWQ Hub research has generated an impressive collection of valuable findings for understanding and overcoming barriers to reducing N loss to the GBR, 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 the NESP TWQ Hub projects has been the delivery of highly applied science, coupled with close collaboration with stakeholders in project design and implementation and guided by a end user based 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 Nutrient risk to the GBR

Specific examples of potential management outcomes and applications for GBR ecological health include:

- A structured approach was developed to show how cumulative impact assessments can inform decision-making, building on the Drivers-Pressures-State-Impacts-Responses (DPSIR) framework.
- The new cumulative impact risk maps could guide management decisions around development proposals.
- Results will inform spatial and temporal assessments of ecological risks, and management opportunities for a range of activities in the coastal zone and inshore GBR waters.
- The eReefs model was refined to derive WQ management scenarios expected to maximise coral survival in a warming climate.
- A new Water Quality Index was developed that can be considered for application in the GBR. The index relates directly to ecological impacts and considers chronic effects of light stress.

In the longer term, a **potential reduction in ecosystem impacts** could be expected from i) improved understanding of different applications for overcoming barriers to N reductions, ii) improved water quality monitoring tools and protocols, and iii) the application of the new indicators of ecosystem health within monitoring programs.

3.2 Reducing nutrient runoff from GBR catchments

Specific examples of management outcomes and applications for new or improved solutions for overcoming barriers to N loss reduction from NESP TWQ Hub research are listed below. These outcomes are potentially relevant to a range of audiences including growers, extension staff, government policymakers, investors and NRM groups implementing on-ground funding programs.

Identifying actions

- **Changing from urea to EEFs may allow a reduction in N application rates that does not risk reduced production**. This may reduce runoff losses, but effects are

site and season-specific and rely on the crop being able to capture the additional N retained in the soil. EEFs will be successful in some locations / circumstances but need to be used in a way that maximises their effectiveness and integrated with other management operations.

- Sophisticated **decision support tools were integrated to allow scheduling and automation of irrigation practices** in the Lower Burdekin sugarcane area: "How much water does that crop need?" … and, "When should it be applied?" and "How can I do this in a practical and effortless way?"
- **Retiring lower yielding, high DIN loss sugarcane areas** – 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. There is an opportunity to combine these methods with credit or trading schemes.

Understanding participation

- **Development of the 'smarter irrigation management platform'** can overcome some of the most common barriers to improved irrigation management – having tailored products to deliver time and resource savings, which are much less labour intensive and easy to use. Having the ability to automatically transfer information between independent, smart decision support tools addresses these barriers.
- A robust framework has been developed for the **design and implementation of sub-catchment scale monitoring, modelling and extension programs** in GBR sugarcane areas. The framework supports definition of pollution generation 'hotspots' that will help to maximise intervention efficiency.
- Project 25 addressed **water quality science-farm management communication challenges** through a collaborative model by collecting and providing locally relevant data on agricultural impacts on water quality, communicating data at appropriate spatial and temporal scales, and developing local trust in science to facilitate practice change.
- The social research conducted as a component of Project 25 highlighted many aspects relevant to the design and implementation of future practice change programs. In particular, the **importance of investing to build a trust-based environment for dialogue between growers and scientists** on a contentious topic, grower engagement in planning and implementation, opportunities for two-way dialogue, maintaining research practice and data transparency and the provision of real time data were identified as important factors influencing grower participation and engagement. It was also highlighted that establishing collaborative relationships and frameworks for behavior change takes time, is resource intensive and is multi-disciplinary (expertise in water quality, sensor-telemetry, IT, user experience etc).
- Research identified **barriers and enablers of management change in relation to agricultural run-off** to encourage best management practice uptake amongst land managers. For example, the need for a holistic approach which clearly acknowledges the issues and identifies and implement solutions in consultation with key stakeholders was highlighted by Rundle-Thiele et al. (2021). Some key recommendations included: (i) fostering shared responsibility (localised evidence is needed so that all stakeholders involved understand that 'this is my problem'); (ii) upskilling extension support services (stakeholders identified the need for advisors to

provide consistent advice with guidance focused on optimising change outcomes and farming practices); (iii) change communication practices (need for positive stories - which can deliver hope and inspiration for others- and more simplified information); (iv) change industry leadership practices (strong advocacy from leaders in industry is needed to acknowledge that pesticide and nutrient reduction is a necessity and that industry is taking ownership and is part of the solution); and (v) change evaluation practice (From a 'prove' mindset towards an 'improve' mindset, focusing on learning from experiences gained to understand which improvements are needed to extend program success. Evaluations should be undertaken throughout the project, not just at the end, to avoid costly mistakes through early identification of approaches that are not working. Recognise all stakeholders shared responsibility using mapping methods such as 'Creating Collective Solutions'. Coordinated evaluations (farmer-focused, not project focused) led by an independent third party which no involvement in the sugarcane sector are recommended).

- Research provided **guidelines for the development and modification of communication material in the agricultural-environmental sector** with the aim of increasing uptake of water quality improvement programs in the GBR catchment. Main issues identified included complex language, message tone and unintended effects of certain visual imagery. Recommendations included (i) use a two-way communication strategy; (ii) use social marketing tools; (iii) write material at no more than grade 9 school level; (iv) identify and work around prevailing social norms; and (v) follow certain principles of design (updated content, credibility of spokesperson, useful visual imagery, etc).

New instruments

- A **nitrogen trading market** among landholders in sugarcane catchments could deliver improved economic and production efficiency under a whole of catchment N load cap. If a trading scheme was introduced, the market price for N would increase as the cap on emissions tightens, making the conversion of marginally productive sugarcane land in key locations to wetlands more economically viable. Additional assessment would be required to assess the viability of a N trading market in different catchment characteristics.
- A trading approach could reward growers who can most effectively reduce their nitrogen pollution and maximise production on better soils. This could help incentivise innovation and implementation of existing best management practice and new approaches.
- **Water quality credit trading** in nitrogen and sediment offsets between point source buyers (sewage treatment plants, aquaculture, urban development) and non-point source suppliers (landholders and land remediation proponents) has the potential to be an important facilitator of cost-effective future economic expansion along the GBR coast, with no net decline in water quality.
- **Insuring against the risk of sugarcane yield loss** with reduced N fertiliser applications is technically feasible, however establishing commercial viability will require considerable effort to build understanding of, and trust in, the product amongst farmers.

Evaluating programs

Evaluation of existing investment programs highlighted the following findings that are relevant to future management choices:

- Program design should be adjusted away from a reliance on simple grant mechanisms to processes that optimise price discovery and project selection.
- Data on cost-effectiveness should be automatically collated at the project level when predictions of improvements are made and funding is allocated.
- There are large variations in cost-effectiveness within and between projects and regions - this underpins the case for better project selection and prioritisation and indicates the sizeable benefits from targeting.
- Understanding of the drivers of cost-effectiveness is limited, also there is currently limited consistency of cost-effectiveness measures.
- Benchmarks should be applied in program funding to set limits on program and project funding levels, and help in prioritisation of projects – and be further developed to identify lower, average and upper ranges for expected cost-effectiveness benchmarks.
- Importance to consider site-specific influences (specially soil type) and other mechanisms-related factors.
- Specific lessons were identified **to inform the design of future tender-based environmental funding programs**, including the need to: (i) systematically build ex-post evaluations into all competitive tenders, covering both participants' experiences as well as effectiveness, and ideally in two times (one right after program completion and another one 3-5 years later to explore longer-term results), and including an external reference group in the analysis; (ii) treat information sessions as an opportunity for educating landholders about conservation issues (which can create intrinsic motivation); (iii) provide technical advice for bid development and maximise accuracy of costing assumptions; (iv) maximise transparency of processes and communication of funding decisions; (v) offer assistance to try to overcome impediments to project implementation and be prepared to reallocate unused funding to bids down the order of merit; and (vi) engage with industry at grass-roots levels in the design of new policies and programs, to maximise industry acceptance and collaboration.

3.3 Project legacies

The 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[25].

Furthermore, the projects that **directly explored new policy instruments for reducing N losses to the GBR** have involved trial or piloting of the approach for management application so that managers can understand whether these are genuine options for the

[25] https://terrain.org.au/major-integrated-project/

future management of GBR water quality. These projects provided a highly unique research theme for the GBR and its catchments, and some have secured additional funding through other programs to continue to develop the potential policy instruments (for example, insurances and sustainable financing).

A recent and ongoing policy application of NESP TWQ Hub research includes the current review of the Reef 2050 Long Term Sustainability Plan (Commonwealth of Australia 2020). In particular, the review of the 2050 Plan incorporated NESP TWQ Hub research outputs related to scenarios for managing cumulative impacts in the GBR, including nutrient enrichment.

All of the research results are also available for development of the 2022 Scientific Consensus Statement and the review of the Reef 2050 Water Quality Improvement Plan. The outcomes will make a valuable contribution to the new and refined knowledge for reducing nutrient runoff to the GBR.

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.

4.1 Investment priorities for research to address knowledge gaps

Additional research has been suggested to continue to inform management and policy decisions that will assist in overcoming barriers to reducing N losses to the GBR. Specifically, future research in the following fields, including foundational understanding of nitrogen sources, delivery and transport processes, will assist in the facilitation of successful implementation of policy instruments for supporting N reductions:

- Continuing investment in improving catchment water quality modelling to incorporate the latest scientific advances in knowledge of DIN transport and reductions in bioavailable nitrogen from sediment reductions. This should be supported by continued scientific investigation of: DIN transport via drainage/groundwater pathways, and parameterisation of catchment models for reductions in bioavailable nitrogen achieved through the abatement of fine sediment.
- Advancing the mechanistic understanding of the dynamics and actions of specific EEFs in different soils and seasonal conditions, so they can be incorporated into P2R modelling and nutrient management decision support systems.
- Further investigating how seasonal climate forecasting can be used to optimise farm management (Biggs et al. 2021).
- On-going research into wetlands and sugarcane 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.
- Continuing technological developments such as low-cost distributed real-time water quality sensing, integration of irrigation automation technology and Smart phone apps for N trading credit suppliers and credit buyers.
- Understanding the group and/or individual social processes that can maximise the adoption of improved in land management once farmers understand and accept local water quality issues.
- Broaden application of the quantitative risk manage concept that underpins insurance to more general farm management advice (e.g. quantifying the risk associated with changing irrigation scheduling).
- Develop crop yield insurance for sugar mills to help manage year to year climate variability, therefore improving financial sustainability.
- Assessment of the interactions of the range of N reduction mechanisms trialled, and how they could work in conjunction at different scales, e.g. insurances and trading,

potentially supported by a fine scale monitoring program. This would require consideration of the biophysical, social and economic aspects of the program design.

4.2 Integrated research and on-ground actions

The combined outcomes of the suite of projects described in this report provide an insight into a potential suite of solutions for reducing N losses to the GBR. The outcomes of the on-ground studies, combined with the research investigating new instruments, highlight some noteworthy integrated outcomes that may warrant further investigation. While the relationships between the projects are highlighted conceptually in the diagram in Figure 3, a number of specific examples can be emphasised.

For example, the role of transitioning low-lying sugarcane 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 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 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 under different landscape and climate contexts – for example, projects in the Dry Tropics are needed, as well as testing more explicitly denitrification efficiencies under local site nuances (e.g. temperature, dissolved oxygen, flow, vegetation/carbon availability etc.). Research into the efficacy of denitrifying bioreactors is underway (e.g. Chessman et al. 2020), however data on other technologies are needed.

The investigation of an insurance scheme (Thorburn et al. 2020) supports the perception of growers that there is a potential risk of loss in crop yield from reducing N application rates below Six Easy Steps rates. The data from the EEF studies (Bell et al. 2019, 2021) supports the view of growers to some extent, and demonstrates that in some situations, reduced crop yields as a result of lower N fertiliser rates can be a risk to growers and mills without the adoption of alternate fertiliser technologies which are currently more expensive. Together, the research findings from these two projects offer solutions for managing fertiliser application rates that will suit a range of individual needs – whether it be to opt for the insurance scheme, or to employ a combination of fertiliser management products and techniques as explored by Bell et al. (2021), or a combination of both. While the insurance scheme shows real potential, further investigations required include (i) better estimates of product pricing and farmer demand, (ii) extending the N prototype to other regions and (iii) exploring the creation of insurance opportunities for other inputs (notably irrigation) and yield. The concept could also be extended to crop yield insurance, to decrease variability in income streams of farmers and, especially millers, and increase industry financial sustainability. Developing a decision support system to help growers to identify where and when EEFs provide production and environmental benefits would be very beneficial, and such a tool will need to keep abreast of developments in fertiliser technologies (e.g. biodegradable coatings, new inhibitors). The outcomes from Project 25 (Davis et al. 2019, 2021) provide significant insights to understanding grower participation in efforts to reduce N losses to the GBR, and the important role of increasing knowledge and building trust in overcoming barriers to adoption of management improvements. The outcomes also highlight several aspects of program design and implementation that could inform the evaluation of future management options; not only do the results show how the project methods affected grower engagement and participation, but also how a mix of tools (in this case, real-time data, education and engagement) could be used to generate improved management outcomes. Sugarcane and grazing industries support the roll out of more Project 25 programs across other priority hotspots for water quality to engage producers in runoff from farming practices, monitoring, peer learning and improved trust in GBR science.

Overall, it would be possible to implement a combination of the approaches demonstrated through this research to reduce N losses at a catchment scale. To facilitate this, it would be valuable to undertake further desktop evaluation of how this could occur in the most effective way, given the characteristics of a particular landscape. It would be feasible to conduct this evaluation in a number of locations, but potentially most efficiently in the Tully basin where considerable spatial analysis was performed in relation to the cost-effectiveness of management options in Waltham et al. (2017, 2020) and Smart et al. (2016, 2020). In addition, the effort of the Wet Tropics MIP and organisations such as Sugar Research Australia in promoting and facilitating tailored solutions is likely to continue. This kind of evaluation could be developed over a 6 to 12 month period and would require considerable stakeholder consultation.

5. CONCLUSIONS

The research outcomes of the NESP TWQ Hub provide a highly valuable contribution to reducing N losses to the GBR. NESP TWQ Hub research on the ecological impacts of N losses to the GBR focused on the cumulative impacts of multiple stressors, including nutrients, to reef ecosystems. The majority of the research in relation to nutrient management focused on investigating solutions associated with on-ground actions for reducing N losses and developing new instruments for facilitating management changes. The latter is a unique research area for the GBR and its catchments and has proven to be of significant interest to investors and decision makers.

The overall framework developed for the catchment interventions (within Figure 3) provides a clear way to communicate the key stages in overcoming barriers to reducing N losses to the GBR: by identifying actions, understanding participation, exploring new instruments and evaluating options. The NESP TWQ Hub research outcomes have also highlighted how these stages are integrally linked. It is recommended that any further work in this area of research continues to utilise this framework to ensure that the outcomes remain integrated both spatially but also across multiple disciplines. It is also relevant to managing other pollutants in the GBR and could be considered in future management frameworks for improving GBR water quality.

The NESP TWQ Hub research has been conducted in collaboration with a wide range of stakeholder groups and is of interest to an even larger range of audiences. The research findings are significant to the future management of the GBR and its catchments. Extensive effort should be implemented in future programs to 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.

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APPENDIX 1: RELEVANT NESP TWQ HUB PROJECTS

Table A1.1. List of NESP TWQ Hub projects and relevant information relevant to the synthesis topic 'Overcoming barriers to reducing nitrogen losses to the GBR'. 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
Ecological impacts of DIN on GBR ecosystems				
Project 1.6 - Multiple and cumulative impacts on the GBR: assessment of current status and development of improved approaches for management (Sven Uthicke, AIMS)	Uthicke et al. (2016)	• Provided a review and synthesis of existing tools and qualitative and quantitative studies that describe cumulative impacts on reef ecosystems. • Road map to develop a practical framework to support assessment and management of cumulative impacts on the GBR.	New dynamic mechanistic model that enables predictions of cumulative risk in space and time for complex environmental scenarios.	• A structured approach was developed to show how cumulative impact assessments can inform decision-making, building on the Drivers-Pressures-State-Impacts-Responses (DPSIR) framework. • The new cumulative impact risk maps could guide management decisions around development proposals.
Project 2.1.6/5.2: From exposure to risk: novel experimental approaches to analyse cumulative impacts and determine thresholds in the GBRWHA (Sven Uthicke, AIMS)	Brunner et al. (2020); Humanes et al. (2016); Marques et al. (2020); Negri et al. (2019, 2020); Uthicke et al. (2020)	• Concentration-response experiments were performed for selected species under different conditions (sediments, turbidity, nutrients, light, salinity and temperature) to determine critical exposure thresholds. • Exposure maps were produced for individual stressors and cumulative pressures. • Guideline Values for pollutants were adjusted to account for thermal stress events. • Cumulative effect of nutrient enrichment and high temperatures had a negative impact on the overall larval supply and recruitment of Acropora tenuis in experimental conditions.	Climate adjusted thresholds for water quality guidelines. A set of 25 important environmental pressures were combined into exposure maps available through the eAtlas. Online interactive tool.	• Results will inform spatial and temporal assessments of ecological risks, and management opportunities for a range of activities in the coastal zone and inshore GBR waters.
2.3.1/5.3- Benthic light as ecologically-validated GBR-wide	DiPerna et al. (2018); Magno-	• Water Quality indicators were developed based on the amount of light that penetrates to the seafloor, using satellite data validated through in-situ light loggers.	The new water quality indicator will allow estimating	• The new indicator could become a cost-effective means to directly inform Reef Integrated Monitoring Plans and

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indicator for water quality: drivers, thresholds and cumulative risks	Canto et al. (2019); Robson et al. (2019, 2020)	• Minimum light requirements and thresholds for healthy corals were also determined using experimental and field data.	trends and predicting ecological consequences of human activities (e.g. run-off, dredging).	Reef report cards.
Project 3.3.1: Quantifying linkages between water quality and the thermal tolerance of GBR reefs (Line Bay, AIMS)	Cantin, Baird, et al. (2021); Morris et al. (2019)	• The ability of corals to resist and recover from bleaching was assessed under different water quality parameters (nutrients/light/turbidity). • Nutrient availability and metabolism affect the stability of coral-zooxanthellae symbiosis. • Historical nutrient conditions mediate host-symbiont compatibility and bleaching tolerance over proximate and evolutionary timescales.	New modelling framework to identify management options that would mitigate the effects of warming on reefs exposed to WQ pressures.	• The eReefs model was refined to derive WQ management scenarios expected to maximize coral survival in a warming climate.
Solutions: Identifying actions				
Project 2.1.8/5.11: Improved water quality outcomes from on-farm nitrogen management (Mike Bell, UQ)	Bell et al. (2019, 2021); Janke et al. (2019, 2020, 2021)	• Assessed whether a number of inter-related strategies could be used to maintain sugarcane productivity while improving fertilizer N use efficiency and minimizing N loss in runoff and drainage. • Combines improved N fertiliser technology (using Enhanced Efficiency Fertilisers – EEFs) with fertilizer N rate reductions that better match the N applied to the crop demand in a productivity zone which can range in scale from intra-block, several blocks or whole farm. • Benchmarked the performance of different EEF technologies against conventional urea fertilizer under conditions consistent with applications in sugarcane fields (i.e. concentrated sub-surface fertilizer bands) in both laboratory and field experiments. • Results showed that:		• While the use of EEF technologies on their own did not provide substantial benefits in runoff water quality and could actually cause greater N runoff losses than urea when applied at high rates, their use did allow a reduction in application rates with a lower productivity risk. • Lower N rates applied as EEFs can reduce N losses in runoff and deep drainage, provided the crop can capture the additional N. • EEF's need to be used in a way that maximises their effectiveness, and integrated with other management

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		• The use of the EEF blend consistently improved fertiliser-N recovery by the crop, but there were no consistent crop yield increases. • Runoff varied between sites, seasons and treatments – with N reductions varying between 30-80% in surface runoff and up to 90% in drainage losses with the EEF treatment. These were lessened or reversed if the EEF blend was applied at the higher district yield potential rate. • EEF's offer a way to reduce N rates without compromising yields, and reduce the risk of yield loss, but there can be higher costs. • Trials of concentrated banding of urea with and without coatings or inhibitors showed limitations in the benefits of N transformation and availability compared to incorporation or broadcasting.		operations. • Further testing is needed for clearer guidelines on which EEF technologies are most effective, which soil types and application times are most likely to deliver benefits from EEF use, the likely size of water quality benefits (an urgent requirement) and the extent to which fertiliser application rates can be reduced. • Given the additional cost/kg fertiliser N applied as EEFs, more extensive testing of agronomic and environmental impacts of different combinations of EEF technologies and fertiliser application strategies (locations, rates and timing) will be needed before widespread government or industry investment in these approaches can be justified.
Project 3.1.2: Improving water quality for the Great Barrier Reef and wetlands by better managing irrigation in the sugarcane farming system (Yvette Everingham, JCU)	Wang et al. (2020)	• Decision support tools have been integrated to allow scheduling and automation of irrigation practices in a trial in the Lower Burdekin sugar cane area. • An Uplink program was developed to automatically log the irrigation and rainfall data to IrrigWeb, from the WiSA irrigation system. The results showed that a significant amount of time had been saved via this process. • A Downlink program was developed to connect IrrigWeb to WiSA, which can download, extract, calculate and apply irrigation schedules automatically. • The Downlink program successfully mimics the IrrigWeb	Two irrigation decision support tools, IrrigWeb and WiSA (automatic irrigation scheduling) were integrated to develop a full decision support tool and further supported by the Internet of Things	• A 'train-the-trainer' model in the installation and testing of the Uplink program in the Burdekin presents a plausible pathway to wider adoption and builds regional capacity to ensure the project outputs are easily accessed after the project finish date. • Automated irrigation systems support best practice irrigation management for reducing runoff and DIN runoff. This automated data exchange process will reduce the time imposed on a farmer

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		generated soil-water deficit for all fields. The Downlink program improves scheduling by incorporating practical limitations, such as pumping capacity or pumping time constraints, that are found on the farm. • Combining the Uplink and Downlink programs, the smarter irrigation management platform provided an innovative and working solution to the questions "How much water does that crop need?" … and, "When should it be applied?" and "How can I do this in a practical and effortless way?". •	output by connecting them and developing a system to monitor the implementation of the smarter irrigation system.	considerably. The ability to automatically transfer information between independent, smart decision support tools, reduces the barriers to adoption and improves the chance of long-term adoption. • Smarter irrigation systems represent a solution to saving energy and improving water quality by transferring more farmers to B class practices. It will save farmers time and money, and allows farmers to keep better irrigation records enabling them to assess their improved irrigation performance. • Despite these benefits there will still be some barriers to wider adoption. Besides trusting new technologies, another major barrier is the perceived large capital outlay to purchase the infrastructure. Opportunities for incentive programs to make this transition easier and less riskier for producers should be explored.
Project 2.1.2: Scoping options for low-lying, marginal cane land to reduce DIN in priority wet tropics catchments / 5.12 Burdekin and Mackay Whitsunday catchments (Nathan	Waltham et al. (2017, 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	A decision support tool has been developed integrating spatial and economic information to assist with examining options for transitioning	• 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 relatively small areas of poorly performing sugarcane land, while best management practice adoption initiatives should focus on the remaining, more productive sugarcane

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Waltham, JCU)		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).	low-lying cane land, with a high risk of dissolved inorganic nitrogen (DIN) loss, to lower DIN-risk uses in the Wet Tropics.	land. • It is recommended that this framework be tested, evaluated and refined via a pilot. • There is a paucity of quantitative information on the DIN removal capacity and conversion costs for wetland restoration or constructed treatment wetlands in the Wet Tropics. Therefore, there is uncertainty around the cost-effectiveness values and end users should be cognisant of the assumptions used in the framework. 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.
Project 4.10: Evaluating the costs and benefits of agricultural land conversion to wetlands (Nathan Waltham, JCU)	Waltham 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.		

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Solutions: Understanding participation				
Project 1.8: Sub-catchment scale monitoring, modelling and extension design to support reef water quality improvement (Aaron Davis, JCU)	Davis and Waterhouse (2016)	• Outline of the process for the design and implementation of a sub-catchment scale monitoring, modelling and extension program in GBR sugarcane areas. • Monitoring framework for design and implementation of finer scale water quality monitoring in pollutant generation hotspots in sugarcane. • Review of sampling collection methods and application of real time monitoring instrumentation. • Case studies of finer scale monitoring: Sandy Creek, Herbert catchment, Lower Burdekin irrigation area, • Definition of different standards of monitoring design to suit requirements – ‘gold, silver and bronze’. • Identification of tools to define smaller scale hotspots including spatial mapping and modelled pollutant load data. • Pollutant hotspots: • N management across Wet Tropics cane areas; • PSII herbicide management in Mackay Whitsunday and Lower Burdekin. • Integration of program outcomes into broader, concurrent water quality monitoring and modelling programs, e.g. value of expanding beyond concentration data to include flow (calculate loads), concurrent collection of agronomic data, appropriateness of design to meet objectives and mechanisms for industry engagement.		• Definition of pollution generation ‘hotspots’ maximises intervention efficiency. • If sub-catchment monitoring is to move beyond rudimentary ‘concentration’ only data presentation, toward robust and versatile data collection with a range of uses, it will require major and ongoing investment across different levels of government and industry. • Significant time and local capacity investments required to develop a robust water quality monitoring program, particularly at sub-catchment scale. • Appropriate conceptualisation of the key indicators, spatial and temporal loss dynamics, catchment hotspots (which may not entail initial outlays) will be needed to provide critical, locally relevant data to ensuring ultimate design in terms of requisite instrumentation, sampling location etc is optimally implemented. • It is critical to manage expectations about what fine-scale monitoring can truly achieve with regard to eliciting practice changes and will almost certainly need to be part of a broader, coordinated policy landscape.

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Project 2.1.7/ 4.8: Engaging with farmers and demonstrating water quality outcomes to create confidence in on-farm decision-making (Project 25) (Aaron Davis, JCU)	Davis et al. (2019, 2021)	• The Project has: ○ Enhanced the capacity of some grower participants to act as leaders and influencers within their local farming community and networks. ○ Provided clear capacity for DIN 'hotspot' identification in the broader Russell-Mulgrave catchment. ○ Identified sub-catchment areas consistently responsible for generating relatively high nutrient losses emerged with ~3 years of monitoring effort. These are focus areas for additional finescale monitoring, extension and engagement effort from industry support programs. • Establishing robust trust frameworks is important in delivering desired program outcomes. Real time data provided greater confidence from growers in the project results. • Improved communication, an improved trust environment with more direct oversight of monitoring data, and 'space' to learn and experiment are contributing factors to grower engagement in the project. • The Digiscape Future Science Platform produces interpretive materials that help growers understand links between runoff following events and N in local waterways. • Additional outcomes from in-situ monitoring highlighted the contribution of first flush runoff events to the total catchment DIN load, identifying the opportunity to investigate treatment options for smaller scale events.	• Inclusion of Real Time Water Quality Monitoring instrumentation for measuring nitrates. • Adopted a very deliberate combined approach of water quality monitoring with strong elements of social science to build grower trust and facilitate land management change. • The Digiscape Future Science Platform has been used to produce interpretive materials.	• Global experiences suggest that spatially identifying and prioritising landscape 'hotspots' of pollutant generation for management intervention, and small catchment-scale water quality monitoring in collaboration with landholders, are among the most promising strategies for reducing diffuse water quality pollution. • The use of traditional, as well as emerging water quality monitoring approaches, and social research to identify mechanisms to maximise grower engagement with science, will help to enable farmers to directly link their activities with catchment water quality conditions. • Meaningful grower involvement in program design provides advantages and opportunities for effective communication of not only basic water quality science, but also government policy aims, back to industry. • Presentation of real, locally developed data is clearly a very effective tool for addressing known challenges or points of contention in sugarcane industry understanding of water quality issues and building grower confidence in the science.
Project 2.13/3.13:	Hay and	• Research identified the barriers and enablers of	Development of	• Research identified the barriers and

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Harnessing the science of social marketing in communication materials development and behaviour change for improved water quality in the GBR (Lynne Eagle, JCU)	Eagle (2019); Hay et al. (2018)	behavioural change in relation to agricultural run-off to encourage best management practice uptake amongst land managers. • Key barriers identified included (i) conflicting information and changing advice over time; (ii) distrust of government agencies and certain denial on the link between their activity and the GBR health; (iii) lack of tailored communications for different personalities; (iv) resistance of some extension officers to change; (v) uneven coverage of land manager properties by extension officers; and (vi) complexity of applications and perceived unfairness of funding initiatives. • Key ‘enablers’ included (i) engagement of extension staff in presenting this results; (ii) upskill extension officers in social marketing, (iii) ensure communications send consistent and integrated messages and preferably from trusted sources; (iv) develop systems for monitoring and analysing messages and minimising conflicting messages; (v) tailor information strategies according to land managers preferences; (vi) incorporate long-term relationship management strategies; and (vii) develop specific strategies for engaging those who are less committed to adopting recommended best land management practices. • Research provided guidelines for the development and modification of communication material in the agricultural-environmental sector with the aim of increasing uptake of water quality improvement programs in the GBR Basin. Main issues identified included complex language, message tone and unintended effects of certain visual imagery.	‘Best Practice Guide for development and modification of programme communication material’	enablers of behavioural change in relation to agricultural run-off to encourage best management practice uptake amongst land managers (see summary of research outcomes for more details). • The project also concluded that improving the way projects communicate and get buy-in from land managers can help to ensure greater project uptake, associated positive results and lasting behaviour change. Recommendations included (i) use a two-way communication strategy; (ii) use social marketing tools; (iii) write material at no more than grade 9 school level; (iv) identify and work around prevailing social norms; and (v) follow certain principles of design (updated content, credibility of spokesperson, useful visual imagery, etc).
Solutions: New instruments				

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
Project 3.12: Development of an offset financial contribution calculator for Reef Trust (Martine Maron, UQ)	Maron et al. (2016)	• This research designed a draft calculator to determine the amount of money that a proponent would pay when voluntarily using the Reef Trust as an offset provider. • The approach developed was consistent with relevant policy principles, such as the EPBC Act Environmental Offsets Policy, and end-user needs. • The prototype calculator is a transparent and easy-to-use spreadsheet style tool that considers: (i) surrogates (matters of national environmental significance that are likely to be impacted by proposed projects); (ii) surrogate condition factors (accounting for the ability of habitats/species to respond to conservation actions); (iii) implementation costs; (iv) time delay (time difference between impact and benefit from offset activity); and (v) administration fees.	Current offset approaches in Australia were conceptualised primarily for terrestrial ecosystems. This new approach has been adapted to the GBR context and could significantly increase the likelihood that marine biodiversity offsets are successful.	• The prototype calculator outlines a framework for estimating liabilities. • The method still requires data to quantify the components of the calculation before it is fully functional. • Further synthesis of existing data and expert elicitation are recommended to progress the development of the approach to implementation stage.
Project 2.2: A tradeable permit scheme for cost-effective reduction of nitrogen runoff in the sugarcane catchments of the Great Barrier Reef (Jim Smart, GU)	Smart et al. (2016)	• A tradeable permit scheme involves a fixed cap on the total amount of emissions and a tradeable allocation of emission permits among polluters. This approach was explored for N trading in cane in the Tully catchment. • Key elements of a successful water quality-trading scheme are the establishment of a regulatory cap, clear identification of the pollutants to be traded and geographic trading area, development of trading rules and supportive institutional structures. • A spatially explicit model was used to explore DIN losses and gross margins under different N application rates. Landholders are allocated with equal permits to meet the end of river N load cap, and then can trade permits if they know their gross margin will increase if they are able to apply more N.	Trading N is an innovative way to apply and manage an end of catchment N load cap.	• The outcome of spatial modelling indicated that a nitrogen trading market could deliver improved economic efficiency. As the cap tightens the market price for nitrogen increases and conversion of marginally productive cane land in key locations to wetlands becomes economically viable. • A trading approach could reward growers who can most effectively reduce their nitrogen pollution and maximise production on better soils. The trading approach will help incentivise innovation and implementation of existing best

Project Title	**Refs.**	**Summary of research outcomes**	**Innovations**	**Implications for Management**
		• Buying and selling is managed through a 'smart market' to maintain the overall cap. • N credits from constructed wetlands on less productive cane lands were also incorporated. • Results show that there is sufficient variability in gross margins across Tully grid cells to drive an active trading market, with more than half of the grid cells buying or selling N-permits in all simulations; gross margins are increased through trading.		management practice and new approaches. • Future research should examine the potential for point to non-point smart market trading of nitrogen in key catchments and among urban, industrial and agricultural sectors. The capacity of landholders to participate in nitrogen and other reef stressor trading is not well understood.
Project 3.1.6: Exploring trading in water quality credits as a cost-effective approach for managing water quality in the Great Barrier Reef (Jim Smart, Griffith Uni)	Smart et al. (2020)	• Examined the potential for point to non-point smart market trading of N in key catchments and among urban, industrial and agricultural sectors, focusing on future scenarios. • Considered supply of DIN credits from (i) improvements in fertiliser management practice in sugarcane production, (ii) setting aside less productive sugarcane land, (iii) constructed nitrogen treatment systems (i.e. landscape and embellished treatment wetlands and bioreactors), and (iv) reductions in bioavailable nitrogen that accompany reductions in fine sediment loads. • In the current situation, the sugarcane practice change step from 'Minimum Standard' to 'Best Practice' can produce DIN reductions at modest cost around \$8 - \$50/kgDIN. However, full adoption of the Reef Protection Regulations and further improvements beyond this standard (to 'Best Practice') are less likely to be cost effective (typically costing upwards of 60 – 250 \$/kgDIN). Therefore, future scenarios showed that constructed and landscape N treatment wetlands in the Wet Tropics are potentially able to supply DIN credits at a cost of ~40 – 60 \$/kgDIN, with 1ha of wetland	Trading N is an innovative way to apply and manage an end of catchment N load cap.	• Water quality credit trading in N offsets has the potential to be an important facilitator of cost-effective economic expansion along GBR coast, with no net decline in water quality. • DIN credit trading can help deliver DIN load reductions, ideally at relatively low cost, where the buyers are not emitters (e.g. Qantas etc). Where the buyers are emitting N loads (e.g. STPs) and are offsetting via DIN credit purchases, this simply reduces the cost maintaining catchment DIN loads by offsetting loads which would otherwise push the total end of catchment DIN load above its current level. • Considerable effort would be required to establish and manage an N trading scheme in the GBR catchments.

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		potentially supplying 550 - 750 kg of DIN credits annually. • Sewage Treatment Plants (STPs) are licensed point source N emitters and potential buyers of DIN credits along the GBR coast. Aquaculture has less potential due to the strict discharge requirements for new developments. • Farm-scale constructed treatment systems and other forms of land-use change look particularly promising as a source of DIN credits in cane-growing catchments. • The implementation of a trading scheme in the context of current legislation, offset policies and emissions between land uses (quantity and costs) identified several potential challenges, most of which could be overcome with suitable governance arrangements. • However, additional investigation still required around quantifying N losses (transport pathways from paddock to Reef esp. via drainage, delivery ratio, equivalency ratio and environmental integrity), launching scheme at scale and in-catchment monitoring technology. •		
Project 3.1.8: Exploring economic levers: a system for underwriting risk of practice change on cane-farming (Peter Thorburn, CSIRO)	Thorburn et al. (2020)	• A prototype insurance product was developed for insuring the risk to cane yield from reduced N rates. • Simulation based methods were used to assess risk of loss and size of a loss related to N application and cane yield. • Sugarcane farmers, Canegrowers and insurance companies collaborated in the development of this prototype product. • Indicative pricing shows that there are many situations where premiums are less than money saved on fertiliser.		• Insuring against the risk of sugarcane yield loss with reduced N fertiliser applications is technically feasible, however establishing commercial viability will require considerable effort to build understanding of, and trust in the product amongst farmers. • Steps will also be required to facilitate potential insurers and re-insurers understanding and assessing the commercial viability of the product.

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		• The approach has been tested with farmers via participatory rural appraisal processes with positive feedback, and international crop insurance companies think the product is conceptually sound and could potentially be developed to commercial reality however questions about pricing and demand require further consideration. • The wide uptake could result in a reduction in DIN discharge of ~1,000 t/yr.		
Solutions: Evaluating options				
Project 3.10: Benchmarking costs of NRM improvements for the GBR (John Rolfe, CQU)	Rolfe and Windle (2016)	• Cost-effectiveness is the ratio of water quality improvements (such as reductions in sediment or nutrient loads) to the costs of achieving the change. • There is very limited data available on cost-effectiveness of Reef Rescue grant programs, even though returns on investment should have been key criteria for funding allocations. In part this is because modelling information to predict pollutant reduction has been limited for NRM groups when allocating project funds. • Results show substantial variation and heterogeneity in cost estimates, even after allowing for systematic differences in the estimation of both costs and emissions. This confirms that cost-effectiveness should be a key criteria for project prioritisation and funding evaluation. • Benchmarks for cost-effectiveness are a mechanism to set thresholds or caps for funding. Approximate cost-effectiveness thresholds can be set at the average of achieved and predicted costs for end-of-catchment loads: • Sediment: $259/tonne	Benchmarks were established for guiding cost-effectiveness assessment in prioritisation of projects.	• Tools to model pollution changes at the project selection point be developed. • Data on cost-effectiveness should be automatically collated at the project level when predictions of improvements are made and funding is allocated. • There should be greater emphasis on cost-effectiveness in project selection. • Program design should be adjusted away from a reliance on simple grant mechanisms to processes that optimise price discovery and project selection. • Benchmarks should be applied in program funding to set limits on program and project funding levels, and help in prioritisation of projects. • Benchmarks should be further developed to identify lower, average and upper ranges for expected cost-effectiveness benchmarks.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
		• Nitrogen (DIN): $150/kg • Pesticide (PSII): $8,351/kg • There can be considerable inconsistency in cost-effectiveness estimates between programs and regions due to variations in data collection and modelling approaches.		
Project 4.12: Measuring cost-effectiveness and identifying key barriers and enablers of lasting behavioural change in the cane industry (Sharyn Rundle-Thiele, GU)	Rundle-Thiele et al. (2021)	• Research aimed to support and guide investment and planning decisions that translate into water quality improvement benefitting the GBR catchments. • Evaluation of the effectiveness of programs supporting farming practice change, including considerations for site-specific influences (particularly by soil), and other mechanism-related issues. • Examination of the cost effectiveness of past and current government investments in projects supporting farming practice changes, with the cost-effectiveness of Reverse Tenders being substantially better (at an average $7.74/kgDIN at EoC in 2018 dollars) than that reported for other mechanisms for reducing nitrogen losses from sugar cane (e.g. Reef Rescue Programme, at ~$150/kgDIN reduction at EoC). • Identification of enablers and barriers to farming practice change adoption, including a range of demographic, psychographic, financial, information and communication, extension support, training, and farm management factors.	Develop methodologies for assessing cost-effectiveness and for identifying key drivers of variation in cost-effectiveness in data-challenging situations.	The outcomes of this research project point to the need for a holistic approach that clearly acknowledges the issues and identifies and implements solutions in consultation with stakeholders. Key recommendations included: • Fostering shared responsibility: localised evidence is needed so that all stakeholders involved understand that 'this is my problem'. • Upskilling extension support services: stakeholders identified the need for advisors to provide consistent advice with guidance focused on optimising change outcomes and farming practices. • Change communication practices: need for positive stories (which can deliver hope and inspiration for others) and more simplified information. • Change industry leadership practices: strong advocacy from leaders in industry is needed to acknowledge that pesticide and nutrient reduction is a necessity and that industry is taking ownership and is part of the solution.

Project Title	Refs.	Summary of research outcomes	Innovations	Implications for Management
				• Change evaluation practice from a 'prove' mindset towards an 'improve' mindset, focusing on learning from experiences gained to understand which improvements are needed to extend program success. Evaluations should be undertaken throughout the project, not just at the end, to avoid costly mistakes through early identification of approaches that are not working. Recognise all stakeholders shared responsibility using mapping methods such as 'Creating Collective Solutions'. Coordinated evaluations (farmer-focused, not project focused) led by an independent third party which no involvement in the sugar cane sector are recommended.
Project 1.5: Legacy of the Lower Burdekin Water Quality Tender (Romy Greiner, JCU)	Greiner (2015)	Research provided evidence that the Tender: • Engaged in an information and communications strategy which generated high levels of participant satisfaction during Tender implementation, but apparently with less satisfaction in transparency and communication once funding decisions were made; • Incentivised the participation of many farmers who had not previously done anything about WQ; • Effected learning about the impacts of agriculture on WQ, generating intrinsic motivation for many participants to be wanting to do more about improving WQ; • Sparked subsequent investments into WQ	The Tender's focus on information, education and one-on-one engagement with participants generated high levels of participant satisfaction during Tender preparation. But satisfaction decreased after	Lessons identified that could inform the design of future tender-based environmental funding programs: • Systematically build ex-post evaluations into all competitive tenders, covering both participants' experiences as well as effectiveness, and ideally in 2 times (one right after program completion and another one 3-5 years later to explore longer-term results). Include an external reference group in the analysis; • Treat information sessions as an

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		improvements (funded either by farmers or with assistance of other NRM funding programs); and, • Facilitated farming-systems change to more environmentally benign practices in some instances. • The Tender failed in achieving its anticipated pollution reduction because some major projects did not proceed due to cost under-estimation during proposal preparation.	project selection.	opportunity for educating landholders about the conservation issues (which can create intrinsic motivation to 'do the right thing'); • Provide technical advice for bid development and maximise accuracy of costing assumptions. • Maximise transparency of process and communication of funding decisions; • Offer assistance to try to overcome impediments to project implementation and be prepared to reallocate unused funding to bids down the order of merit. • Engage with industry at a grass-roots level in the design of new policies and programs, to maximise industry acceptance and collaboration.

Photo: Nathan Waltham

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