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Final Report

'Project 25': Engaging with farmers and demonstrating water quality outcomes to create confidence in on-farm decision-making

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‘Project 25’: Engaging with farmers and demonstrating water quality outcomes to create confidence in on-farm decision-making

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Cover photographs: (front) Demonstrating real-time water quality monitoring equipment in the field to farmers in the Russell-Mulgrave catchment. (back) Dr Aaron Davis, James Cook University and local canegrower in the field assessing prospective water quality monitoring site locations. Images: Boyd Robertson.

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

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ACRONYMS

BMP.............. Best Management Practice
CSIRO .... Commonwealth Scientific and Industrial Research Organisation
COTS .... Crown-of-thorns starfish
DIN .... Dissolved Inorganic Nitrogen
DAFF .... Department of Agriculture, Forestry and Fisheries [Queensland]
FRP .... Filterable reactive phosphorus
GBR.............. Great Barrier Reef
GBRCA......... Great Barrier Reef catchment area
GBRCLMP.... Great Barrier Reef Catchment Loads Monitoring Program
ICT .... Information and communication technology
IoT................. Internet of Things
ISO................ International Organisation for Standardisation
JCU............... James Cook University
N .... Nitrogen
NESP .... National Environmental Science Program
NRM.............. Natural Resource Management
P2R............... Paddock to Reef
RRRC............ Reef and Rainforest Research Centre
RTWQM........ Real-time water quality monitoring
SRA .... Sugar Research Australia Ltd.
TWQ .... Tropical Water Quality

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EXECUTIVE SUMMARY

Recent monitoring from the Great Barrier Reef (GBR) catchment area suggest current dissolved inorganic nitrogen (DIN) load reduction trajectories fall well below desired targets, despite considerable investment in improved management practise and engagement with agricultural industries. In parallel with the global experience, the demand for more transparent GBR water quality science has increased. This has been driven in large part by agricultural stakeholder concerns about the robustness of the scientific underpinning of government policy, particularly the evidence-base justifying regulation of farm practices that impact water quality outcomes in the Great Barrier Reef. These outcomes highlight fundamental failures of current policy mechanisms to change farmer's underlying attitudes and behaviours.

This report outlines the design, project management, and results of 'Project 25' – farmers, water quality and on-farm decision-making, funded under the Australian Government's National Environmental Science Program's (NESP) Tropical Water Quality (TWQ) Hub. Initiated through discussions between the Australian Government, and large-scale sugarcane producers in the Russell-Mulgrave River catchment, 'Project 25' addresses the expressed need for 'bottom-up' water quality research to engage more directly with farmers to establish stronger, and more tangible feedback loops between water quality science and management. Collective Project results indicate:

- The social research conducted as a component of Project 25 highlighted the importance of investing to build a trust-based environment for dialogue between growers and scientists on a contentious topic. Interviewees reported improved communication, an improved trust environment with more direct oversight of monitoring data, and 'space' to learn and experiment as contributing factors to their engagement. Interviewees also described 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.

- The importance of investment in building trust, maintaining research practice and data transparency with stakeholders, and the critical role of informal learning and training are essential components to achieving impact-based research outcomes. These end-user engagement processes are not trivial, and take considerable time to develop. Broad Project 25 program results align with growing calls for recognising the input of various stakeholders and forms of research outside traditional science-government, within the process of research and development.

- There was clear evidence of progress 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.

- The Project has enhanced the capacity of some grower participants to act as leaders and influencers within their local farming community and networks. Members of the Steering Committee regularly advocate the rationale and benefit of the project in public and particularly 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 is 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 are 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 out into the industry.

- Having near real-time and visual evidence in the 'data' (e.g. nitrate-nitrogen) 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.

- 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 benefits of the project, and with the possible benefits from wider application of the project model to other districts.

As well as the social dimensions to stakeholder engagement and farming practice change, there were also several notable technical, biophysical or program design elements emerging from the water quality monitoring aspects of Project 25.

- Use of emerging Nitrate-N sensor technologies provided a degree of accurate, high frequency detail to sub-catchment nitrate-N fluxes that would be outside the scope (and particularly budget) of most 'traditional', discrete sampling-based water quality monitoring programs. The capacity to provide this local information, in near real-time, to participating Project canegrowers proved a valuable component of stakeholder engagement.

- Monitoring of Project 25 sub-catchment Nitrate-N loss dynamics highlight that, some of the highest nitrate-N concentrations, as well as a significant proportion of annual nitrate load losses from cane-dominated catchments can often occur in the first 3-4 significant rainfall-runoff events of the year. This indicates the earlier portions of annual runoff from sugarcane dominated catchments often transported a greater proportion of DIN mass across the wet season.

- While the 'first flush' phenomenon has been most frequently demonstrated in small urban catchments, a growing body of research from agricultural catchments is also suggesting elements of first flush behaviours in water quality dynamics from farming land-uses. The results of Project 25 (and other recent paddock scale research) suggest that the first flush phenomenon can also occur in GBRCA agricultural watersheds, and the concentrated initial load loss process may provide an important potential intervention point for the management of diffuse pollution. For example, growing numbers of global examples exist of controlled drainage strategies in agricultural ditches (prevalent across GBRCA floodplain) to reduce nitrate-N export through measures such as spatially orientated low-grade, relatively low cost weirs.

- Project 25 also provided clear capacity for nitrate-nitrogen 'hotspot' identification in the broader Russell-Mulgrave catchment. Sub-catchment areas consistently responsible for generating relatively high nutrient losses emerged with ~3 years of monitoring effort. These areas became Project foci for additional fine-scale monitoring, as well as extension and engagement effort from industry support programs.

- The increasing availability and decreasing costs, of reliable, fit-for-purpose, field deployable sensor technologies is opening up genuine scope for fine-scale, sub-catchment monitoring to complement current end-of-catchment GBR water quality monitoring efforts. Recent global experiences suggest that spatially identifying and prioritizing 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. Many outputs of Project 25 support this contention.

1.0 INTRODUCTION

The management of diffuse agricultural water pollution, particularly nutrient eutrophication, remains one of the most significant, pervasive, and costly global natural resource management challenges (OECD 2012, Queensland Government 2015, Sobota et al. 2013; 2015). With projected increases in crop demand to meet global food security (Tilman et al. 2011), associated expansion and intensification of agricultural land use is likely to escalate already significant pressures on aquatic ecosystems. Similar collective policy responses across many industrialised countries are marked by reliance on mostly voluntary approaches to address agricultural non-point sources, but increasing shifts towards regulation of farming activity in regions under most pressure (Kleinman et al. 2015). The failures of largely voluntary schemes to foster practice change are being used to increasingly advocate increased regulation of farming activities (Kroon et al. 2015). Recent appraisals of the cost-effectiveness of some compulsory compliance policies in delivering practice change or water quality improvements are, however, also decidedly mixed (Worrall et al. 2009; Kay et al. 2013). Some of this regulatory failure is attributed to fundamental failures of policy mechanisms to change farmer's underlying attitudes and behaviors (Barnes et al. 2013).

1.1 The Great Barrier Reef catchment area

Much of this global experience has been recently exemplified in Australia's Great Barrier Reef (GBR), and its upstream Catchment Area (GBRCA). Threats to the GBR environment are multiple, cumulative and increasing. The primary drivers of change in the region are climate change, coastal development, land-based run off and direct use (GBRMPA, 2019; Waterhouse et al., 2017). Climate change, in particular, has been identified as 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). Increasing sea temperatures (i.e. 0.8 °C on average since 1910) and marine heat waves caused successive bleaching events in the GBR in 2016 and 2017, followed by widespread coral loss and flow on effects on the overall ecosystem health. GBR ecosystems do have a natural resilience against acute physical disturbances, such as tropical cyclones and heatwaves. However, climate change is exacerbating both acute and chronic disturbances, reducing the timespan of recovery windows and limiting resilience capability (GBRMPA, 2019a). Accordingly, while national and global responses to address climate change are essential, a strong focus is also required on maintaining and improving current ecosystem resilience in the face of a variable and changing climate (Commonwealth of Australia, 2015).

Poor water quality, mostly due to land-based run-off (i.e. mainly nutrients, fine sediments and pesticides associated to agricultural industries) from the adjacent catchments, is another major driver of change within 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 can cause important ecological impacts including lower coral diversity, algal blooms (that can also reduce light), enhanced outbreaks of coral-eating crown-of-thorns starfish (COTS), increased susceptibility to coral bleaching and some coral diseases. Dissolved inorganic nitrogen (DIN) is considered most relevant of the nitrogen species in terms of ecological impact, due to its immediately availability for biological uptake, with particulate nutrients typically bound to sediment particles or in a more refractory organic form, talking time for biological transformation (Waterhouse et al. 2019a).

Across all catchments discharging into the GBR marine ecosystems, agricultural land use is the major source of nutrients, pesticides and sediments (Figure 1; Kroon et al., 2016). Pastoral grazing systems occupy >80% of the area and account for most of the sediments loads to the GBR (Waterhouse et al., 2012). Intensive cropping systems (sugarcane, bananas) occupy <5% of the area but account for most of the dissolved inorganic nitrogen (DIN, nitrate + nitrite + ammonium) discharged from the catchment (14–940 tonnes year^{-1}, Napel et al., 2019). Sugarcane (*Saccharum officinarum* L.) is the dominant crop contributor to anthropogenic nitrogen load exports from the GBRCA (Thorburn et al., 2013; Thorburn and Wilkinson, 2013), contributing 43% of the total load and 78% of the anthropogenic load (Bartley et al., 2017). This is by virtue of its large land area (~380,000 ha of the whole GBRCA; Furnas, 2003), location on the coastal fringe, crop growth in many zones of high rainfall or irrigation (1000–4000 mm year^{-1}), and significant annual synthetic nitrogen fertilizer applications (130–200 kg N ha^{-1}; Thorburn et al., 2013; Davis et al., 2017).

Other land uses - including urban, mining and industrial areas - contribute relatively small but concentrated pollution loads, for example, urban areas contribute 9% of the anthropogenic DIN load. These land uses usually only cover small areas, so the total load delivered to the GBR is comparatively small to the more widespread agricultural land uses, however may have important local impacts depending on the characteristics of the receiving environment (Bartley et al., 2017). Whereas undisturbed landscapes can export large quantities of DIN, but generally at low concentrations (Brodie and Mitchell, 2005).

Key management responses by the Australian and Queensland Governments in the GBRCA include incentive-based voluntary management initiatives for landholders for adoption of improved land management practices, regulation of sugarcane and grazing management practices in priority areas, agricultural extension programs, and paddock and catchment water quality monitoring and modelling initiatives to both quantify and/or predict water quality improvements associated with specific management change (Brodie et al., 2012; Carroll et al., 2012). The Australian and Queensland Government's recently released Reef 2050 Long-Term Sustainability Plan set a target of 60% reduction of anthropogenic end-of catchment DIN loads by 2025 (Commonwealth of Australia, 2018). Achieving these targets requires farmers in the GBR catchments to alter crop management so that nitrogen losses to the environment are minimised.

The export of DIN from sugarcane farms is directly related to 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 et al., 2013). Applying N fertiliser in excess of crop needs is a rational response by farmers growing high value crops, including sugarcane, to minimise the risk of crop growth and yield being limited by N. Thus, the primary and most well proven path to reducing DIN impacts on the GBR is to encourage farmers to reduce N fertiliser application rates to sugarcane crops (Thorburn and Wilkinson, 2013); currently other approaches are secondary to this goal.

While there have been some improvements in catchment water quality on a regional scale due to modest improvements in agricultural land management practices (e.g. such as adoption of the CANEGROWERS Smartcane Best Management Practice framework for the sugarcane industry), poor water quality continues to affect inshore areas of the GBR (GBRMPA, 2019a; Gruber et al., 2020). The most recent Reef 2050 Water Quality Improvement Plan Report Cards (2015-2019) for example, highlight, that while landholders have made some progress in adopting improved land management practices across the GBRCA, the uptake of improved practices remains slow. Pollutant load reduction trajectories fall well below desired target reductions particularly for DIN and Photosystem II herbicides, two parameters of significant relevance to GBRCA sugarcane cultivation (The Government of Queensland, 2018). These most recent 'Report Cards' highlight the need for identification of priority issues and spatial priorities for investment in water quality improvement initiatives, supported by robust and comprehensive monitoring and evaluation techniques.

Similar to the contested environment of other 'wicked problems' such as climate change – one with substantial complexities and uncertainties, profound interdependencies, few 'silver bullet' solutions, and dynamic challenges, the science and management of diffuse water pollution is facing growing scrutiny. With GBR water quality science increasingly used to shape policy (Waterhouse et al., 2017), scientists, research organisations and policy-makers are increasingly required to justify why they made certain decisions or provided certain advice. In parallel with the global experience (Duarte et al., 2015, Browman, 2016, Özkundakci et al., 2018), and the demand for more transparent GBR science has increased (Larcombe and Ridd, 2018). The spectre of government regulatory oversight of farming practices since 2008-2009, in particular, has seen repeated pushback from GBR primary industries, driven in large part by questions of the robustness of science underlying policy. This contention has evolved to a point of a recent formal Australian Government Senate Inquiry into the robustness of the evidence-base justifying regulation of farm practices that impact water quality outcomes in the Great Barrier Reef (Australian Government, 2019; 2020).

Evidently, while the biophysical understanding of sources, fates and consequences of pollutants in the GBRCA has advanced markedly over recent decades, fostering effective farming stakeholder engagement and practice change clearly remains a considerable challenge to long-term water quality improvements. The need for innovative approaches to promoting farming practice change and targeting investment are increasingly recognised (Great Barrier Reef Water Science Taskforce; Department of Environment and Heritage Protection, 2016). Similarly, many of the key recommendations emerging from the recent Senate Enquiry explicitly emphasise the need for much more considered, and constructive, scientific and policy engagement with key agricultural commodity stakeholders (Commonwealth of Australia, 2020).

1.2 The Russell-Mulgrave catchment and origin of "Project 25"

While farming industry concerns surrounding GBR water quality science were exemplified in the recent Senate Inquiry, they have been evident, or at least emerging, for a considerable period of time. Recurrent themes in GBRCA canefarmer attitudes to various water quality issues and policies include; scepticism that water pollution problems even exist; aversion to responsibility for contributing to water pollution problems; lack of faith in scientific information/modelling collected by external agencies (particularly government); and absence of local data directly relevant to their farming activities (Di Bella et al., 2015). Indeed, it was these concerns that led to the inception of Project 25. The then Federal Minister for

Environment, the Hon. Greg Hunt, met with large scale sugar producers in the Russell-Mulgrave River catchment in late 2015, during the launch of the Australian Government National Environmental Science Program (NESP; a funding program to support decision-makers through provision of the best available information, to help them to better understand, manage and conserve Australia's environment). Local canefarmers collectively advocated for the need for GBR water quality research to engage more directly with farmers, and to establish stronger and more tangible feedback loops between science and industry. Through discussions with local canegrowers, the Minister proposed an approach that engages growers through a citizen science monitoring program conjoined with a robust scientific monitoring program. The development of more localised, adaptive, targeted and timely feedback loops between water quality information and growers was desired to strengthen the trust relationship between scientific outcomes and decision-making relating to on-farm practices.

The underlying premise of Project 25 was that local canegrowers would 'steer' the catchment water quality research effort, and collectively use it to identify 'hot spot' sub-catchment sites through comparative analysis of the water quality data. This approach would enable growers to participate directly in the monitoring design and collection of results, ensuring that farmers can recognise themselves as part of the solution to improving catchment water quality. Learnings emerging from this model were then to be used to inform a range of broader extension activities in other districts relating to water quality issues. While emphasising 'canegrower empowerment' in program management, the Project was still developed to ensure clear alignment with stated Australian Government NESP TWQ Hub Research Priorities, namely:

1a) Local scale identification of priority contaminant export loss (hot spots) for better targeting of on-ground works and 'tailored extension' activity.

1c) Develop/evaluate practical on-farm nutrient and sediment loss mitigation and capture and land management practices that will influence behavioural change and improve water quality outcomes.

1e) New methods for encouraging behaviour/practice change/improving compliance with BMP.

The project emphasised industry ownership, and enabled growers to participate directly in the water quality monitoring design, overall management, and delivery of locally targeted water quality data and extension effort to facilitate practice change within the sugarcane industry. A broad philosophy of the project was to also provide a greater understanding of behaviour change drivers relating to on-farm management practice decision making and water quality outcomes to inform future Reef Plan extension and engagement activities.

2.0 METHODOLOGY

2.1 Project study area

The Russell-Mulgrave is one of the larger catchments in the GBRCA's Wet Tropics, in terms of area, rainfall, and discharge to the Reef lagoon (Furnas, 2003). The Russell-Mulgrave basin is one of the wettest areas in Australia with high run-off to rainfall ratios and frequent run-off events. The average annual rainfall on the coastal plain in the Russell-Mulgrave exceeds 3,000 mm year^{-1}, with 60 per cent of the annual rainfall occurring in the summer wet season (December-March). Due to the steep topography of the region and the close proximity of mountain peaks (Mount Bellenden Ker and Mount Bartle-Frere) to the coastline (<25 km), transit times between coastal rainfall and oceanic discharge are very rapid, suggesting minimal residence times. These major discharges from the combined Russell and Mulgrave rivers contribute to the frequent flood plumes within the Reef lagoon.

The Russell-Mulgrave catchment is one of the top five basins contributing anthropogenic dissolved inorganic nitrogen (DIN) loads from the GBR catchment area (930 tonnes year^{-1}) (Scientific Consensus Statement, 2017). Moreover, catchment DIN yields in the Russell-Mulgrave catchment also rank as some of the highest in the GBR catchment area (~470 kg km^{2} year^{-1}), with the Reef 2050 Water Quality Improvement Plan 2017-2022 (WQIP), identifying the Russell-Mulgrave as "High risk" for DIN (State of Queensland, 2018). Most DIN comes from sugarcane production, and some banana cultivation, within the catchment area.

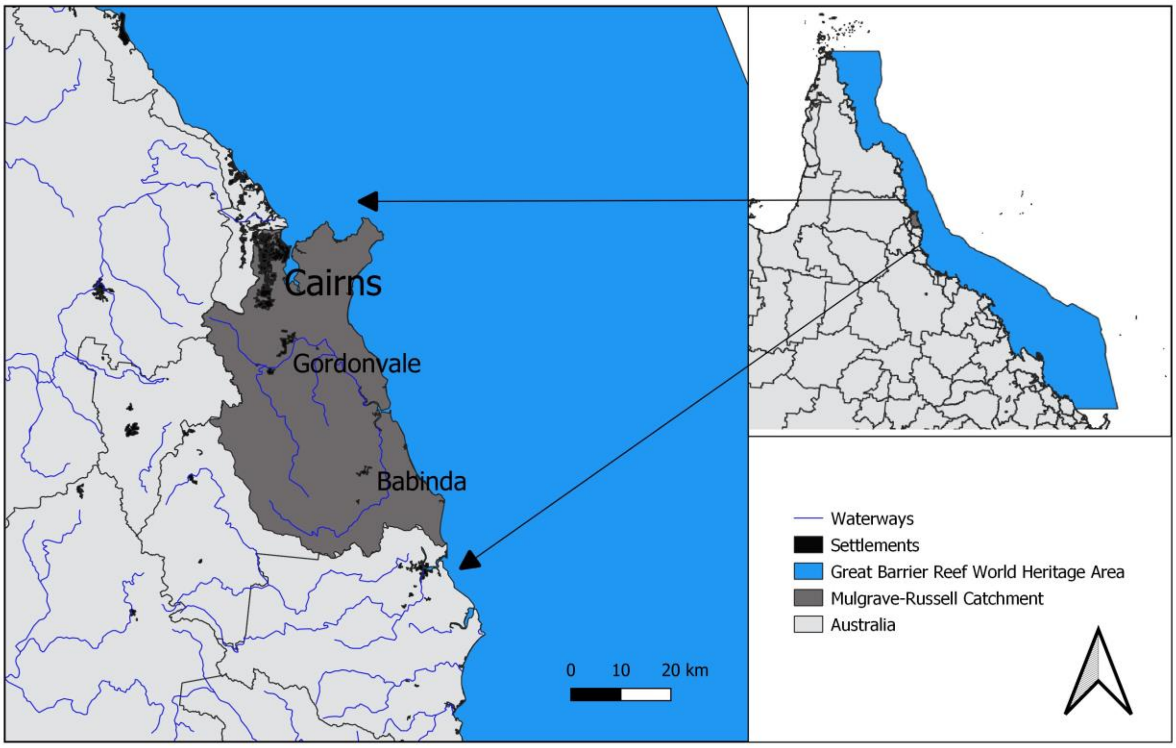

Figure 1: Map of the Russell-Mulgrave catchment, Wet Tropics and Great Barrier Reef World Heritage Areas. Source: Simon Fielke (CSIRO)

Many of the water quality and agricultural stakeholder communication and engagement challenges mentioned earlier at both global, and GBR scales are also readily apparent in the Russell-Mulgrave catchment. Current GBR water quality monitoring, evaluation and communication is centred around the Queensland Government's Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program; 'P2R'), integrating data and information on agricultural management practices, catchment indicators, paddock monitoring and modelling; and catchment load monitoring and modelling (Carroll et al., 2012). The catchment load monitoring component of P2R is conducted by the Great Barrier Reef Catchment Loads Monitoring Program (GBRCLMP), managed by the Queensland Government Department of Environment and Science. Initiated in 2005, the GBRCLMP monitors and reports on the total suspended solids and nutrient loads as well as pesticide risk exported from major priority river basins adjacent to the GBR, and assists in evaluating progress towards the water quality targets of Reef Plan. While the Great Barrier Reef Catchment Loads Monitoring Program was implemented in 2005, it is only relatively recently (the 2014–2015 monitoring year), that two end-of-catchment sites in the lower Mulgrave River and Russell River were commissioned into the monitoring program. It is only recently, therefore, that local farmers had access to water quality monitoring data and reporting from their own catchment.

The broad scale of traditional catchment-based water quality monitoring programs such as the GBRCLMP typically lack the spatial and temporal resolution to inform and convince individual landholders of their role in contributing to water quality impacts, but also managing catchment-scale pollution at local scales. The two relatively recent GBRCLMP monitoring sites on the Russell and Mulgrave Rivers, for example, are essentially end-of-catchment sites, accounting for 522 km^2 (93% of catchment area) and 789 km^2 (98% of catchment area) respectively (Wallace et al., 2016). These large monitored catchment areas, containing dozens of individual farms, as well as several other major land uses, can confound or trivialise the perceptions of individual landholder contributions to cumulative water quality impacts. GBRCLMP results are also, for example, typically reported collectively across catchments and land uses. Because of the scale of data collected, delays associated with laboratory sample analysis, discharge data collection, compilation and validation, and quality assurance, reporting of results typically occurred approximately 1-2 years after a specific year's monitoring took place (see Wallace et al., 2016; Huggins et al., 2017). While the current, long-term GBRLMP design is world-leading, and entirely appropriate to its primary aim of monitoring and bench-marking catchment progress toward Reef 2050 Plan targets, site number, scale and reporting delays do present many constraints for its use with associated natural resource management (NRM) initiatives, particularly engagement with key stakeholders in the agricultural sector of the Russell-Mulgrave catchment.

Another notable feature of the Russell-Mulgrave cane growing industry, is the scale of its farming enterprises in comparison to other priority catchments across the GBRCA. The Russell-Mulgrave catchment generally has much smaller farm sizes than other wet and dry-tropical cane farming regions (Davis and Waterhouse, 2016). This creates associated challenges for farmer practice change– with the relative costs of changes likely to be larger on these smaller farms due to economies of scale (see Poggio et al., 2014; van Grieken et al., 2014; Smith, 2015). Because of this local history surrounding water quality monitoring and engagement (or lack thereof), the Russell-Mulgrave catchment was an area clearly posing considerable challenges for water quality-related extension, and promoting uptake of improved farming practices for water quality.

2.2 Project inception, Social setting and project oversight

2.2.1 Establishment of Stakeholder Steering Committee.

The appropriate mechanisms for identifying ‘the who’ with respect to industry engagement and ‘buy-in’ is an important consideration, often overlooked in the design, implementation and communication of water quality monitoring programs. The use of people from farming backgrounds or trusted networks is well-known to enhance message uptake and farmers’ inclination to process in-group messages. Farmer-to-farmer programs in Canada and the U.S. have been very effective in delivering conservation practice technical assistance, but usually required additional funding, as well as the use of dedicated extension agents to work directly with small groups of farmers to encourage adoption of nutrient management practices (Blackstock et al., 2010; Osmond et al., 2012). Establishment of a ‘Integrated Area Wide Management’ working groups with local farmers, key service providers (selected peak industry representatives, extension staff) and scientists-government agency personnel were similarly a cornerstone of the cotton industry efforts in achieving demonstrable water quality improvements in central Queensland (Wolfenden and Evans, 2007; Kennedy et al., 2012).

Longer-term discussions with disgruntled large sugarcane growers in the Russell-Mulgrave catchment led to the establishment of the Stakeholder Steering Committee for Project 25 well before the project itself was even announced. At this point, growers were being blamed for the poor water quality run-off to the reef from the catchment. The initial invited grower collective that met with the Minister for the Environment in 2015 were specifically identified and recruited for their industry roles as large, influential growers, and reputations as industry leaders. Rather than a typical engagement approach often previously seen in the GBR catchment area involving interactions with ‘the willing’ farmers (‘low hanging fruit’), Project 25 specifically targeted and engaged major industry operators from the outset of the program development. Part of the subsequent agreement with these growers for their role in Project 25 oversight and management would be their willingness to act as Project advocates and spokespeople at local industry levels.

> *“Increasingly, we hear the concerns about the impact of farming on the Reef. To be honest, we believe some of it, but most of the reports we are sceptical about. We are sometimes told that we are the worst polluting catchment and at other times that title goes to Tully or the Herbert. We are told that the information comes from the ‘end of catchment’ water quality modelling. I can tell you that very few farmers believe that modelling. However, it would be TOTALLY wrong to say that we are NOT committed to improving our region and want it to be the best it can be.”*
>
> Sugarcane grower, Babinda

The stakeholder steering committee also included State-level CANEGROWERS organisation members, non-government organisations (NGO) and science/academic members to provide the requisite policy and technical oversight.

2.2.2 Communication and trust frameworks

A critical part of the early development of the Project 25 model was the industry engagement necessary to establish robust science-industry trust frameworks, particularly industry faith in the overall process. Global extension experiences consistently stress the critical importance of often complex agronomic, technical and/or environmental advice being delivered to involved farmers through trusted, high credibility contacts (i.e., key service providers, extension staff) as a key driver of change (Blackstock et al., 2010; Kennedy et al., 2012; Osmond et al., 2012). High credibility sources are particularly important when messages are complex, there is little available experience, and/or a message carries a high personal risk (Blackstock et al., 2010). These are all issues characteristic of agricultural sector engagement with water quality and practice change. Given the consistent concerns on the part of the GBR catchment area canegrowers regarding the veracity of current catchment modelling-monitoring initiatives, these trust frameworks became a critical design consideration for Project 25. Use of water quality scientists with established experience and rapport with the sugar industry and water quality issues was accordingly also an important part of the program development.

Appropriate information confidentiality and data dissemination frameworks were similarly a critical consideration in study design for grower engagement and collaboration. While freedom of information considerations may desire immediate transparency of monitoring data (particularly in taxpayer-funded programs), because of the potential immediate accessibility and sensitivity of water quality monitoring programs in particular, lack of context could result in misinterpretation of results made publically available in 'real-time'. Recent experiences within other GBR sugarcane catchments highlight a safe learning environment is essential for data sharing partnerships to consolidate (see Di Bella et al., 2015). While there was stakeholder steering committee agreement that data would eventually become publicly available, interim embargoes or limited access to real-time data streams were established with data presentation limited to directly involved project stakeholders. Recognising industry desires to receive appropriate opportunity to digest and interpret monitoring outcomes, and proactively develop strategies and implement activities to address identified issues are an important component of the trust framework, and one that has been used successfully in similar programs (see Di Bella et al., 2015).

> *"This project allowed us to monitor the catchment in real-time. More importantly … it allowed us to place the automatic monitors where we believe we needed the information – like testing the water out of the rainforest and around the towns as well as big farming sites. A big effort was made for us to see the results quickly without the information being used against us. We can now see where the problems are and where they are not."*
>
> Sugarcane grower, Babinda

This initial data provision and presentation is an important component for both steering committee growers and scientists involved in the project. It provides scope for local catchment knowledge to be framed into better message delivery from scientists to industry, and also developing consistency in appropriate messaging and data interpretation back to the broader industry. Steering Committee canegrowers were regularly appraised on program updates and results (in some cases as notable local water quality events such as nitrate 'spikes' were taking place). Annual wet season summary meetings were also held after the cessation of each wet season, with all results presented and discussed with the collective steering committee. This provided both farmers and scientific staff the opportunity for detailed discussions as to the local contexts and possible drivers of observed results (antecedent weather, timing of farming operations etc.). Local water quality results were then typically disseminated to the broader growing community through a variety of processes such as annual local CANEGROWERS meetings (50-100 growers), through to small-scale shed meetings at a local sub-catchment scale (5-6 growers) coordinated with local extension agencies (CANEGROWERS etc.).

Recognising and cultivating these trust frameworks (which do not happen instantaneously), are a critical and requisite first step required before major effort is made on attempting to significantly change grower behaviour on-ground. Feedback from Project 25 canegrowers includes:

> "*It has been invaluable that the growers and researchers are communicating, sharing their issues and ideas, understanding each other's challenges and building a trust framework. This approach can only have a positive effect and because of this, real gains are achieved*".

And,

> "*Minimising our own impact on the surrounding environment, that is what all sectors of the community strive for. A project such as this, building knowledge and trust, puts the farming sector in a position to best control the impact that they have on water quality*".

A major evolution of Project 25 (and evidence of local cane industry faith and comfort in the process and scientific interaction) was stakeholder committee agreement to partnership with CSIRO to include Project 25 as a key partner in the GBR Water Quality theme within the CSIRO 'Digiscape' Future Science Platform (https://research.csiro.au/digiscape/). The Digiscape initiative identified how canefarmers can best use local environmental information collected through sensing technologies (near real-time water quality, weather, crop production data) to alter management decision-making on farm, and ultimately change farming practices. Project 25 canegrowers were key contributors to development of the 1622™WQ web app that makes local water quality monitoring data more accessible and relevant to farmers (see Vilas et al., 2020, and section 4.1 of this report). So while initially limited data sharing may give the perception of a project acting as a 'black box' (a criticism farming stakeholders often direct a government programs), results suggest farming stakeholders become amenable to broader data sharing and engagement with external groups once they feel comfortable with trust processes and collaborators.

2.2.3 Program Water Quality Monitoring Design

A key industry aim of Project 25 was to characterise the water quality impacts and relative contributions from the distinct land-use types found across the Russell-Mulgrave catchment, and quantify the sugarcane industry's specific role in end-of-catchment water quality. Through grower input and advice, sub-catchment waterway sites were identified and selected to represent the major land uses of the region, namely sugarcane, urban, banana, or natural 'rainforest' land use categories. Sites were also selected based on factors such as wet season accessibility to the site, and the size of the waterway. A total of nine sites were initially selected for the monitoring program through the period 2015-2018 (Figure 2). Monitoring focused primarily on nutrient (nitrogen and phosphorus) and sediment water quality parameters, as these are typically identified as the most important management challenges for north Queensland industries, and considered most relevant to Great Barrier Reef water quality issues (Brodie et al. 2012).

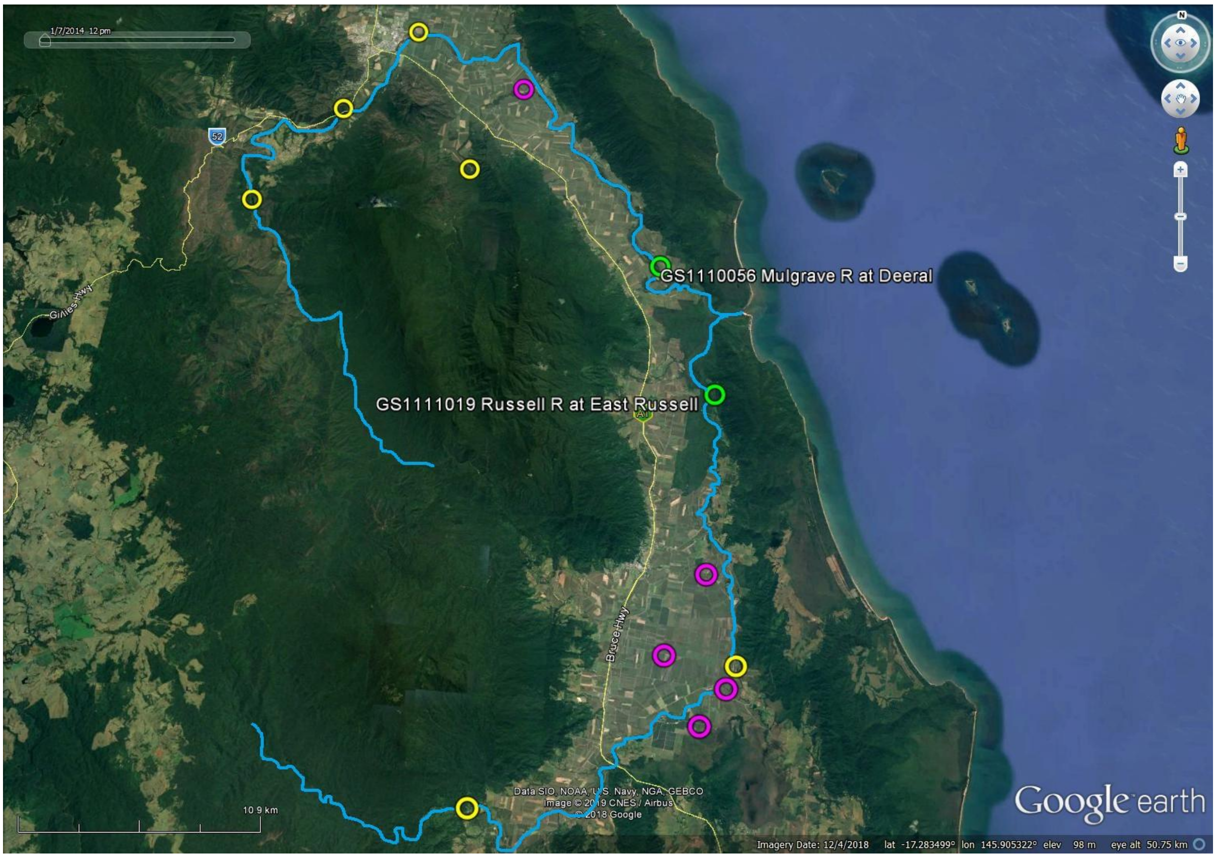

Figure 2: Map of current Project 25 and GBRCLMP water quality monitoring locations in the Russell-Mulgrave catchment. Project 25 Real-time water quality monitoring sites indicated by purple markers, discrete water sample collection sites by yellow. Queensland Government GBRCLMP sites labelled and indicated by green markers.

A key cane industry desire voiced in early stages of program design was for local water quality information to be underpinned by high quality data. A substantial proportion of program budget was therefore dedicated to collection of high quality, long-term water quality data at monitoring sites. Water quality monitoring for Project 25 was based around the integration of relatively traditional monitoring approaches used in the GBR catchment area (discrete sample collection for subsequent laboratory analysis), as well as emerging real-time (sensor-based) water quality monitoring approaches (RTWQM) at a smaller subset of sites. RTWQM uses sensors to provide a high temporal frequency of data, and when coupled with telemetry and cloud based data display infrastructure, can deliver this high frequency data in real time to any end user with an internet connection. The development of real-time information and feedback on local water quality dynamics is a relatively novel approach to landholder engagement that is yet to be meaningfully explored in natural resource management programs. Project 25 trialled these new technologies from both the perspective of an engagement-extension tool, and also their reliability in water quality monitoring applications across multiple spatial scales (paddock to catchment).

Discrete samples for water quality provided the primary monitoring foundation, and were conducted at all sites on an approximate monthly or bimonthly basis during dry-season low flows. Sampling frequency increased to daily (and sometimes multiple samples a day) during wet season flood events, particularly the several initial early wet season 'first-flush' events, to capture initial high concentration run-off dynamics from the immediate catchment area, events that typically provide the highest water quality parameter concentrations, and often a significant proportion of wet season load exports (Davis et al., 2017). Samples were collected either manually or by rising-stage samplers by project scientists, or support staff trained individually in the correct sampling and quality assurance procedures developed in conjunction with the James Cook University TropWATER Water Quality Laboratory.

Water samples were collected in pre-rinsed 1-L polypropylene bottles using an extendable sampling pole. Unfiltered nutrient samples then subsampled into 60-mL polypropylene vials (Sarstedt, Germany), and filterable nutrients filtered on-site through pre-rinsed filter modules (MiniSart 0.45 μm cellulose acetate, Sartorius, Germany) into six 10-mL polypropylene vials (Sarstedt, Australia). Samples were stored on ice following sampling and on-site processing, for transport to the laboratory for subsequent analysis. Water samples were analysed for total nitrogen, ammonium nitrogen, oxidised nitrogen (nitrate + nitrite), filterable reactive phosphorus and total suspended solids following standard methods (Hosomi and Sudo, 1987; APHA, 2005; Bainbridge et al., 2009). Periodic duplicate samples and field blanks were also collected under both wet and dry season conditions as part of Quality Assurance/Quality Control QA/QC procedures.

RTWQM equipment was initially deployed in three selected Russell-Mulgrave sub-catchments in the broader Project 25 monitoring design, identified in discussion with cane industry steering committee personnel. Sensors were current market-ready technologies, in this case TriOS NICO and OPUS optical sensors (https://www.trios.de/en/). Optical sensors are susceptible to reduced performance from biofouling and sedimentation of the optical lens (Steven et al., 2013; Pellerin et al., 2013). Optical sensors utilised during Project 25 were initially cleaned utilising an integrated compressed air blast system to automatically clean the optical window. Recent development of automated, externally mounted lens wiper technologies by TriOS saw these new cleaning technologies added to some sites towards the end of 2018 (Figures 3a, b). Lens were also cleaned manually at least monthly, and often more frequently during significant flow events when sites were safely accessible. Calibration checks of each sensor were conducted at least every three months, using 0, 1 mg/L, 5 mg/L and 10 mg/L nitrate calibration standards provided by the TropWATER Water Quality Laboratory. Initial station design in 2015-17 involved stream water being pumped from the waterway into a flow-through cell, with the nitrate sensor housed inside the streambank sampling station. Some early power issues and equipment failures saw sites re-designed with the sensors installed instream in a PVC pipe, and subsequent sensor measurements all taken *in situ* (Figure 3c).

A key theme emerging from both global and local GBR catchment area experiences is the considerable additional investment and monitoring effort required to elevate 'concentration only' data collection to more detailed data types (Davis and Waterhouse, 2017). The collection of additional datasets to complement concentration data, such as catchment hydrology (streamflow discharge), does require substantial additional monitoring infrastructure and data collection and processing. The broader data formats possible from this investment (pollutant loads, Event Mean Concentrations (EMCs) etc.) are, however, amenable to a much more diverse range of potential uses such as trend analyses, pollutant export coefficients and pollutant loadings from specific land use types. Sampling locations in Project 25 were co-located in several cases with existing streamflow discharge monitoring infrastructure (Queensland Government or Cairns Regional Council gauging stations).

In cases where these were not available, stream height-discharge relationships (rating curves) were developed through standard methods. Stream stage (height) at sites was measured continuously using a Campbell Scientific CS451 pressure transducer hardwired to a CR1000 data logger (Campbell Scientific, Inc., Logan, UT, USA) at all RTWQM sites. Due to minor tidal effects on stream stage at some sites, a simple low-pass Butterworth filter was applied to remove semi-diurnal tidal signal from the measurements (Pagendam and Percival, 2015). A stage-discharge rating curve for sites was derived from repeated discharge measurements over a range of stream stage heights. Instantaneous discharge measures for each site's rating curve were calculated by conventional current meter methods for wade-able streams at lower stream depths (digital water velocity flow meter, Global Water – FP 311, Xylem, USA) and stream cross-sectional areas. Discharge at higher river stages was calculated from water depth and velocity measurements through an accessible bridges or road culvert control sections (Bodhaine, 1968) located near sampling sites.

Figure 3: Alternative optical lens cleaning options utilised throughout Project 25. (a). Compressed air blast; (b) Automated, externally mounted lens wiper. (c). Real-time monitoring station during wet season flood event.

Catchment water quality loads across sites were calculated via linear interpolation using the Loads Tool component of the Water Quality Analyser program (version 2.1.1.6; eWater CRC, 2018). Catchment boundaries and land-use coverage data upstream of all monitoring sites were sourced from the Queensland government land use mapping program (QLUMP; https://www.qld.gov.au/environment/land/management/mapping/statewide-monitoring/qlump/qlump-datasets).

2.2.4 Understanding the social and cultural aspects of industry engagement

An early indication of the engagement success of Project 25 was the willingness of participating stakeholders (particularly within the cane industry) to support additional research into the sociological basis and outcomes from Project 25. An important evolution of the project was the addition of a major social science component in 2018, undertaken in collaboration with researchers from CSIRO Land and Water. The aim of this research was to better understand the human behavioural components of research engagement with the sugarcane industry. These learnings are intended to better design, implement, and evaluate industry wide science engagement programs, better understand the day-to-day challenges facing cane farmers, and to recognise, value and accelerate their efforts to adopt farming practices that help improve water quality.

The underlying rationale for including the Project 25 sociological component was that integrating new engagement models, technologies or monitoring practices within farm businesses and agricultural sectors is widely appreciated as a challenge. Where these new approaches generate information or seek to inform farmer decision-making about environmental performance of their operation, as well as productivity, the difficulty and complexity of that challenge increases significantly. Insights from the scientific literature on agricultural decision-support systems, technology adoption and agricultural innovation systems underline the importance of effective, local collaboration between farmers, scientists and other service providers (such as extension specialists) in the process of designing, trialling and evaluating the benefits and risks of these approaches and their deployment. The benefits of collaborating in this way can be understood as three propositions:

i. the use of the new models or technologies can be more readily tailored to local needs and conditions and therefore more successfully embedded in local farming systems;

ii. it presents an opportunity for farmer and expert, scientific knowledge to be integrated more effectively and for joint-learning between scientists and farmers; and

iii. improves trust in the data / information source and its application to on-farm and wider decision-making.

The incorporation of a participatory social assessment activity within Project 25 was intended to test all of the above propositions, specifically:

i. Elicit project participants assumptions, expectations and concerns about the Project 25 process itself, the monitoring technologies;

ii. Monitor participants (growers, scientists and others) attitudes towards and experiences with the Project 25 model, process, technologies, information and collaboration over time;

iii. Identify strengths and limitations of the approach to inform ongoing adaptive management and delivery of the project; and

iv. Identify issues related to scalability and/or transferability of the approach to other locations or farming systems.

The sociological research methods used in this activity included a range of interviews, focus groups or social survey instruments with participants, observation at field days or project workshops or other interactions; and/or social network analysis of participant advice and information networks over time. The study relies predominantly on a qualitative constructivist/interpretivist methodology with data gathered through both participant observation in several project-related forums, and through semi-structured interviews with project participants and stakeholders. Ethics approval for obtaining and incorporating participants' data into the study was granted through the CSIRO Human and Social Research Ethics Committee. Twenty in-depth predominantly qualitative interviews were conducted for the first phase of analysis. These interviews were undertaken between September and November 2018, subject to the availability of participants.

Participants included growers in the Russell-Mulgrave catchment area who were participants in the Steering Committee and other growers who were not directly involved in the project; local industry extension officers; industry representative body officers; and, scientists working on the project. Interviews were conducted mainly face-to-face in the catchment (e.g. on growers' farms or in the workplaces of partnering organisations) or where requested, by telephone. Interviews were semi-structured, exploring several topics through discussion with interviewees. Length of interviews ranged from 40 minutes to 1.5 hours. Informed consent was obtained from participants prior to initiating the interview. With permission, the discussion was audio recorded and transcribed for analysis.

Analysis of interviews involved in the first instance a topic-based coding strategy against the main themes of the interview for the different types of participants (e.g. grower; extension; science). This was followed by a secondary coding strategy that identified influential constructs (e.g. trust, knowledge, risk, ownership etc.). This approach assisted in developing an understating of 1) experiences of different types of participants; and 2) some of the more influential factors shaping that experience. Interview topic areas and questions broadly addressed issues such as motivations for involvement and expected benefits; familiarity and experience with the monitoring network; trust in information sources and perceived value of the monitoring data; and participant perceptions on adaptive management and transferability to other catchments.

The behavioural change logic model outlined below (Figure 4) is a useful schematic for checking and evaluating the social research project team's assumptions about farmer attitudinal and behavioural change generated though Project 25.

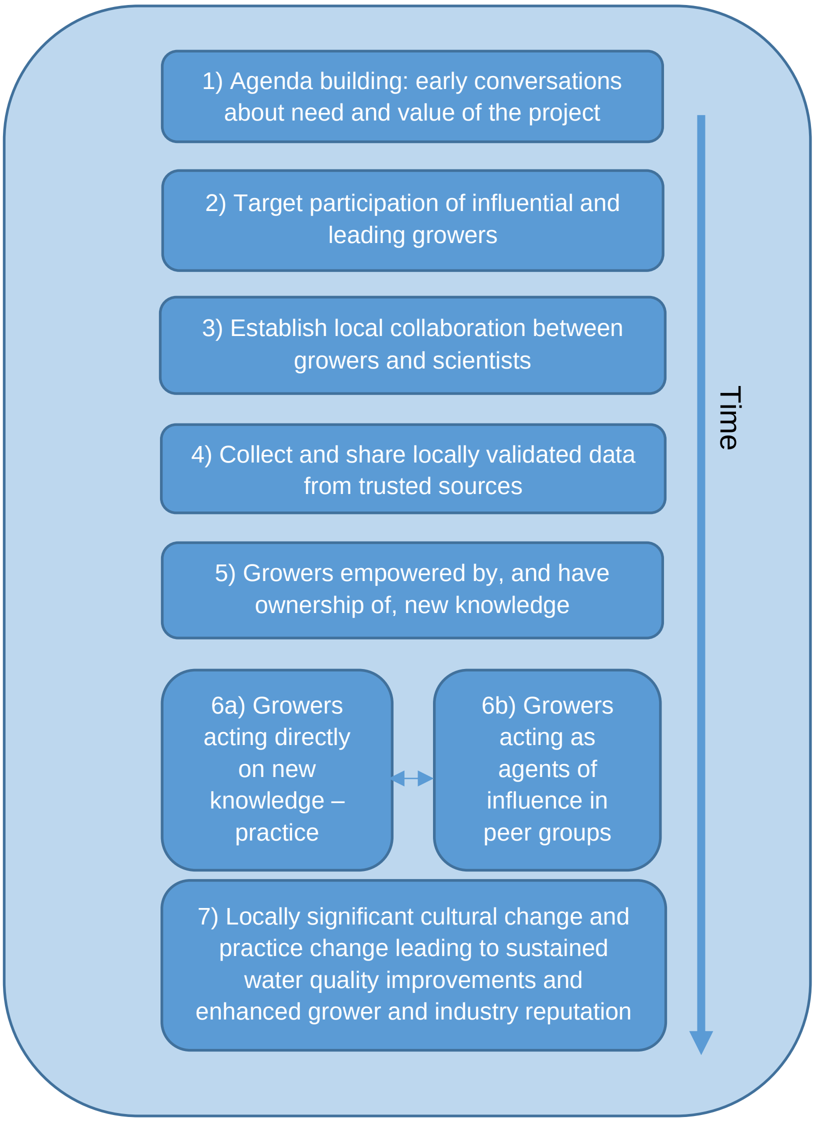

Figure 4: Representation of the Project 25 change logic model. (supplied by Bruce Taylor, CSIRO)

A second round of qualitative, semi-structured interviews, followed by a 5 likert-scale question with Project 25 Steering Committee (n=6) and non-involved farmers (n=5), advisors (n=4), and researchers (n=3) were conducted by one of the research team members (Simon Fielke) during March-April 2020 (n=18). The second round of interviews asked questions of 18 of 19 of the original respondents who were interviewed in late 2018 as one advisor was no longer working on the water quality topic with farmers. This round of interviews was conducted to gather perceptions of change in the same cohort of respondents. Interview questions covered farmer experiences: of interactions within their farming peer groups and shifts in local group norms; about water quality data and information; and, about interactions with cane industry and scientific stakeholders participating in the project. Audio recordings of interviews were transcribed for analysis.

3.0 RESULTS AND DISCUSSION

3.1 Social analysis of Project 25 model

Here, we assess the contribution of the Project 25 model and its implementation in: (i) creating peer group leaders and changing farmer perceptions about nitrogen movement through the Mulgrave-Russell catchment; and, (ii) altering farmer perceptions of, and highlighting demonstrable changes made to, fertilizer management practices. We describe the methods for this second round of analysis and provide a high-level synthesis of findings against the Project 25 'theory of change' (see Figure 4, and Davis et al 2019). Next, we detail the findings against the two key research questions. This section finishes with reflections on the efficacy, transferability and scalability of the project model.

The material below includes direct quotes from those transcripts with respondents coded according to a number and their categorisation: Steering Committee farmer (SCF), Not involved farmer (NIF), advisor (Ad) or researcher (Re). All excerpts presented in the text below are taken from the second (2020) round of interviews except for one, which is labelled as 2018. This quote was used as it indicates practice change that was already evident in 2018. Quotes are labelled as 'farmer', 'advisor' or 'researcher' where relevant and individuals are not identifiable. Steering Committee members are noted to reinforce the points being made. The social researchers also attended, participated in, and made written observations from several water quality related workshops, meetings and other forums linked to the project or involving project participants (e.g. Canegrowers, Sugar Research Australia, and CSIRO Digiscape Future Science Platform (GBR) project team) including the launch of the 1622™WQ application.

3.1.1 Results from analysis to answer key research question relating to the creation of peer group leaders

1) *How* has the project empowered growers to act as leaders and influencers in their peer groups and the broader farming community? *What* factors enable this change? *When,* over the course of the project's life, did this influence occur?

As reflected in the Project 25 change logic (see Figure 4), our current assessment is that the capacity of farmers involved in the project to act as leaders and influencers within their local farming networks has increased and continues to grow. Having near real time and visual evidence in the 'data' (e.g. nitrate-nitrogen readings, rainfall data and river height at various points in the catchment) 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 has created the opportunity for growers to share and discuss experiences with neighbours, enabling peer-to-peer leadership. As one farmer explains when discussing an interaction with a neighbour:

> *"At first everybody was a bit negative towards it [the link between nitrogen fertilizer and water quality], but now everybodys starting to accept it to a certain degree… I know when it [the water quality sensor] first went in, one of my neighbours, he just threw fertiliser on a crop and then we got eight inches of rain*

overnight and she spiked that machine something severe… Then he came around and said 'oh, that was my doing'. He said, 'I fertilised the day before yesterday before the rain came down'. I said 'well, it certainly spiked the machine, the monitor'. He said 'yeah, I'll have to change my ways'. It hasn't happened since. So, there's one neighbour that's sort of put himself into gear."

NIF 6, 2020

Confidence in the water quality data generated by Project 25 was a result created by opportunities for timely and responsive engagement with scientists. The main water quality scientist leading the project reflected on how this responsiveness can contribute to improved spatial targeting of excessive nutrient loss in the local area, and in doing so, catalyse grower-led (social) interventions with their peers:

"We had that bigger [rain] event, and I was up there, and we drove around for about three hours collecting buckets of water from different parts of the drain and eventually I isolated specific paddocks... He [farmer X] was really quite interested in that and was going to go and have a "chat" to the grower [farmer Y] about it [to enquire about implications of practices in relation to water quality readings]."

Re 1, 2020

The regular and ongoing character of engagement at shed and industry organisation meetings between researcher/s and leading farmers in the community was an important factor in allowing grower confidence and influence to build-up over the course of Project 25. One farmer explains this process and states that if the Project (and/or others like it) is to continue then there is a shared responsibility for passing this knowledge on to other members of the farming community, as advocates and educators:

"So even though you're not [a water quality expert], but you are slowly educating yourself what it all means, I think, which is a good thing… The ones within Project 25, they talk about it. They're really wrapped in it… The other blokes, it's just early days. We've got to educate them more, but we'll - that's the next step forward, too. We've got to look at that and educate them in it… The thing is, how much [value] do you put on education?"

SCF 2, 2020

The process of collecting and sharing locally validated data from trusted sources resulted in some farmers being empowered by, and feeling ownership of, new knowledge. While this process is ongoing, there is evidence that farmers are acting as agents of influence within their peer groups and, if this work to engage with the farming community continues, their efforts could increasingly influence the broader sugarcane farming community.

3.1.2 Results from analysis to answer key research question relating to evidence of change

2) Is there demonstrable or reportable evidence of change (e.g. from independent reports, self-reported behaviour change, observed activity, grower and stakeholder narratives) in categories of: (i) *on-farm* practice change; (ii) changes to *individual* beliefs or

attitudes towards N management; and, (iii) changes to shared or collective beliefs or actions in the local social *network*?

During the first round of interviews in 2018, there was early but limited direct evidence of actual changes in N management practices by farmers in the group. However, at the time, one farmer stated:

> *"Once I start getting my soils healthier, then I can start playing with my fertiliser a bit more… it's all got to be reporting back to us, and seeing how we can look at data helping us make more informed decisions on - and going out there and trialling lower rates of nitrogen and such. Because it's showing to me that lower rates can work, but I can't do that on the rest of our farms. I can do it on my place, which I have done for a couple of years now, run down to as low as 80 units of nitrogen. It's - it does have a few problems, but I've just got to work through it all"*

NIF 5, 2018

In this second round of interviews there was growing evidence that Project 25 has contributed (directly and in concert with other interventions) to (i) *on-farm* change and practice experiments. By early 2020, several of the farmers interviewed identified specific practice change over the course of the preceding 18 months. Some of these quotes follow, regarding fertiliser management practice:

> *"Since then [interview in late 2018], I've gone away from granular onto liquid fertiliser which has got molasses in it and organic carbon. I very much focus on that, and on pour rate control. It is proper GPS rate controlled and everything, so I'm getting precision application. Every block, I can put on exactly what I want… you can see [in] that first flush… I did a lot of research… so it ticked a box like a slow-release fertiliser for me, and focussed with the surges that I know with the first flush data, well, it's a way around the fact - to keep my stuff on my land and help the environment, because I'm not at the end of the chain… So, as well as efficiencies that come….and productivity and profitability, there was also an element of environmental stewardship and it ticked that box as well, so I'd say it [Project 25] did have a part in that… I'm about 500 hectares, [another Farmer] went to it as well… they've got 1500 hectares of the catchment… that is fertilised that way. We're the two biggest growers in the area."*

SCF 2, 2020

Regarding application of fertilizer as early as feasible:

> *"I would rather turn around in two weeks and fertilise it [sugarcane] in October, late October, than fertilise it in December [now]. You've got less chance of that big rainfall event. If we have the rainfall event going… what comes out of the soil goes into the creeks."*

NIF 5, 2020

Regarding following best management practice:

> *"Well, we do our Six Easy Steps… I've been Smartcane BMP [best management practice] accredited [in the last 18 months], so I've been following that, with their recommendations, yeah… some neighbours are adhering to it, some people aren't. Some people are doing their own thing. Some people try and, well, they're basically like me, they've tried it and then they've got to wait for your result of what comes of it next year."*

NIF 6, 2020

There was also evidence from farmers that benefits or new knowledge from the project were contributing as one of a broader complement of changes or improvements in nitrogen efficiency, soil health and related goals on the farm. For example, one farmer highlighted the importance of soil health in general and associated practice change that will help achieve increased N use efficiency:

> *"There's a lot - there's starting to be a move toward wider rows for compaction, which it's not - that's what I've got to try to explain them. Compaction isn't about growing the cane or whatever. It's about soil health. That's what you're after, so that in time, you should get a trade-off... It's going to take about two cycles, [about 10] years, but if you can get your soil health right with the legumes or with compaction, less compaction, all that, well then you should have a better soil structure that then you will reap benefits of better nitrogen use efficiency."*

SCF 2, 2020

Another farmer explains that a diversity of alternate fallow crops has been a big success compared to their previous practice:

> *"Well even this year we've done multiple species in our fallows, like before you'd have a break crop, but that would normally be just a legume or [cow pea] but this year we've had mixed species, five different species planted and it's actually been a real big success… It's been a magnificent crop, like each one of those species adds different - because we're a monoculture industry where we're just growing cane all the time, I can see that there's a benefit in soil health by having a mixed species in the fallow box.'*

SCF 5, 2020

Farmers also reported changes in their (ii) *individual* perspectives about N use that Project 25 had influenced in a positive way. For example, farmers now made clear links between available data and the central hypothesis that the first large rainfall event of the season (flush) and the application of N fertiliser on top of the ground, too close to this event, caused spikes in dissolved inorganic nitrogen in the waterways:

> *"But one of the things that does stand out with what we've learnt through this, with the water quality, is that certainly the first flush is probably the biggest contributor to the nitrate and the spike in the nitrate. I know that we probably thought that that might have been the case before, but the evidence is pretty strong. So if we want to look back at best practises it was only a few years ago*

> *that most of the agronomists and SRA and that were saying 'oh you need to leave the cane get to about 12 weeks before you fertilise it'. Now the consensus is that once it gets closer to the end of the season, as soon as you can put it on, the better. So already there's been that sort of - maybe not even practice change in a sense, a lot of farmers were probably doing that to a certain degree, they were putting it on whenever they could, as soon as they could, but the whole industry now is looking at yes that is probably best practice, is to get it on as quick as you can or as soon as you can to give it the amount of time, even if the cane is small."*
>
> SCF 5, 2020

Moreover, one farmer reported the direct role the project has had in helping to shift broader farming norms and expectations described above:

> *"It's [Project 25 data] telling farmers that are putting their fertiliser on top of the ground just before a rain event that they cause the problem"*
>
> NIF 5, 2020

The role of Project 25 to change perspectives of farmers was also evident in data collected as part of a short set of Likert scaled questions administered after the semi-structured questions at the end of each interview. Farmers involved with Project 25 reported on average a higher increase in 'knowledge about water quality on their farm' between 2018 and 2020 compared with those farmers not involved directly in the project, who reported on average a slight decrease in knowledge (Figure 5). Similarly, those farmers involved with Project 25 also felt the 'water quality leaving farms in the district' and their 'ability to be part of the water quality debate' increased between the two rounds of interview (Figure 5). The involved farmers were also more likely to think 'Project 25 would work elsewhere', in other regions, and 'industry wide' than those not involved in the project. These results, while indicative only and not statistically significant, do suggest a pattern of farmers participating in Project 25 identifying strongly with the benefits of the project and with the possible benefits from wider application of the project model to other districts.

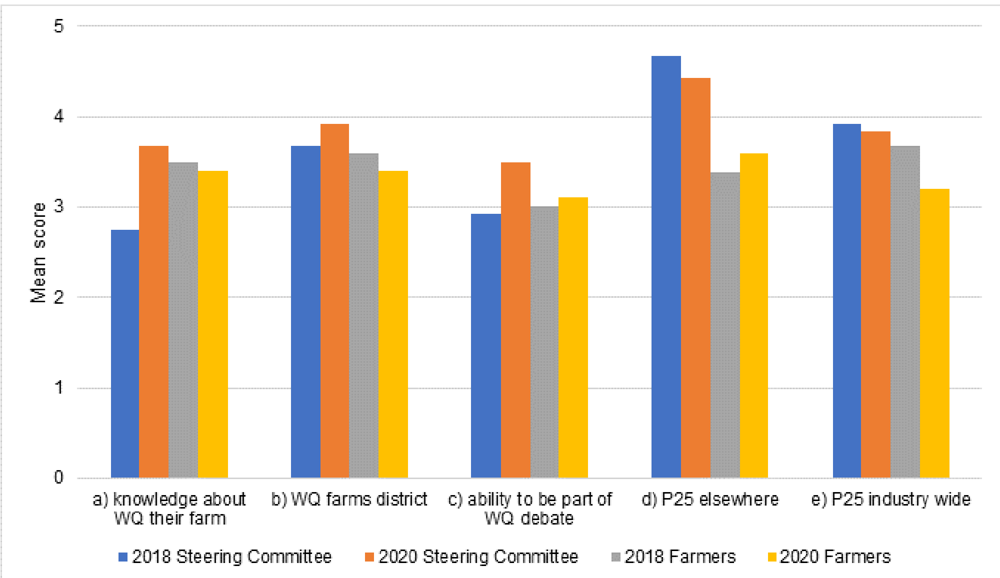

Figure 5: Mean scores for Project 25 Steering Committee farmers (2018 n=6, 2020 n=6) and not involved farmers (2018 n=5, 2020 n=5).

There is also evidence of change in the collective thinking or group norms within the broader farming (iii) *network* associated with the implementation of Project 25. Farmers shared their learning with their farming peers and are developing greater levels of trust in the water quality science outputs. For example, an advisor and farmer described evidence of change in that they felt confident about "*taking that [water quality information] out to the growers" (SCF 5, 2020)* in the industry:

> *"Project 25 has been going for a few years. Most of them [Project 25 Steering Committee] are aware of who's getting what data and what's actually happening there. That it actually - they're not trying to catch someone out, or something extreme, like that - reporting to the government all this data, or something crazy… so there is more acceptance, and probably just genuine interest in what all of it does and means."*

Ad 3, 2020

> *"You actually can see about the first flush and all that stuff, and if you put it over on top of the ground, there's a bit of that in that, where you'll get more loss, so I think now it's actual data, and it gives them [the farmers involved in Project 25] more comfort that they're not looking at a spreadsheet and [it's] telling them what to do. Because there's always that. They'll [other farmers] always question that, where now, they can't really question it."*

SCF 2, 2020

One of the participants in Project 25, however, offered a different assessment on the impact of fertiliser use and management on water quality, and on the role that water quality data has on providing evidence of that impact. This farmer explained, that in their view the amount and type of data the project generated was insufficient to show links between changes (for better or worse) in the environment with N fertiliser application in sugarcane farming at scale:

> *"I think for anybody to make change you'd have to accumulate a decade - a couple of decades of - when I say a couple of decades I mean four or five decades - 50 years of data - before you could say that what we're doing is making a change to everything"*

SCF 4, 2020

This particular view, while not widespread amongst the farmers interviewed, points to how the two related but separate questions of 'what is my local impact' and 'what is the impact of farming on the Reef' can be conflated, and in doing so create a barrier to grower engagement with water quality data, and on water quality improvement more broadly. Broad narratives surrounding the negative impact of farming on the Reef set up an antagonistic dialogue between farmers and others who expect farmers to change behaviour at the local level.

There was also a suggestion from the second round of interviews that the involvement of growers in the project has contributed to greater levels of adaptability or capacity to cope with changes in practice standards coming from new government regulations. An agricultural advisor working in the region described how, in their experience, farmers involved in the project had a more positive view about the future of the industry and felt less threatened by the requirements of the new water quality regulations:

> *"It's a fairly tight group [Project 25 Steering Committee and research team] really that we work with closely. Those guys, they didn't see it [new government regulations] as a threat. They could read it and be like 'oh yeah, I can work with that'. But the other people… they really think it's… going to cost them in yield and it's going to send them broke."*

Ad 4, 2020

3.1.3 Discussion on efficacy, transferability and scalability of the Project 25 model

The first round of interviews in 2018 suggested the project was contributing to the creation of a trust-based environment for dialogue between growers and scientists on a contentious topic. Project 25 was providing feedback to growers on the effects of different fertiliser strategies (timing, rate) and was supporting local grower leadership on the issue of water quality. The results from the second round of interviews confirm and extend these findings. Overall, the project design has been successful at progressing farmer participants through the stages of the project's theory of change (as indicated in Figure 6). There is clear evidence of progress 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.

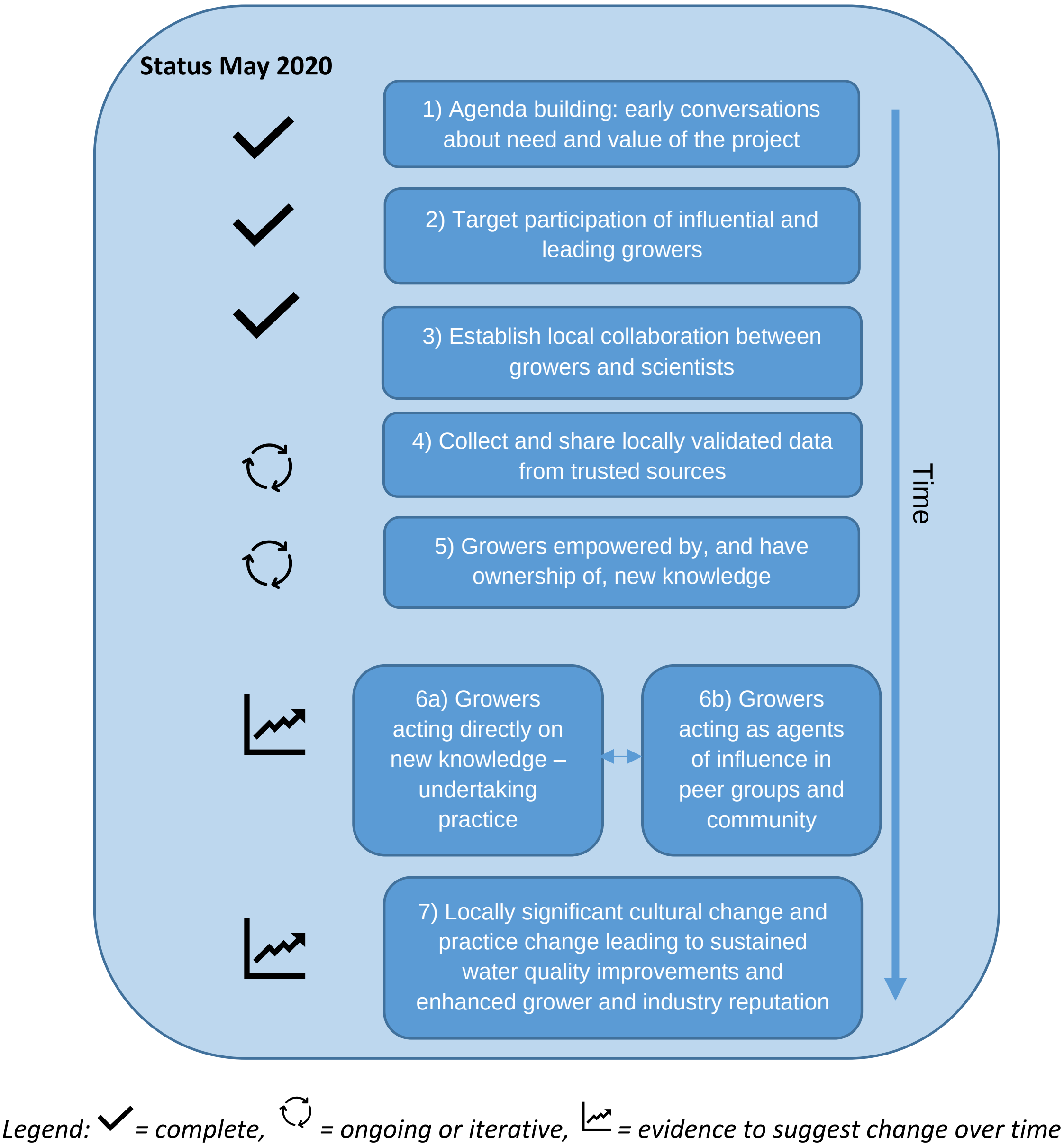

Figure 6: Synthesis of findings against the Project 25 Theory of Change logic from the two rounds of interview analysis, observations and interactions with the project stakeholders and participants.

The core elements or principles of the project 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 is still debate about when and how the data shown to farmers through Project 25 could or should be shown to others outside the Steering Committee because of the nature of the implications if it is used to regulate or create benchmarks in an inappropriate timeframe.

The Project 25 model of a bottom-up, collaborative water quality monitoring group that provides locally relevant feedback to growers on the consequences of their nutrient management decisions, is also compatible with other elements of a broader water quality improvement delivery program. The project model (e.g. through further extension or advisory processes, financial or other incentives) could also contribute, indirectly, to the local validation of regulatory requirements, thereby improving compliance outcomes. In relation to the question of scalability of the project model, both from the interviews and from observations made during the project, two considerations arise that could be influential – digital literacy and accessibility; and the role of social capital.

Digital literacy and accessibility

One of the strengths of the project model is its flexibility in incorporating new tools and partners to complement the core water quality sampling and Steering Committee components of the project design. One of these additional tools introduced during the life of the project was a smartphone application and supporting data analytics capability [1622™WQ] to enhance the visualisation of the relationship between water quality and rainfall event data (see Vilas et al. (2020) for more information). While this tool 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 (see Fielke et al. 2020).

The role of social capital

The role of different forms of social capital in supporting or hindering collaboration in local catchment management has been studied for some time (see for instance Lubell (2004). The ‘tight group’ of growers and advisors described above reflects the ‘bonded’ form of social capital that often exists within local or peer-based farming communities or groups (see also King et al. (2019). These strong social ties, shared beliefs and norms can be helpful if an intervention is using peer-led strategies to encourage changes in behaviour or establishing new norms *within* the group. It can mean, however, that in the absence of ‘bridging’ social capital (relationships that connect individuals to outside groups, skills and world views) that these tight bonds can make the introduction of new ideas or ways of doing things difficult to begin with, requiring long periods of relationship and trust building in the early phase of projects. The resourcing implications of having dedicated scientific staff available and responsive within that initial time period across multiple smaller groups of growers, over several target catchment areas, would need to be considered in any scaling strategy. Exploring ways of ‘networking’ these multiple otherwise standalone groups, as a broader connected learning community, could assist with both the resourcing issue and help generate bridging social capital within the industry necessary to overcome some of the more dominant cultural postures towards water quality issues.

3.1.4 Social research conclusion

The social research conducted as a component of Project 25 has highlighted the importance of investing to build trust, maintain research practice and data transparency, and the critical role of informal learning and training as essential components to achieve impact-based research outcomes. These findings are not trivial and contribute to growing calls for recognising the input of various stakeholders and forms of research within the process of research and development (Polk, 2015). Without the dedication of the farmers, advisors and researchers involved the evaluation of social impacts could have been very different.

While yet to be meaningfully pursued in the specific context of Project 25, appropriate and meaningful involvement and ownership of farmers in the early stages of water quality monitoring programs, could well make subsequent integration of programs with government water quality monitoring (and other NRM initiatives) efforts much more likely. Open and transparent dialogue between farmers and government, across multiple scales of monitoring, would seem a natural evolution of the Project 25 model into the future.

3.2 Tailoring water quality monitoring results to industry

Broad water quality results from Project 25 largely paralleled those documented in similar wet and dry tropical catchments of the GBRCA (see, for example, Bainbridge et al., 2009). Oxidised-N concentrations, for example, were elevated in the sugarcane, banana dominated sub-catchments compared with the undeveloped rainforest land use (Figure 7a). In catchments with monitoring paired upstream and downstream of agricultural development, significant increases in oxidised-N concentrations were consistently documented downstream of farmlands, with median concentrations ~4-6 times higher downstream of intensive farming land-uses (Figure 7 b, c).

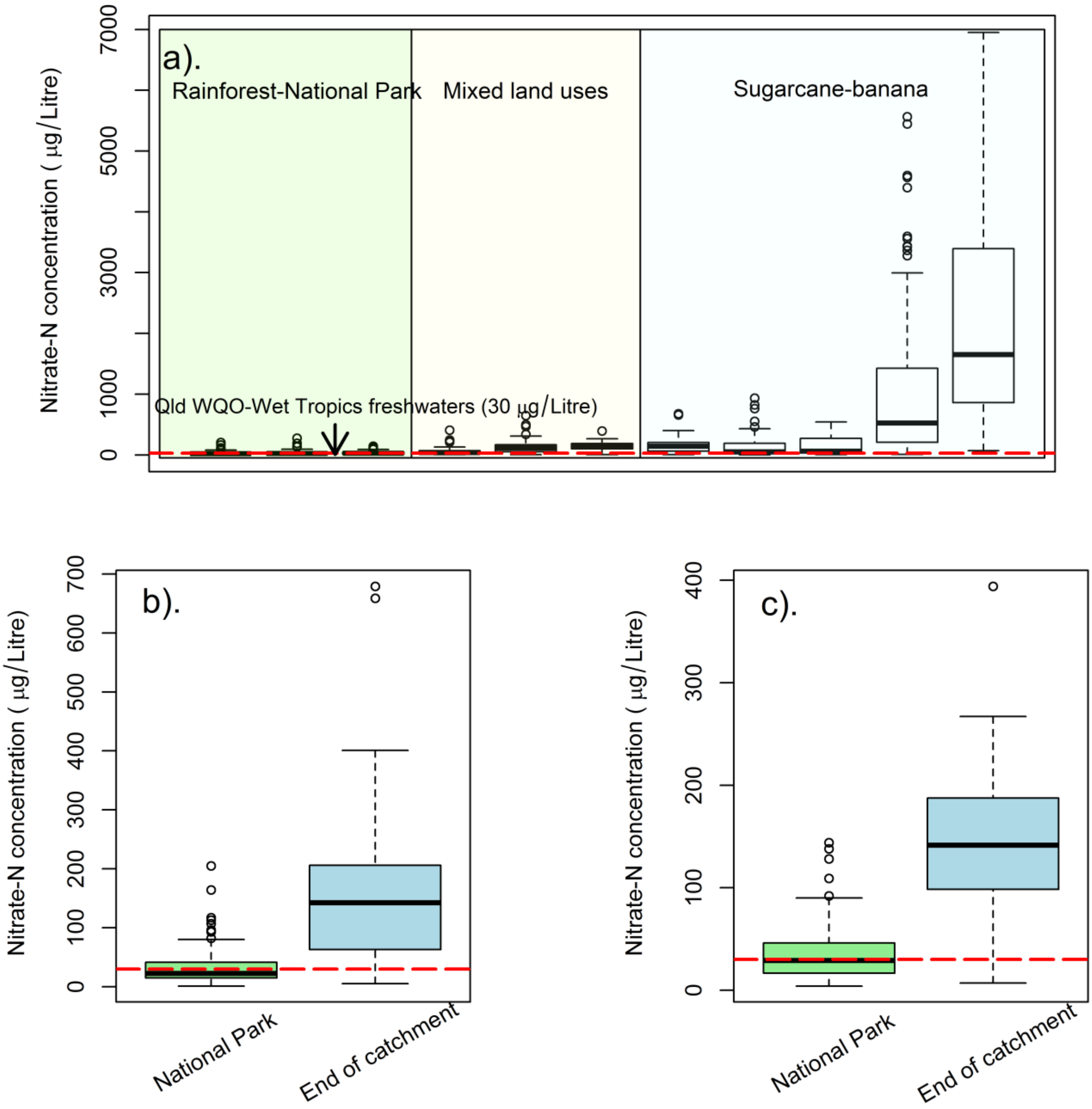

Figure 7: a). Summary boxplots of oxidised-N concentrations (µg/Litre) from discrete samples collected across Project 25 sampling locations (2016-2020) grouped into different land-use types. b-c). Summary boxplots of paired upper catchment rainforest versus downstream developed landuse oxidised-N concentrations in individual Russell-Mulgrave sub-catchments. Site boxplots depict median values (denoted by the horizontal line), with the box representing the inter-quartile range (containing 50% of the data). The whiskers extend from the box to the highest and lowest concentrations, excluding outliers (circles), which are defined to be outside 1.5 box-lengths (outside the 25th and 75th percentiles). Red dotted line indicates the Queensland Water Quality Objective-Guideline for Wet Tropics freshwaters oxidised-N (Department of Environment and Heritage Protection, 2013).

Another benefit of meaningful grower involvement in program design, is the advantages and opportunities provided for effective communication of not only basic water quality science, but also government policy aims, back to industry (i.e., anthropogenic load reduction targets in Reef Plan). The fundamental foundation of Project 25 was a local water quality program designed, in large part, with providing clarity and locally relevant data on particular industry concerns. Discussions with stakeholder committee growers highlighted considerable confusion around GBR catchment monitoring within the broader sugarcane industry, particularly misconceptions around end-of-catchment targets identified in government policy, and issues such as the relative contribution of land-use types such as rainforest to end-of-catchment loads. Local data (‘real data, not modelled’) to provide clarity on these issues to the broader grower community was identified as a specific information gap to be addressed by Project 25 in its early stages of development (when GBRCLMP data was largely absent from the catchment).

One of the strengths of the Russell-Mulgrave catchment, is the relative simplicity of the catchment and defined spatial extent of specific land-uses. The ‘before and after’ program design to capture land use water quality signatures as they change along the rainforest-sugarcane continuum, provides powerful capacity to quantify and communicate the impact of anthropogenic land uses back to stakeholders in several ways. Figure 8 outlines an example of typical Project 25 feedback to industry from one monitored catchment, partitioning the end-of-catchment nitrate-N load changes documented using local rainforest and sugarcane water quality data collected through a wet season, into a ‘natural’ and ‘anthropogenic’ component. Knowledge of land-use areas upstream of monitoring locations also allows conversion of load data in per hectare load losses from farming inputs (in this case ca. 9-10 kg Ha year^{-1}), but also theoretical load reduction targets (the 70% reduction desired under Reef 2050 Plan targets for Russell-Mulgrave canegrowers to achieve, equating to 6-7 kg Ha year^{-1}). From feedback with local canegrowers, this was an issue surrounded with considerable confusion in parts of the cane industry.

Working through the data collection process, the underlying concepts, and presenting data in this way, with local data from familiar sites, and in units more familiar to the farm input language of canegrowers (kg Ha^{-1}), proved an effective method for engagement, and addressing the confusion and scale of issues in ways more digestible to growers. The presentation of data in this format to both Project Steering Committee canegrowers, but also larger cane growing audiences proved a powerful tool for framing and communicating local water quality issues in a coherent, and understandable manner.

Feedback directly from Project Steering Committee members included:

> “*we’d hear at every local meeting about GBR water quality that rainforests contribute most of the nitrate to the Reef. After seeing some of this data, we can put those issues to bed now*”.

Project 25 Steering Committee canegrower, Babinda

This industry perception of the role of rainforest as the major contributor to catchment DIN export is not unique to the Russell-Mulgrave catchment, and is pervasive across other GBR canegrowing regions (Di Bella et al., 2015). The inclusion of pristine rainforest monitoring data in other water quality monitoring programs is likely to prove a similarly powerful communication tool in other catchments.

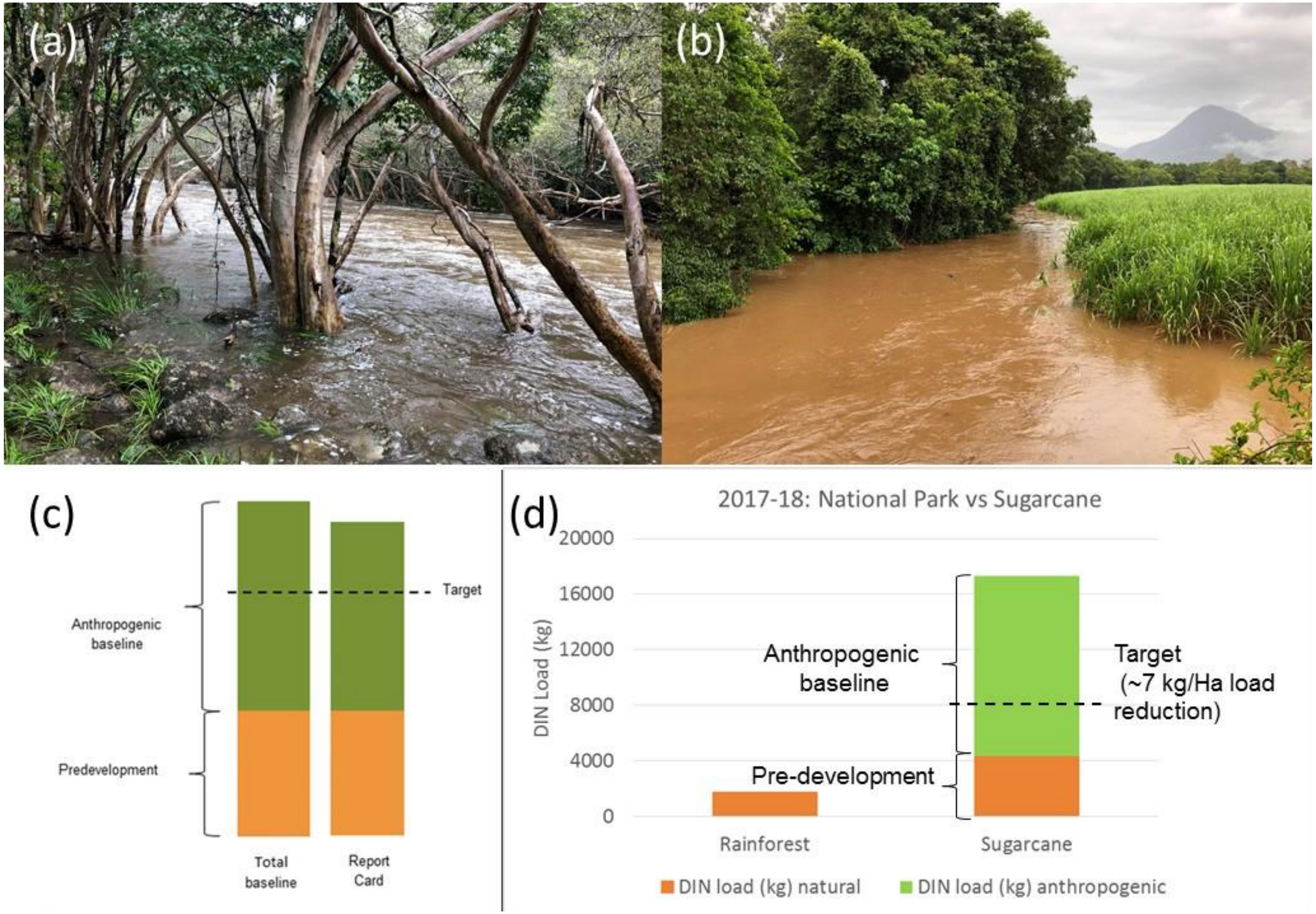

Figure 8: Example data presentation from a paired 'upstream-downstream' Project 25 sub-catchment back to industry stakeholders, contrasting rainforest-sugarcane water quality impacts. Panels a) and b) outline sampling locations (upstream rainforest and downstream sugarcane). Panel c) the Reef Plan load reduction target concept (sourced from Reef Plan 2013). Panel d) 2017-18 wet season data compiled and presented in the same format as Reef Plan, tailored to the local catchment and sugarcane industry.

The underlying process for data generation and interpretation even allows scope to present data in the context of historically contentious topics such as Paddock to Reef (P2R) modelling of sugarcane inorganic nitrogen losses across different districts (not shown here). Grower anecdotes from the Project 25 steering committee include observations such as:

> "*amongst growers there was a lot of apprehension about the results that were presented from modelling. It has been a learning experience for both the growers and the researchers comparing the modelled data to the actual data*".

Project 25 Steering Committee canegrower, Babinda

Presentation of real, locally developed data emerged as a very effective tool for addressing known challenges or points of contention in sugarcane industry understanding of water quality issues.

The communication and media landscape of Great Barrier Reef water quality science is often emotive, imprecise, with considerable confusion or messaging across all catchment stakeholders. Growers in the Russell-Mulgrave catchment have, for example, been directly implicated by either media or government communications in significant losses of water quality pollutants such as sediment and phosphorus to the Great Barrier Reef marine environment. A key consideration in Project 25 design involved 'upstream and downstream' collection of samples from major urban centres in the catchment. Results identified consistently elevated filterable reactive phosphorus (FRP; a measure of orthophosphate, the soluble, inorganic fraction of phosphorus directly taken up by plants) as a key signature of the urban water quality footprint, compared to other major land uses in the catchment, such as sugarcane (Figure 9). Through the monitoring period, FRP concentrations at all Project 25 monitoring sites, with the exception of urbanised land use, was ≤4 µg/L (the current Queensland ecosystem protection water quality guideline for wet tropics lowland environments). Median FRP concentration values collected below the catchment's major urban centre was >50 µg/L.

This was an outcome generating considerable interest and debate from local canegrowers;

> "*I've received letters from Queensland government saying canefarmers in my area are responsible for losing significant amounts of phosphorous to the Reef. It's good to see data showing this doesn't seem to be the case, or at least that people in towns need to be more aware of their impact on water quality. I want to know what I'm most responsible for, not get blamed for other issues*".

Project 25 Steering Committee canegrower, Babinda

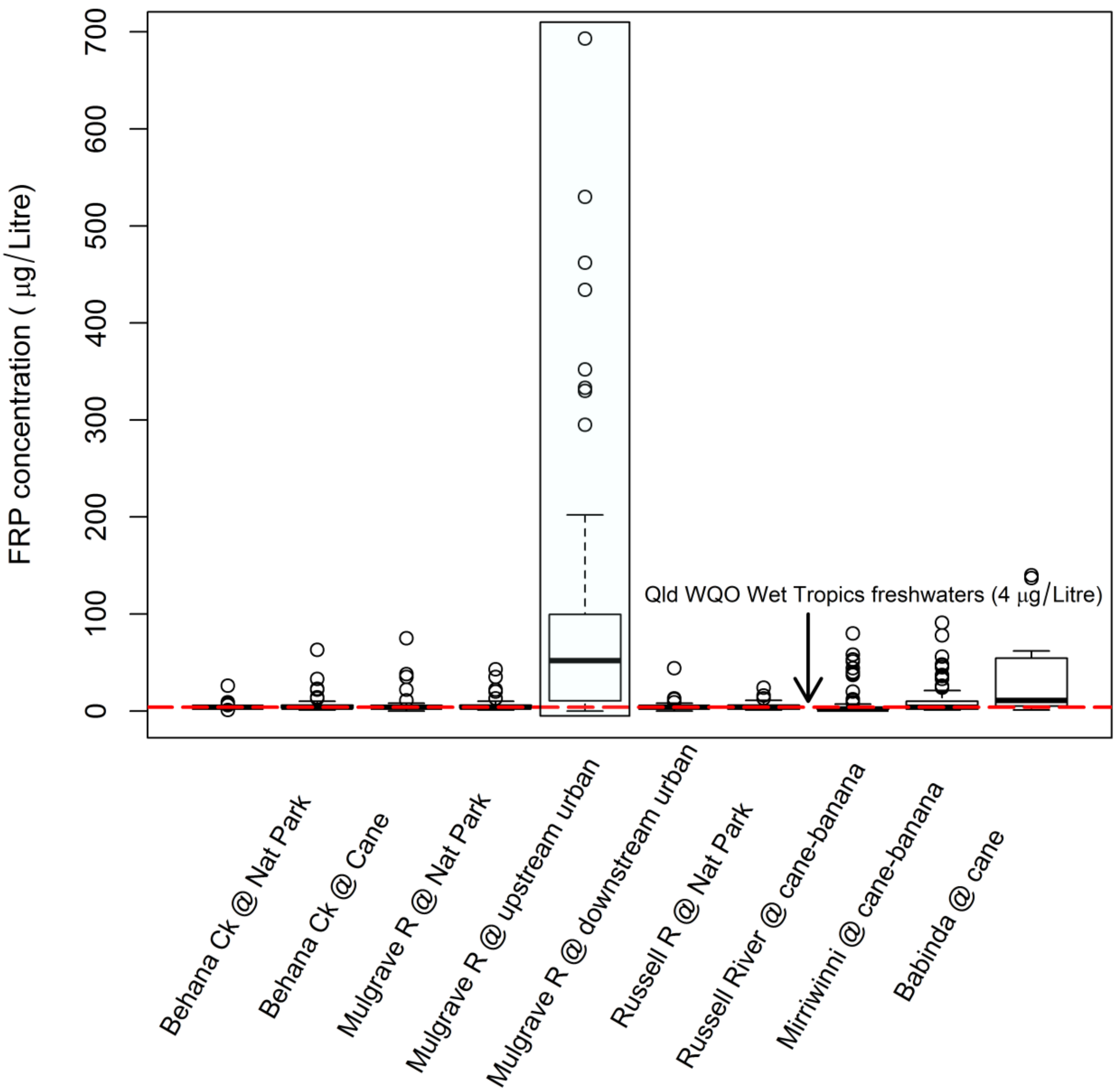

Figure 9: Summary boxplots of Filterable Reactive Phosphorus (FRP) concentrations (µg/Litre) across Project 25 sampling locations (2016-2020). Site boxplots depict median values (denoted by the horizontal line), with the box representing the inter-quartile range (containing 50% of the data). The whiskers extend from the box to the highest and lowest concentrations, excluding outliers (circles), which are defined to be outside 1.5 box-lengths (outside the 25th and 75th percentiles). Data collected from immediately downstream of the catchment's major urban centre is highlighted in the blue box. Red dotted line indicates the Queensland Water Quality Objective-Guideline for Wet Tropics freshwaters filterable reactive P (Department of Environment and Heritage Protection, 2013).

> *"So this project, like I say, initially was to validate the modelling. We have found some flaws in some results that were getting attributed to us* [the previously mentioned phosphorus losses]*. We have found those flaws, and I'm willing to talk about that later in my presentation"*

Project 25 Steering Committee canegrower to Rural and Regional Affairs and Transport References Committee Senate Committee Inquiry; Hansard transcript, July 2020.

> *"Do we as growers have an impact on the environment? I'm not getting into the Barrier Reef. I'm not a scientist. I'm just looking at our streams. We've got monitors there. Yes, we do—the same as everyone sitting around this table, which everyone forgets. Everyone has an impact on the environment. So the whole idea is: how do we minimise it?"*

Project 25 Steering Committee canegrower to Rural and Regional Affairs and Transport References Committee Senate committee Inquiry; Hansard transcript, July 2020.

These sorts of results and expressed sentiments have considerable value in highlighting the specific local water quality issue the industry should focus attention on, while also building trust in the Project framework in addressing industry concerns about the water quality impacts of other land uses. This provides actual evidence for the industry to respond to, and to counteract future external claims about local water quality issues, and also makes industry stakeholders more amenable and comfortable discussing their own land-use-water quality challenges.

Positive feedback is also similarly an essential element in encouraging any form of behaviour change by farmers, and positive feedback has been shown to be more effective than negative feedback (OECD, 2017; Pickering et al., 2018). Promoting 'good news' stories in results and providing positive recognition around cane industry practice changes also encouraged more open dialogues around all water quality issues. Soil erosion rates from conventionally cultivated sloping cane lands in wet-tropical north Queensland had, up until the 1980's, been measured in the range of 47-505 tonnes Ha year^{-1} (av. 148 tonnes Ha year^{-1}) (Prove et al., 1986; 1995). Subsequent industry uptake of conservation practices such as reduced tillage and harvest residue retention (green cane trash blanketing) reduced these losses significantly (i.e., <15 tonnes Ha year^{-1}; Prove et al., 1995). The presentation of locally collected suspended sediment data across different land use types underline the success of these collective industry responses to historic water quality challenges to Project 25, and other canegrowers (Figure 8).

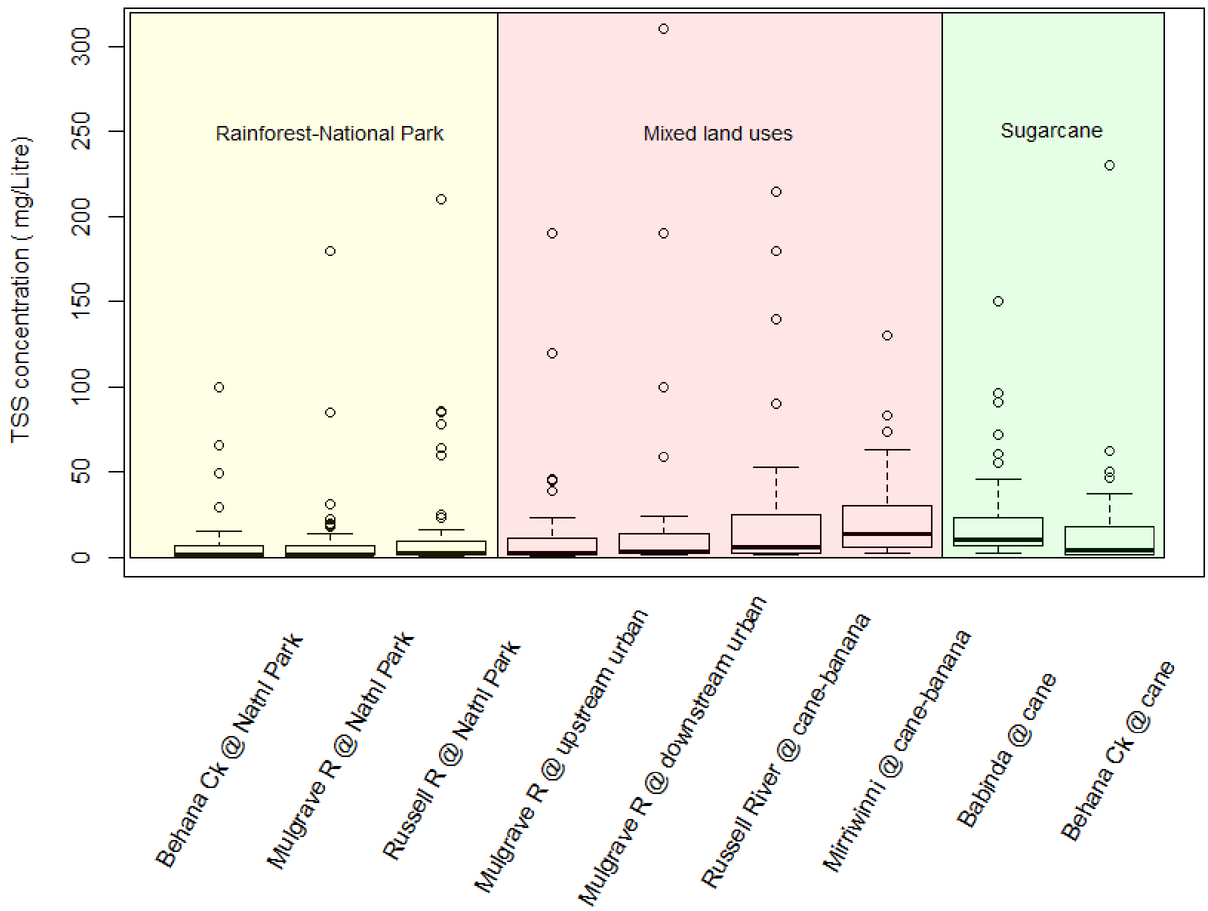

Figure 10: Summary boxplots of Total Suspended Solids (TSS) concentrations (mg/Litre) across Project 25 sampling locations (2016-2018). Site boxplots depict median values (denoted by the horizontal line), with the box representing the inter-quartile range (containing 50% of the data). The whiskers extend from the box to the highest and lowest concentrations, excluding outliers (circles), which are defined to be outside 1.5 box-lengths (outside the 25th and 75th percentiles).

3.3 Nitrate-N sensor performance

One of the key considerations in the trialling of sensor technologies and provision of real-time data to landholders during Project 25 was the performance of the nitrate sensors themselves, and the accuracy of the data they provide.

Figure 11 provides comparison of nitrate-N concentrations of sensor readings and discrete water samples collected for subsequent laboratory analysis through the current Project 25 monitoring period. It should be noted that due to water depths and site access constraints (particularly during flood events), these discrete samples were not always collected at exactly the same time (but usually within 1 hour) or at the exact point and depth in the stream at which the installed nitrate sensor takes a reading. Nevertheless, correlation between collective laboratory concentrations and sensor values was significant, and essentially 1:1 over the entire concentration range documented throughout the project. Analysis of this relationship at lower concentration ranges (>1 mg/L nitrate-N), however, documented weaker (although still significant) correlation between approaches, with a lower R^2 (lower explanatory power) and a slope significantly less than 1.0. This result highlights challenges with sensor performance primarily at lower nitrate concentrations, namely a tendency toward detection failures or over-estimates at the lower end of the nitrate-N concentration scale (typically <0.5 mg/L). Such results that are not entirely unexpected given the stated detection limits for the instruments in these cases were ~0.15-0.5 mg/L nitrate-N (1mm-2mm path length sensors). Optical sensor data accuracy (particularly at lower concentrations) is a function of optical path length, with longer path lengths (i.e., 10mm-50mm) offering lower detections limits, but sacrificing reading accuracy at higher concentrations (discussed in more detail below).

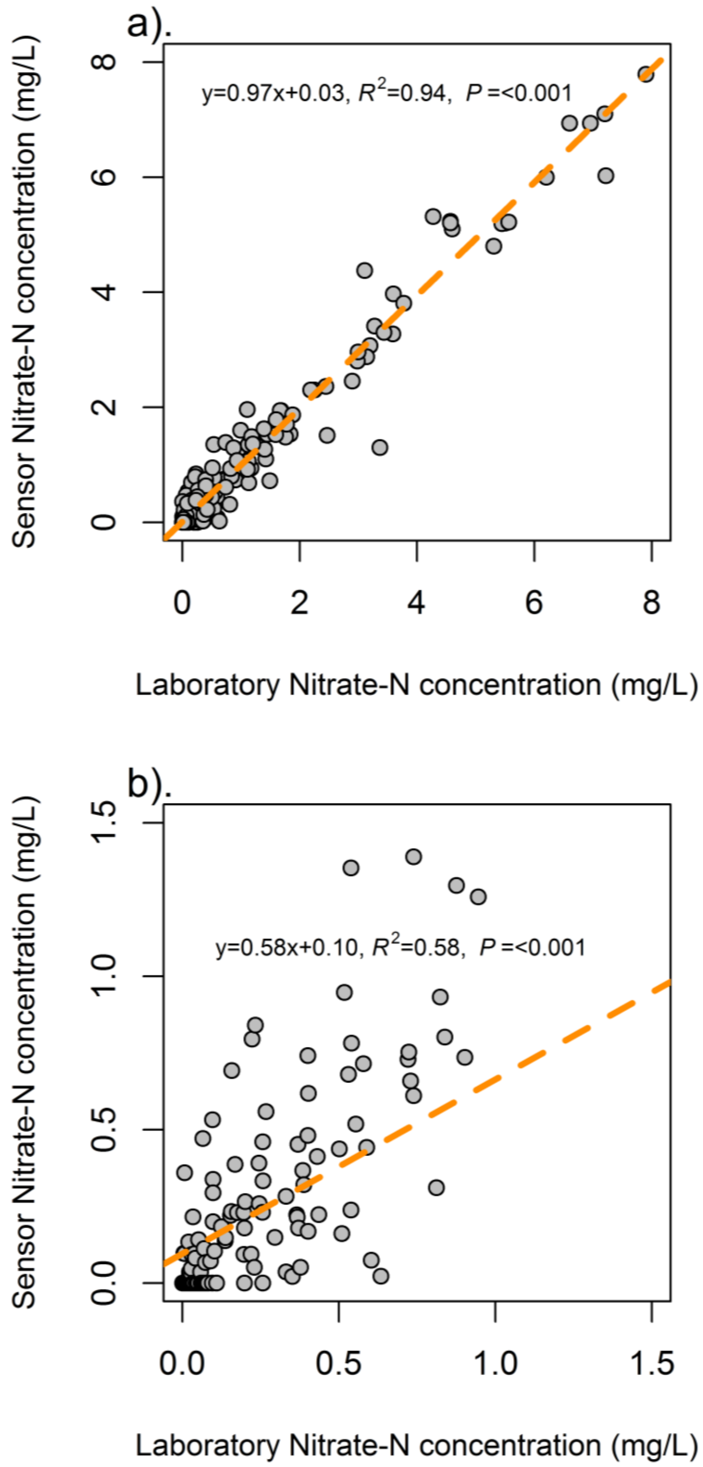

Figure 11: Comparison of nitrate-N sensor readings to laboratory results over; (a) entire concentration range documented over Project; and (b) laboratory nitrate concentrations >1.0 mg/L.

These results are also relevant to the water quality characteristics of many north Queensland sugarcane catchments, and associated sensor-based monitoring efforts. Much Wet Tropics sugarcane is grown in catchments with relatively large upstream undeveloped catchment areas. Coupled with high rainfall-runoff volumes, and hence significant inflows into creek systems of dilute, low nitrate concentration waters, nitrate concentrations can often be >0.5 mg/L nitrate-N for significant periods of the year, particularly during the high flow flood events of most interest to many monitoring programs. Varying patterns of land use development can, accordingly, have important implications for local water quality dynamics and aspects of sensor selection, even over small spatial scales. Within the modestly-sized Russell-Mulgrave catchment, for example, pronounced differences in catchment characteristics can produce very different water quality dynamics, even at a very localised scale. Catchments with relatively large upstream undeveloped catchment areas (and hence significant inflows of low nitrate concentration water from rainforests) can produce nitrate-N concentration fluxes approaching an order of magnitude lower than similar nearby catchments dominated largely by intensive agricultural land uses (see Figure 19). These pronounced differences in concentration range can reflect catchment landuse makeup as much as farming practice, and concentration alone should not be relied upon as an indicator of landuse practice-water quality relationships.

Many commercially available, optically-based nitrate sensors have lower analytical detection limits approaching 0 mg/L, which would seem to capture these low concentration scenarios. The specific path length of the sensor (i.e. the distance from the emitting UV light source lamp to the detecting spectrometer) does, however, play a critical role in determining instrument sensitivity, detection ranges and how well the instrument compensates for interferences such as turbidity. In general, a shorter path length will limit the sensitivity of the analyser for low concentrations (see Figure 11), but will generally increase the nitrate detection range and minimize adverse effects from high turbidity and suspended sediment. A longer path length will conversely provide greater sensitivity for low-level concentrations, but will reduce the detection range and increase the effect of interferences. Analysers differ in their light sources, optical configuration, communication protocols, antifouling measures, and algorithms used to compute nitrate from the UV absorbance of the water sample.

Some instruments have capacity to modify features such as path lengths, some models have fixed path lengths, but some are available with a range of variable, fixed path length options (Pellerin et al., 2013). The TriOS sensors utilised in Project 25, for example, are available with various set optical path lengths ranging from 0.3mm to 50mm. Catchment monitoring applications in situations with low ambient and event nitrate-N concentrations and/or substantial turbidity fluxes may require informed selection of particular brands, and the technical unit specifications (path lengths) of specific models to optimise performance. Prior knowledge of likely scale of water quality parameter dynamics can provide valuable guidance into appropriate sensor selection, and it is unlikely that a ‘one size fits all’ approach to sensor selection will produce best results.

Another critically important aspect of the operation of advanced optical equipment such as nitrate and phosphate sensors, is they are among the most maintenance intensive of water quality sensor technologies (Steven et al., 2013; Pellerin et al., 2013). This is due to optical sensor susceptibility to reduced performance from biofouling and sedimentation of the optical lens. Optical sensors utilised during Project 25 were initially cleaned utilising an integrated compressed air blast system to automatically clean the optical window. Early observations of optical window cleanliness, and periodic calibration testing of sensors highlighted that at least monthly physical cleaning of lens was also required for satisfactory performance at some sites. The recent development of automated, externally mounted lens wiper technologies, and ultrasonic lens cleaning technologies by TriOS (Figure 4) highlights lens cleaning is recognised as a key factor in sensor performance, even by manufacturers. While data is not presented here, automated physical wiping of sensor lens provided much more consistent, and longer-term data accuracy than air blast cleaning technologies during Project 25. Whatever the best lens cleaning technology (or combination) are deemed suitable to a particular monitoring application, they do add additional layers of technical complexity, as well as increasing system cost and maintenance. Even with the integration of lens cleaning technology into a sampling station platform, optical-based sensors will still require regular maintenance and additional cleaning (probably at least monthly).

These caveats are not outlined to undermine the application of RTWQM technologies, but simply to highlight (like any water quality monitoring technique), the considerable investment and attention to appropriate protocol required to ensure optimal performance. While real-time sensors are sufficiently developed to warrant broader application, they still represent an emerging-developing technology. Practical guidelines for instrument selection, deployment and collection methods for data quality assurance, control, and management are accordingly still under development, even in countries with comparatively long-standing experiences and broad scale RTWQM deployments (see Snazelle, 2011; 2015; Pellerin et al., 2013; 2016; Rozin, 2014).

3.4 Guidelines for future implementation of RTWQM as an integrated water quality monitoring-engagement tool

Despite the challenges in ensuring nutrient sensor performance, and the almost inevitable familiarisation periods required with their initial deployment and performance, the richness and detail and accessibility of the intensive data these new technologies can provide is noteworthy. Achieving the temporal detail of nitrate-N fluxes depicted in Figure 17 (panel a), for example, would be outside the scope (and very likely budget) of most 'traditional', discrete sampling-based water quality monitoring programs, particularly as number of monitored sites across a catchment (or program) increases. Beyond purely water quality monitoring perspectives, the fact that this information can be available in essentially 'real-time' is an additional exciting aspect for its potential use as a communication tool to landholders. Several of the predominant 'pros and cons' of sensor versus traditional discrete water sampling technologies in this landholder engagement context are also outlined in Table 1.

Table 1: Some brief considerations of comparative capacities of traditional discrete water sample collection versus sensor-based technologies for integration in stakeholder engagement monitoring programs. For more comprehensive technical reviews see Pellerin et al. (2016) and references therein.

Feature	Sensor technologies	Traditional discrete water sample collection
Costs	Substantial for individual sensors, but costs are decreasing steadily. For example, relatively recent costings estimated ~US$60,000 for 'a one-time nitrate measurement using an optical sensor would cost approximately US$60,000 when taking the procurement cost of a sensor ($20,000-25,000) into account along with operation, maintenance, and data validation costs' (Pellerin et al., 2016). Current 2020 estimates sit ca. $30,000 AUD (~US$23,000 for entire capital costs for an individual site, Ryan Turner, Department of Environment and Science, pers. comm). Note that sensor data progressively become less expensive per data point as sampling frequency of increases (at ~AUD$50,000 site installation cost, hourly monitoring over 4 months equates to $17/data point)	A discrete water quality sample collected and analyzed by the U.S. Geological Survey (USGS) for nutrients costs approximately $4,400 on average (based on 2013 estimates) once salary, equipment, and laboratory analyses are included (Pellerin et al. 2016).
Water quality parameter suites	Relatively limited, but available technologies already capture many nutrient and water clarity based parameters (nitrate, ammonium, phosphorus, turbidity) relevant to agricultural monitoring contexts. Monitoring of several key agricultural pollutants such as pesticides, however, remain decades away). Most sensor instruments are also currently limited to 1-2 variables. This necessitates purchase and installation of multiple sensor instruments for measurement of multiple parameters.	Essentially unlimited, at least from perspective of typical agro-chemicals of likely interest to agricultural watershed monitoring programs. Also often require just single sample for a combined, multi-parameter analysis.

Measurement accuracy.	Increasing improvements in accuracy and detection limits (comparable to laboratory alternatives in many cases). Many instrument's detection limits are eminently appropriate to 'edge-of-field' or small watershed monitoring scales, where highest parameter concentrations are typically found. Note performance of some sensors (i.e. optical sensors) can, however, be affected by matrix effects (presence of other constituents in water that affect absorbance spectrums).	Minimally affected by matrix effects or other water quality constituents in samples for most laboratory techniques.
Data reporting timelines and availability	Essentially instantaneous reporting of environmental concentrations (e.g., seconds to minutes if desired). Can also be coupled with associated discharge measurements for real-time reporting of pollutant load fluxes. Does require substantial investment in telemetry, 'cloud' infrastructure and software platforms to deliver results in real-time	Several days to weeks at best (following sample retrieval and laboratory analysis), often several months (or more) for environmental concentration data reporting (and requires additional analysis for load flux calculations).
Capacity for continuous, fine scale measurement and monitoring of transient, short term fluctuations at small catchment scales	Essentially unlimited (but will be dependent on site specific equipment layouts).	Typically severely constrained by logistical and financial challenges relating to on-site sample collection frequency, storage, collection and subsequent analysis considerations.
Data management requirements	Substantial. 'Continuous monitoring of a single parameter at 15 minute intervals results in over 35,000 measurements per year, with that number easily increasing by orders of magnitude when additional sensors and diagnostic data are also included' (a 'data deluge'; Pellerin et al. 2016).	Variable, but even collection of daily discrete samples at a site results in orders of magnitude fewer data points that typical RTWQM

While representing an exciting, possibly transformational tool, sensor-based monitoring and RTWQM frameworks will also have their own suite of challenges, costs and limitations as a farmer-landholder engagement tool. We present several guidelines based on case studies and recent global experiences – described below – to maximise effective implementation of these new technologies into a broader toolbox of coordinated farm monitoring, management and extension effort in agricultural catchments. These guidelines build largely upon extension principles emerging from recent sub-catchment or farm-scale water quality improvement projects, but with added considerations specific to integration of water quality sensors and RTWQM technologies.

Guideline 1: Be aware of current limitations of high frequency sensor technologies, and associated infrastructure and supplementary requirements for meaningful monitoring.

High frequency sensor-based monitoring cannot be a standalone monitoring effort entirely substituting conventional water sampling approaches, but instead requires integration and support from more traditional methods. Costs of sensor technologies, and specificity to individual water quality parameters, means ensuring sensor selection is appropriately matched to local pollutants is critical in program design. Recent research in the GBR catchment area, for example, suggest ammonium, rather than nitrate, is often the dominant inorganic nitrogen form leaving canefields in some major sugarcane growing regions (Di Bella et al. 2015; Davis et al. 2016; Ryan Turner, DES pers. comm.). Pilot water quality monitoring to inform sensor selection, and ongoing monitoring to validate sensor results (via traditional discrete sampling methods) are critical components of quality assurance. Similarly, to value add to sensor concentration data, calculation of catchment load losses will require substantial additional investment in monitoring infrastructure and development of stream discharge and rating curve relationships.

Guideline 2: Developing local scale trust.

Appropriate information confidentiality and data dissemination frameworks need to be considered in study design to allow for grower engagement and collaboration. While freedom of information considerations may desire immediate transparency of monitoring data, because of the potential immediate accessibility and sensitivity of sensor-based RTWQM monitoring programs in particular, lack of context could result in misinterpretation of results made publically available in 'real-time' (see Stroud, 2018). Recent experiences within GBR sugarcane catchments highlight a safe learning environment is essential for data sharing partnerships to consolidate. It may be advisable to place temporary embargoes on data give access to only project stakeholders (e.g. landholders adjacent to water quality monitoring sites), giving them an opportunity to digest monitoring outcomes, and proactively develop strategies and implement activities to address identified issues (Di Bella et al. 2015), prior to public data release.

Guideline 3: Additional effort required to convert data into actionable knowledge.

While the capacity to generate data from sensor technologies is growing rapidly, the substantial effort required to translate data into a form that is useful and empowering to stakeholders should not be underestimated. The vertical-linear-oriented pyramid of the data-information-knowledge-wisdom hierarchy (DIKW; Figure 12), for example, has formed a conceptual basis for guiding much scientific research into knowledge generation, including information technology (Ackoff, 1989). Data have no value until they are processed into a useable form and given an appropriate context. Information contains data that is organised (through either presentation or systematic analyses). Knowledge represents information that has been understood of put into use, generally by a human. While the DIKW is facing increasing scrutiny and re-formulation (Van Meter, 2020), particularly in light of concerns about underlying assumptions, data mishandling and accuracy, it does serve to simply illustrate a conceptual framework required to convert sensor data into a usable form for stakeholders.

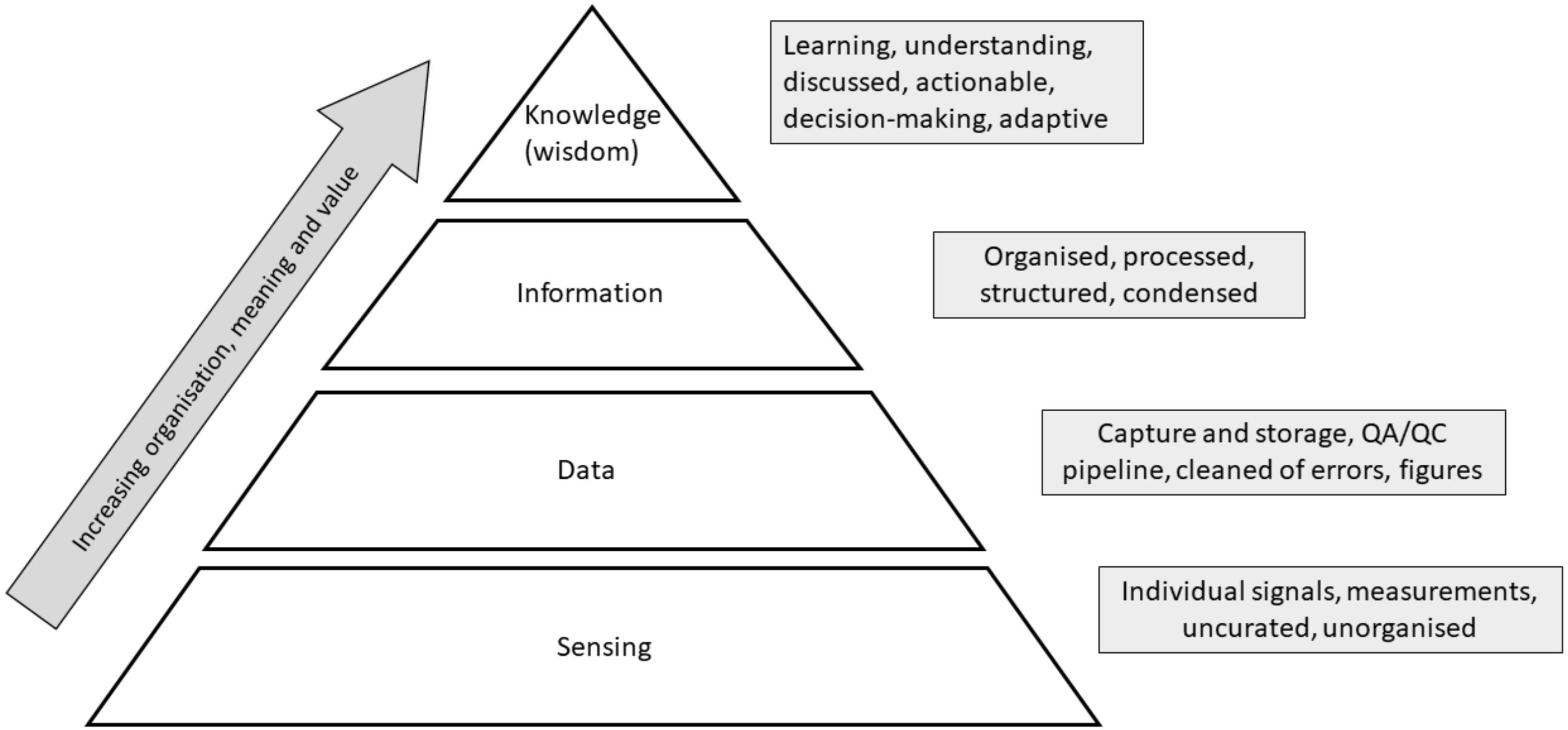

Figure 12: The data–information–knowledge–wisdom (DIKW) hierarchy as a pyramid to translate sensor data into knowledge (adapted from Ackoff, 1989).

As illustrated in recent GBR experiences in providing farmers with real-time information (not just data) on nitrate and other contextual variables in their local creeks and rivers, such platforms require substantial investment in a broad range of expertise spanning water quality, hydrology, software design and user experience (Vilas et al., 2020). Moreover, platform development and maintenance will likely remain an ongoing and iterative process. Coupled with the substantial data management requirements of RTWQM, long-term commitments for dedicated project staff will likely need to be factored into program design in efforts intended to provide real-time data to farmers and other stakeholders.

Guideline 4: Ensuring data quality – a prerequisite for stakeholder trust

Nothing will erode trust in sensor-based, RTWQM data more quickly than erroneous data being presented for action or consideration, which is then retracted. A critical requirement for all RTWQM programs then becomes the inclusion of a suitable QA/QC program. Whilst improvements with measurement instrumentation enable RTWQM, another barrier which prevents organisations from quickly making data real-time data available is the need for quality assurance before data release or publication. WMO Hydrological practices chapter 9 'Data Processes and Quality Control' (WMO, 2009) present the idea that in data quality control, the operator should be conservative when modifying or quality coding data and should follow a set of agreed protocols and practices. WMO also define at a high level, typical data practices and processes.

Above Quality Control is discussed, there is often confusion between quality assurance and quality control. The International Organisation for Standardisation (ISO) defines quality assurance as the processes that assure quality, that is, in this context, those processes that occur before a measurement is taken to ensure quality. These processes would include installation, maintenance, calibration and a regular checks to ensure that the instrument is performing appropriately. Quality control on the other hand, are the processes performed after measurement, the ISO define as "ensure quality control". These are checks, measurement and comparisons that are made on the data by suitable process and personnel to control the quality. All organisations today that have responsibility for water and water quality monitoring/measurement will have systems and procedure in place to quality assure, and to quality control. Queensland Government for example have substantial QA/QC protocols in place which ensure and control quality. These organisations will have sophisticated hydrographic databases such as Kisters Wiski or Hydro International Aquarius provided to help the operator quality control data. The process of quality control typically requires an expert to manually review and quality code the data, and through using appropriate tools and expert judgment (consistent with the principle of being conservative), the quality coding and release of data occurs. The timing of the validation and release process happens on a regular basis, but at times that suit the operating organisation, and often at quite some time after observations have been made.

One of the benefits of delaying the quality control (coding) of water quality data is that additional information relating to the performance of the measuring instrument, and other context including, site or sample collection notes, and comparative laboratory samples can be included in the quality assessment. Most helpful in determining performance of in-situ instruments is comparisons to discrete grab-sample, laboratory-analysed data. As part of quality control, any

RTWQM sampling program should incorporate a grab-sampling sub-program. However, even with comprehensive set of comparative grab samples, it is difficult to get complete agreement due to issues of sample collection (discrete and sensor collection being identical in space and time) as well as handling, transport, processing and laboratory instrumentation issues (Bende-Michl et al., 2013). The goal of delivering RTWQM data to users therefore requires some automated QC process, before finally delivering the data a web portal. An example of this is the QC pipeline described by Vilas et al. (2020). The high-level pipeline is reproduced below in Figure 13. Of note are the three main functions: 1) Outlier removal in which values that exceed the outlier threshold are automatically removed and filled with interpolated values; 2) Rate of Rise Exceedance where values which exceed the rate of rise threshold are removed and filled with interpolated value's, and lastly; 3) Large gap imputation in which large data gaps can be infilled with an imputation model (Zhang et al., 2019).

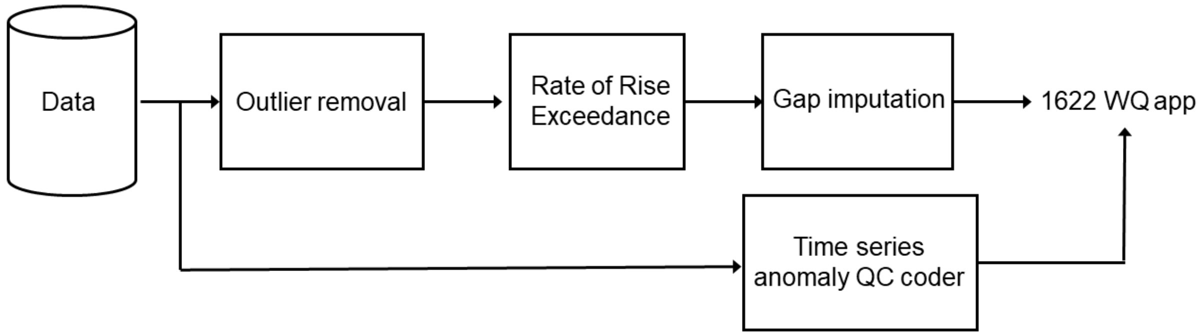

Figure 13: Automatic QC RTWQ Data Pipeline (modified from Vilas et al., 2020, courtesy of Peter Fitch).

An addition could be added to this pipeline in the form of an anomaly classifier. The purpose of this block is not to change or remove the data, but to identify known patterns in a similar way to an expert, and marking the data accordingly. Machine learning models are routinely used for a range of time-series classification and anomaly detection problems (Zhang et al., 2019), and offer significant potential to an auto quality control pipeline for RTWQM data delivery.

3.5 Temporal dynamics of Nitrate-N loss from Project 25 sub-catchments

There has been considerable global research interest in identifying the sources, flow paths and temporal mechanisms responsible for the export of N, particularly Nitrate-N, from catchments across both individual rainfall events, and also over seasonal-annual scales. Despite numerous investigations of N dynamics, detailed studies on the temporal aspects of nitrogen fluxes and stream discharge in agricultural catchments of the GBRCA, are currently scarce. Quantification of nutrient fluxes in sewage systems and urban watersheds have highlighted initial catchment 'first flushes' as driving a significant proportion of nutrient export from watersheds in many scenarios (Lee et al. 2002; Li et al., 2007). The phenomenon is subject to various definitions and the concept covers broad mechanisms such as "concentration-based first flush" and "mass-based first flush" (Sansalone and Cristina, 2004). A "first flush" is, however, normally defined as a disproportionate increase of particulate or dissolved materials in terms of concentration or load in the rising limb of a runoff event, or a pollutant mass emission rate that is higher during the initial portions of run-off than during the last portion, with most of the pollution load transported in the initial part of the event discharged volume (Bertrand-Krajewski et al.1998; Lee et al.2002). While most first flush research has focused on contaminant flux dynamics associated with individual runoff events, the basic concepts and analysis can also be applied to seasonal pollutant export dynamics. For example, Obermann et al. (2007) showed in medium-sized French agricultural catchments that over 2/3 of the annual total suspended solids load can be caused by the first flood event, which strongly influences the annual fluctuation of mass transport.

The concept and definition of the 'first-flush' separation from the total runoff hydrograph was first advanced in the early 1970s, with the intent that significant amount of diffuse pollutants could be isolated for treatment, instead of dealing with the whole volume of runoff during each storm event. Diversion and capture of these events are increasingly used for watershed best management practices (BMPs), such as enhancement of sediment and nutrient removal efficiency by treating the first stage of run-off using sedimentation devices or filters (i.e. ditches, tanks and ponds). and are regarded as an important potential tool in managing poor water quality (i.e., the first ~30% of catchment runoff volume contains ~80% of contaminant loading that can be captured and treated; Al-Mamun et al. 2020). Expression of the first flush phenomenon is uncertain, or debated, particularly in larger catchments, principally due to catchment complexity, and to the dilution and spatial variability in transport of the pollutant to monitoring locations.

The traditional approach to identifying phases of increased nutrient fluxes (such as first flushes), are diagrams of normalised cumulative loads over normalised cumulative flow for a specific runoff event or season (Bertrand-Krajewski et al. 1998; Obermann et al., 2007; Al-Mamun et al. 2020). These types of curves enable a dimensionless classification of the pollutograph in terms of the temporal distribution of loadings over the duration of a particular runoff event. The temporal pollution loading characteristics of runoff can be broadly categorised as advanced, lagging, mixed or uniform, as illustrated in Figure 14 (see Griffin et al. 1980). A first-flushing action is considered as evident, if the contaminant loadings yield a curve which lies above a 45° diagonal line passing through the origin, because the first 50% of the runoff has transported a greater proportion of pollutant mass.

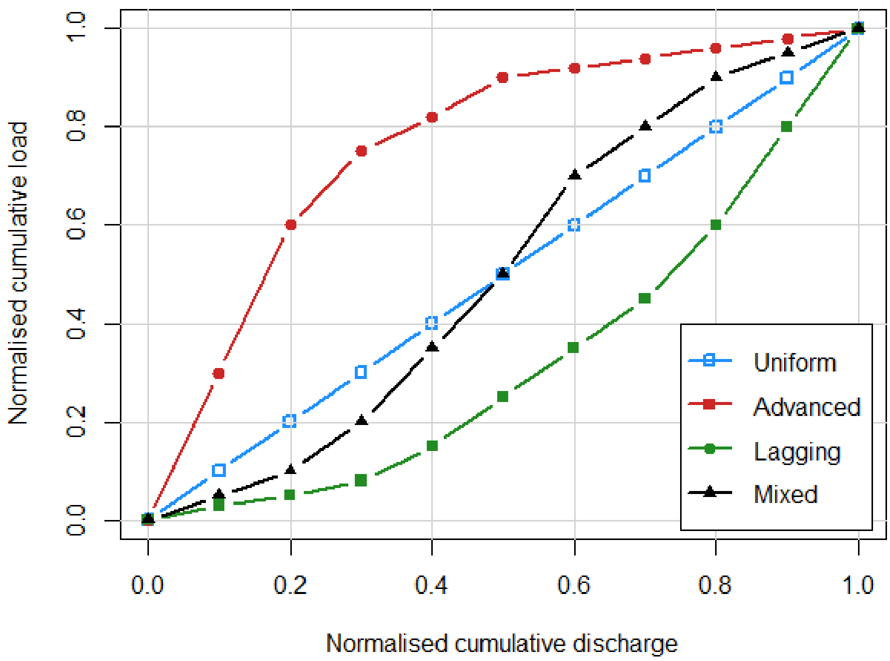

Figure 14: Theoretical examples of different loading characteristics of normalized cumulative loads versus normalized cumulative flow in runoff events.

Monitoring of Project 25 sub-catchment nitrate loss dynamics highlight that, some of the highest nitrate-N concentrations, as well as a significant proportion of annual nitrate load losses from cane-dominated catchments can often occur in the first 3-4 significant rainfall-runoff events of the year (Figures 16 and 17). In the wet-tropical catchments of north Queensland, such as the Russell-Mulgrave, these rainfall events can occur in virtually every month of the year, but are more common in October-December, the typical ‘wet season build-up’ to the highest rainfall months of January-March, when the highest rainfall totals and largest floods typically occur. October-December is recognised as a high-risk period for applied fertiliser losses, being the time of year when fertiliser application following later cane harvests also take place (Figure 15). This represents a critical risk window for water quality, where applied fertiliser is most susceptible to off-site loss from paddocks (i.e., prior to opportunity for significant fertiliser uptake by the growing cane plant).

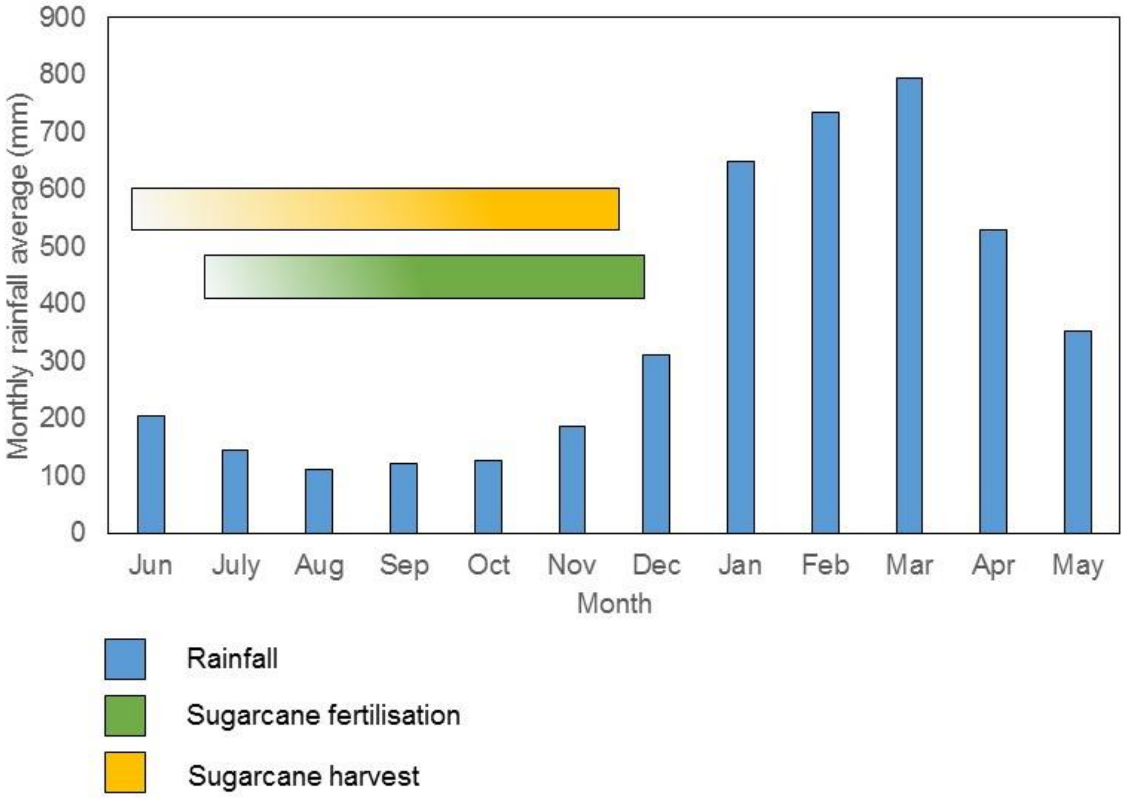

Figure 15: Temporal distribution of key sugarcane farming activities in relation to monthly rainfall averages (Babinda Post Office BOM site 031004) under typical harvesting and weather conditions.

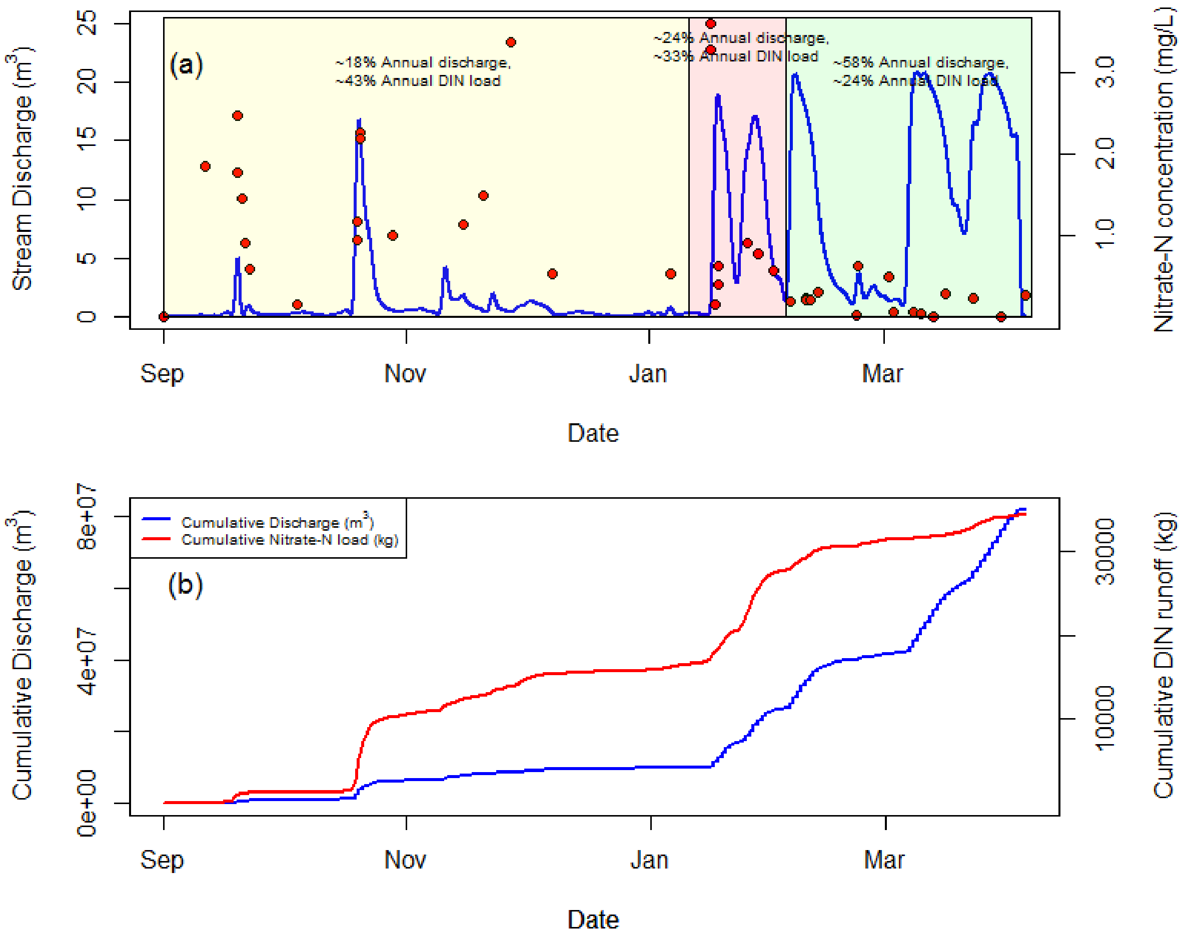

Figure 16: (a) Annual oxidised nitrogen (nitrate) concentration (red circles) and stream discharge dynamics examples from a Russell-Mulgrave, sugarcane dominated sub-catchment (2017-18 wet season). Catchment discharge volumes and nitrate load losses are partitioned into different time periods with the nitrate loads and associated catchment runoff volumes of key events highlighted. (b). Cumulative sub-catchment stream discharge and cumulative N losses in the same period. Arrows indicate approximate point where ≥40-50% Nitrate-N loss have occurred.

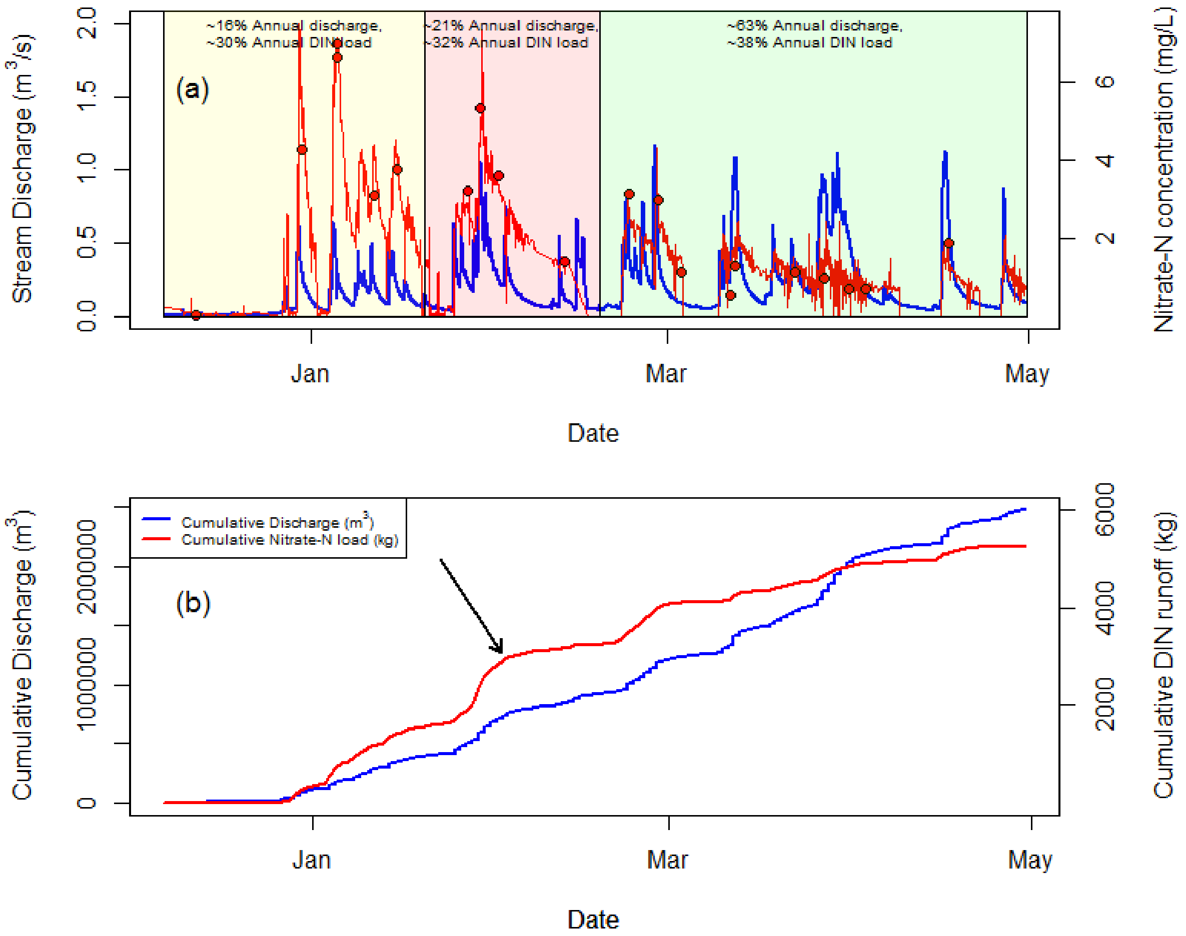

Figure 17: (a) Annual oxidised nitrogen (nitrate) concentration (red circles-grab samples; red trace-continuous nitrate sensor data) and stream discharge dynamics examples from a Russell-Mulgrave, sugarcane dominated sub-catchment (2019-2020 wet season). Catchment discharge volumes and nitrate load losses are partitioned into different time periods with the nitrate loads and associated catchment runoff volumes of key events highlighted. (b). Cumulative sub-catchment stream discharge and cumulative N losses in the same period. Arrows indicate approximate point where ≥40-50% Nitrate-N loss have occurred.

Stream discharge and nitrate export cumulative curve generation for Project 25 monitoring sites reveals that cane-dominated sub-catchments also exhibit characteristics of ‘first flush’ behaviours over the scale of the entire wet season (Figure 18). Multiple catchment’s contaminant loadings yielded export curves which lie above the 45° diagonal line passing through the origin (i.e., cumulative nitrate load losses that lie above a 1:1 uniform load export with cumulative stream discharge volume). Cumulative proportional nitrate-N load losses were, therefore, not directly proportional to cumulative discharge volumes across the course of the wet season. For example, in ‘N load ‘2 in Figure 18, ~40% of nitrate-N load had left the catchment in the first 20% of annual discharge volume. This indicates the earlier portions of annual runoff had transported a disproportionately larger load of annual pollutant mass export.

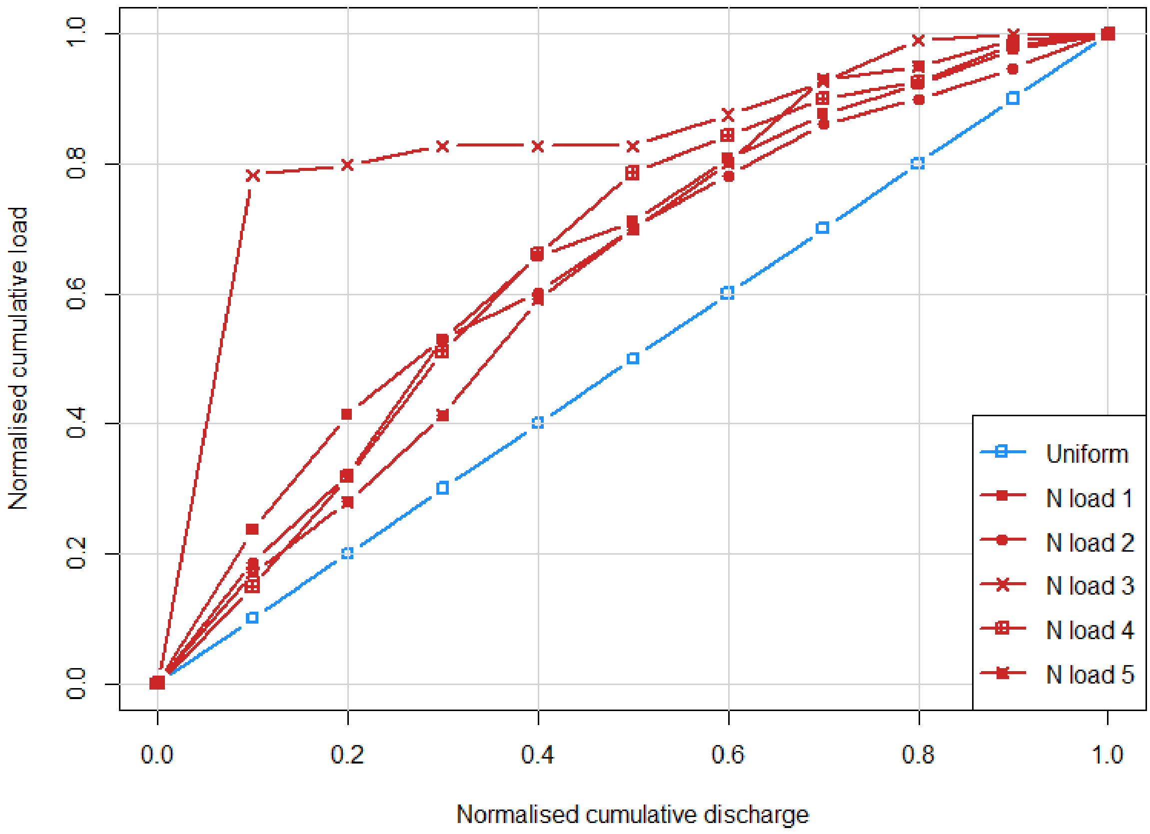

Figure 18: Some cumulative annual nitrate loading characteristics of nitrate export in wet season runoff from several Project 25 monitored catchments.

The concept of initial catchment 'pre-flushes' or 'first flushes' in the early wet season runoff as important annual water quality events for GBRCA ecosystems is well documented (Davis et al., 2017). Many of the environmental-catchment conditions known to drive first flush phenomena in other scenarios (see Al-Mamun et al., 2020) also likely eventuate in wet-tropical farming situations. Small catchments sizes, high-density artificial drainage systems, relatively dry antecedent weather conditions, accumulation of potentially mobile pollutants across the catchment (in this case significant single fertiliser applications to paddocks after harvest) followed by significant rainfall and runoff are common drivers of first flush processes (Al-Mamun et al. 2020). Excess applications of nitrogenous fertiliser, in particular, are also likely to be particularly prone to early loss (discussed below).

The temporal DIN loss dynamics documented at sub-catchment scale in the Russell-Mulgrave catchment, perhaps not surprisingly, parallel the temporal DIN loss dynamics documented at finer, paddock scales from nearby Wet Tropics canefarms. Significant proportions of annual DIN loss from canefields in Mossman often occurred in the earlier stages of wet season paddock runoff (Figure 19), particularly under 'traditional' fertiliser application rates, higher (at the time) than current industry BMP recommendations (Webster et al. 2012). Similarly, the first 2–3 runoff events after fertiliser applications contained both the highest dissolved inorganic N concentrations in surface water runoff, and also exporting the majority of the DIN load loss for each season at nearby Tully-Murray sugarcane farms (Masters et al., 2017). The authors here suggested mitigation strategies that target these initial events could provide significant water quality benefit.

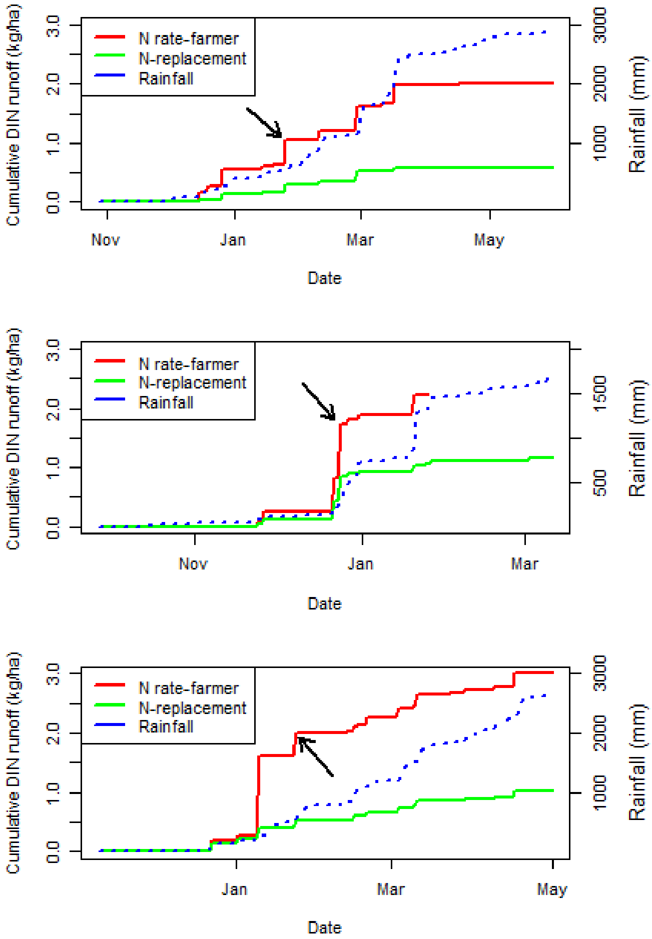

Figure 19: Cumulative rainfall and cumulative DIN load losses in surface water runoff from normal farmer's Nitrogen application rate (N-farmer) and lower fertiliser rate based on replacing N exported in previous crop (N-replacement). Data modified from Wet Tropics dataset (Mossman) of Webster et al. (2012). Arrows indicate approximate point where ≥40-50% Nitrate-N loss have occurred.

The 'first flush' phenomenon has been most frequently demonstrated in small urban catchments characterised by large catchment proportions of impervious area, from which surface flow regime dominates the runoff process. A growing body of research from agricultural catchments is also suggesting elements of first flush behaviours in water quality dynamics from farming land-uses (Obermann et al., 2007; Yang et al. 2015). The results of Project 25 (and other recent paddock scale research) suggest that the first flush phenomenon can also occur in GBRCA agricultural watersheds, and the concentrated initial load loss process may provide an important potential intervention point for the management of diffuse pollution.

3.5.1 Innovative use of existing floodplain drainage networks as a potential water quality management tool?

There is a scarcity of experimental information available on the ability of different wetland and drainage systems to trap pollutants in the hydrological and climatic conditions of the GBR catchment, particularly in wet tropical systems. The role of wetlands, both natural and constructed, particularly on-farm, in capturing farm nitrate run-off losses is still a matter of considerable scientific debate (McJannet et al., 2012; DeBose et al., 2014; Adame et al., 2019). Conventional thinking suggests that because of the extreme rainfall volumes and rapid catchment transit times (minimal residence time) experienced in northern Australia catchments, smaller, on-farm or even small sub-catchment constructed wetlands, may lack the capacity to capture significant volumes for a sufficient period of time for nitrate removal (DeBose et al., 2014).

While the concept of ‘first flushes’ is recognised in some GBR catchment and paddock scale monitoring (Davis et al. 2017), the implications of these processes in potential runoff interception and treatment remained largely unexplored as a potential management tool. As evident in the presented Russell-Mulgrave examples, large, and sometimes dominant proportions of nitrate load export from canelands are associated with rainfall and runoff events of relatively small volumes (<5000ML) in the early stages of the late-dry and early wet-season. While some of the larger events (February-March) are of too large a volume to practically consider for diversion or interception, some of these smaller, earlier events are not. On developed agricultural floodplain systems with significant artificial drainage systems present (Figure 20), there may be considerable potential to retain or divert smaller, earlier, high nitrate concentration runoff events. Such flushes could be held within the drainage system or associated wetland systems for sufficient time for biochemical transformation or uptake of nitrogen, prior to the larger, major wet season runoff events.

Most GBRCA wet tropical floodplain drainage systems are decades old, and were not developed with any water trapping function in mind (in fact quite the opposite). Relatively minor drainage alterations, diversions or water level infrastructure installation at key locations could, however, conceivably deliver targeted interception of significant volumes of annual nitrate loads otherwise exported from agricultural catchments. The concept of finer scale drainage system management (through small weirs and control structures) has been briefly explored as a sediment water quality management tool in wet tropical GBCRA sugarcane catchments (Roth and Visser, 2003; Visser et al. 2007). Similar management for more soluble nutrient forms such as Nitrate-N, in a catchment-scale water quality improvement framework remain largely untested.

Water quality remediation strategies which utilise existing agricultural drainage systems to selectively target, divert and treat high nitrate-N flushes, in cooperative farmer collectives, are not, however, without precedent. Controlled drainage strategies in agricultural ditches such as spatially orientated low-grade, relatively low cost weirs, show considerable promise to significantly improve nutrient (e.g., nitrate, $NO3^{-}$-N) reductions by expanding the area available for biogeochemical transformations, as well as providing multiple sites for runoff retention (Kröger et al. 2014). Growing numbers of global examples are seeing practical implementations of similar concepts (Kröger et al. 2014; Mander et al., 2017; Tournebize et al., 2017; Kumwimba et al. 2018). In the American mid-west, for example, costs are estimated at US$2.1/kg ± 1.5, (Christianson 2011), and are shown to reduce DIN losses by 15 to 75% (Christianson et al. 2016). There are currently ~1000km (300 hectares) of existing drainage board and internal farm drains installed across the Russell-Mulgrave area, representing several hundred hectares of potential drainage management capacity (assuming 3 m average drain width). In combination with significant areas of low-lying wetland with potential drainage connection (or re-connection) and storage capacity in the catchment, at least several hundred hectares of possible drainage intervention already existing on the Russell-Mulgrave floodplain.

Figure 20: Example farm drainage complexes across the Babinda drainage scheme area (Image: Boyd Robertson).

Recent assessments of the water quality improvements delivered by canefarmer practice change alone (i.e., best practice fertiliser management) are clear in recognising they are highly unlikely to deliver the desired nitrate load reduction targets desired to ensure the resilience of the GBR environment, even if successfully implemented across the entire industry (Waterhouse et al., 2017). Innovative, and ‘outside the box’ management practices are clearly needed to supplement the effort of industry to improve water quality leaving farms. Coordinated, catchment scale water volume management strategies could be one such measure, and one more likely to be palatable to industry. This style of management intervention is also complementary to other catchment management initiatives such as wetland and riparian restoration, activities that are often only superficially integrated with water quality improvement by farmers, other landholders and NRM organisations.

3.6 ‘Hotspots’ in diffuse DIN generation in the Russell-Mulgrave catchment.

Emerging global recognition of the complex nature of nominally ‘diffuse’ non-point source pollution is highlighting the need for re-scaling of water quality monitoring and intervention effort at smaller catchment scales. Despite its nomenclature, non-point source pollution still often originates in 'hotspots' or 'critical source areas' from a small portion of the landscape, areas that can be targeted for maximum efficiency (Carpenter et al., 1998; Pionke et al., 2000; White et al., 2009; Kleinman et al., 2011; Kovacs et al., 2012; Kalcic et al., 2015). Not only are certain locations more vulnerable to non-point source pollution, but individual conservation/management practices may be more or less suitable in those locations within a given watershed (Tomer et al., 2013). Spatially targeting the most effective conservation/management practices to locations with the greatest potential for water quality improvement can accordingly decrease the cost of implementation to meet a particular water quality goal (e.g., Veith et al., 2004).

Ignoring these critical source areas can have profound ramifications for cost effectiveness of water quality improvement practices (Sharpley and Smith, 1994). Unfocused implementation of catchment scale water quality remediation efforts that miss critical source areas of pollutants can provide minimal end-of-catchment water quality responses. Examples exist where conservation/management practices installed on as much as 50% of the target watershed resulted in negligible water quality improvement, due to lack of remedial effort on critical source areas that made the dominant contribution to catchment pollutant loads (Kleinman et al., 2011). These considerations have received considerable longer-term recognition in grazing catchments of GBRCA (Bainbridge et al., 2014), at the scales of both sub-catchments, but also at much more specific, and finer scale-hydrogeomorphical features (i.e., gullies) that are recognised as suspended sediment 'hotspots', and are now receiving very spatially targeted and significant remediation effort. The availability of technology to relatively efficiently identify and prioritise these finer scale hotspots (remote sensing, historic aerial photography etc.), and specifically where they occur in the landscape over broad spatial scales, is a critical aspect of this capacity in grazing catchments (Brooks et al. 2019; 2020).

Nutrient generation 'hotspots' are certainly implicit in some aspects of predictive water quality modelling of practice change in GBRCA agricultural commodities such as sugarcane (McCloskey et al., 2017). These are based, however, primarily on coarse-scale data relating to catchment farm management practices, rather than actual identification of comparatively quantified hotspots highlighted by water quality monitoring results. The on-ground identification and subsequent targeting of intervention effort is still in a state of relative infancy in the more intensive agricultural catchment areas of the GBRCA. The recent development of increasingly cheaper, and fit-for-purpose nitrate sensing technologies is, however, opening up significant opportunities for much denser, finer spatial scale sub-catchment monitoring in GBR intensive agricultural catchments. This in turn allows specific identification, and prioritisation of extension and intervention effort on nutrient loss hotspots.

Agricultural industry stakeholders and landholders have been calling for more intensive monitoring and water quality data for many years. RP232 Fine-scale water quality monitoring in high priority catchments has now been funded by Reef Programs, from the Office of the Great Barrier Reef, Department of Environment and Science. Water Quality Investigations team who run the GBRCLMP are now expanding their real-time monitoring network in North Queensland. Up to 40 additional nitrate and sediment sensors will be installed at locations throughout high priority catchments to support community awareness of water quality issues and improved Paddock to Reef modelling. Currently, the priority catchments are the Herbert and Lower Burdekin, as shown in the Reef 2050 Water Quality Improvement Plan. Before the sensors were installed across the Lower Herbert and Lower Burdekin, the Water Quality

Investigations team held meetings with stakeholders in those catchments to discuss the intent of the expansion as well as potential sensor locations (co-design). It is important to note that sensors will show water quality on a sub-catchment level only and individual farms will not be identifiable.

Nitrate-N hotspots across the Russell-Mulgrave catchment

Project 25 provided clear capacity for hotspot identification in monitored sub-catchments of the Russell-Mulgrave catchment. Even when factoring in the inevitable local scale variability in climate, hydrology and timing of farming operations that can confound identification of water quality patterns, within approximately three years, areas consistently responsible for relatively high nutrient losses emerged rather quickly. Figure 21 contrasts the typical scale of nitrate-N fluxes across the three initial RTWQM sub-catchments in the Russell-Mulgrave, all dominated primarily by sugarcane cultivation, and all presented with the same scale. The site in panel (b) demonstrates both significantly higher, but also more sustained and elevated nitrate-N concentrations throughout rainfall-runoff events. While local variations in catchment land use development (i.e. relative area of sugarcane versus pristine rainforest) does have considerable influence on the observed scale of nitrate-N concentration dynamics presented here, these relationships were also consistent with more integrated and directly comparable data formats such as annual nitrate loadings on a per hectare basis from each sub-catchment (i.e., kg/Ha/year Nitrate-N exports yields from the monitored catchments). Yearly wet season DIN loads from the sub-catchment identified in panel (b) was typically in the vicinity of 2-3 times that of the other monitored sub-catchments presented in panels (a) and (c).

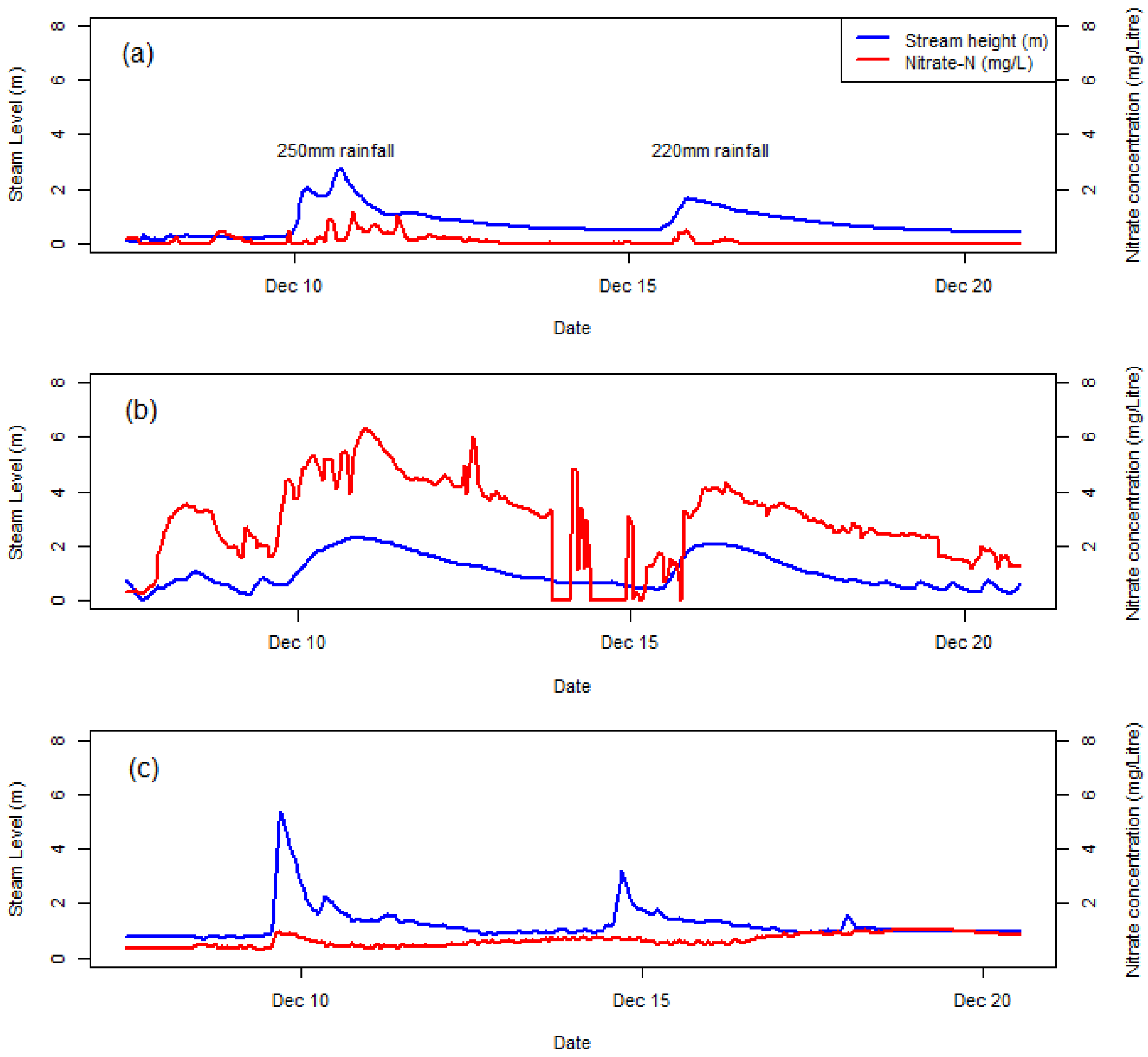

Figure 21: Intensive nitrate-N monitoring from three Project 25 RTWQM sampling stations, located in cane-dominated sub-catchments during, early wet season rainfall events (December 5th to December 20th). Approximate daily rainfall totals responsible for flood events are indicated in panel (a).

The consistent presentation of these local Nitrate-N loss patterns to Project 25 canegrower stakeholder steering committee members over several years of monitoring elicited agreement that finer scale water quality monitoring was needed to move 'up the catchment' to further isolate and understand these hotspots, and engage more meaningfully with specific grower collectives. Site locations for additional new monitoring stations were identified in early 2019 following discussions and site appraisals involving steering committee members and local growers in the target catchment, and installed in July-August 2020. Data from the subsequent 2019-2020 wet season within one targeted 'hotspot' sub-catchment is presented in Figure 22. Similar patterns of Nitrate-N concentration flux were evident across both sites, although concentration peaks were notably higher at the upstream monitoring site, particularly in the early stages of the wet season.

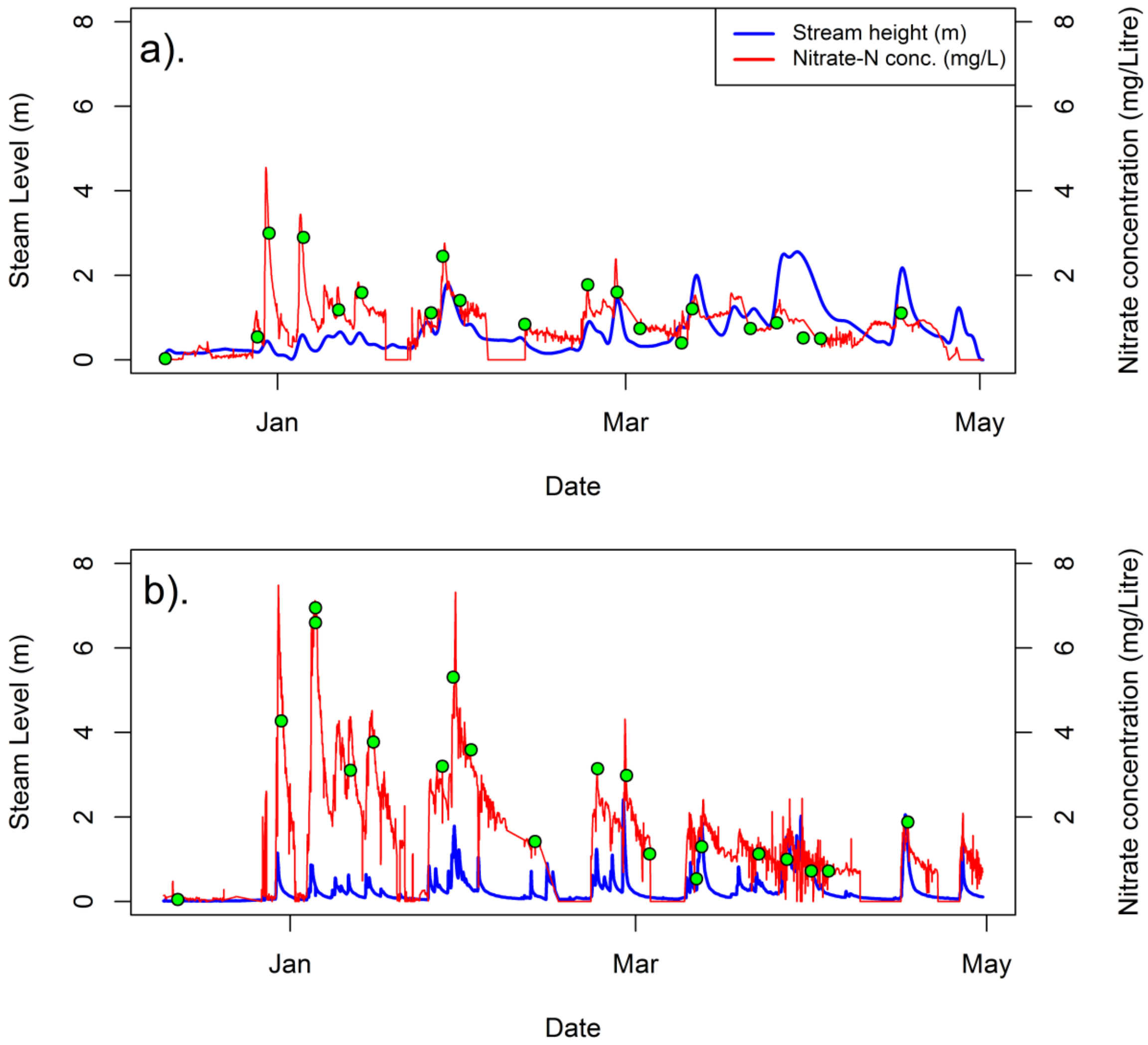

Figure 22: Intensive nitrate-N monitoring from two Project 25 sampling stations, located in cane-dominated sub-catchments during 2019-2020 wet season rainfall events. Downstream site indicated in panel (a), new upstream site installed in August 2020 indicated in panel (b). Green circles indicate discrete grab sample Oxidised-N concentration data; red trace-continuous nitrate sensor data.

Interestingly, one of the Project 25 Steering Committee canegrowers, located in this targeted hotspot catchment (Figure 21, panel b), noted one of the early wet season nitrate spikes through the 1622WQ^{TM} app. With Project 25 scientists, water samples were quickly collected from across the 4-5 upstream farms drained by this monitoring station, and with use of the local nitrate sensor, were able to identify specific farm paddocks apparently contributing a large part of the observed nitrate spikes. This exercise provided the basis of a NESP TWQ Hub stakeholder case study; 'Trust and technology: Tracking down sources of nitrate in the Great Barrier Reef catchment.' (https://nesptropical.edu.au/index.php/2020/05/08/trust-and-technology-tracking-down-sources-of-nitrate-in-the-great-barrier-reef-catchment/?utm_source=rss&utm_medium=rss&utm_campaign=trust-and-technology-tracking-down-sources-of-nitrate-in-the-great-barrier-reef-catchment).

> *"It was really good – (we) drove out and we managed to find out where it was coming from using the sensors. If you had just measured it from downstream at the river mouth like it has been done in the past, you'd never be able to tell exactly where it was coming from. This is why it's good to have accurate water quality data."*
>
> Project 25 Steering Committee canegrower.

> *"There was also something else interesting that I can see in the data, which is that plant cane – which is sugarcane that's been freshly planted season – doesn't seem to take the nitrogen up at the same rate as ratoon cane, which is cane that's grown back been cut back for harvesting."*

Results underline the value of collaborative approaches where local industry input into program and sampling design, knowledge of district farming practices, coupled with mutual trust frameworks, and locally relevant 'real-world' data can used to identify hotspots for improved on-ground prioritisation of water quality monitoring and extension effort within broader catchment areas. It should also be noted, however, that due to the long fertilising season in sugarcane and vagaries of rainfall distribution, that spatial 'hotspots' may have a temporal, even transient component (at a multi-year scale). Results in a single year may be more related to interactions between timing of sub-catchment management practices and localised weather events, rather than a sustained, longer-term geographic signal.

3.6.1 Industry responses Project 25 water quality monitoring results.

As agreed in the early stage of Project 25 development, the local cane industry undertook the responsibility of 'owning results' and driving industry responses to the locally-generated water quality program data. In addition to data presentations to the broader industry, local water quality monitoring was regularly presented by Project scientists in monitored sub-catchments to small grower groups ('shed meetings' or 'Young growers groups'), often in conjunction with other agronomic extension efforts. Local CANEGROWERS extension was also targeted specifically in sub-catchments identified in water quality monitoring results by the Project steering committee as 'hotspot' sub-catchments for nitrate losses. This particularly involved increasing extension effort and support for the industry-owned CANEGROWERS Smartcane BMP program, focussing on improved nutrient management use and planning and plant nutrition (https://smartcane.com.au/). Accordingly, it is possible to document and track the results of this targeted extension effort through the life of Project 25, in areas receiving increased Project 25 and CANEGROWERS extension effort, and areas outside the primary footprint of the project.

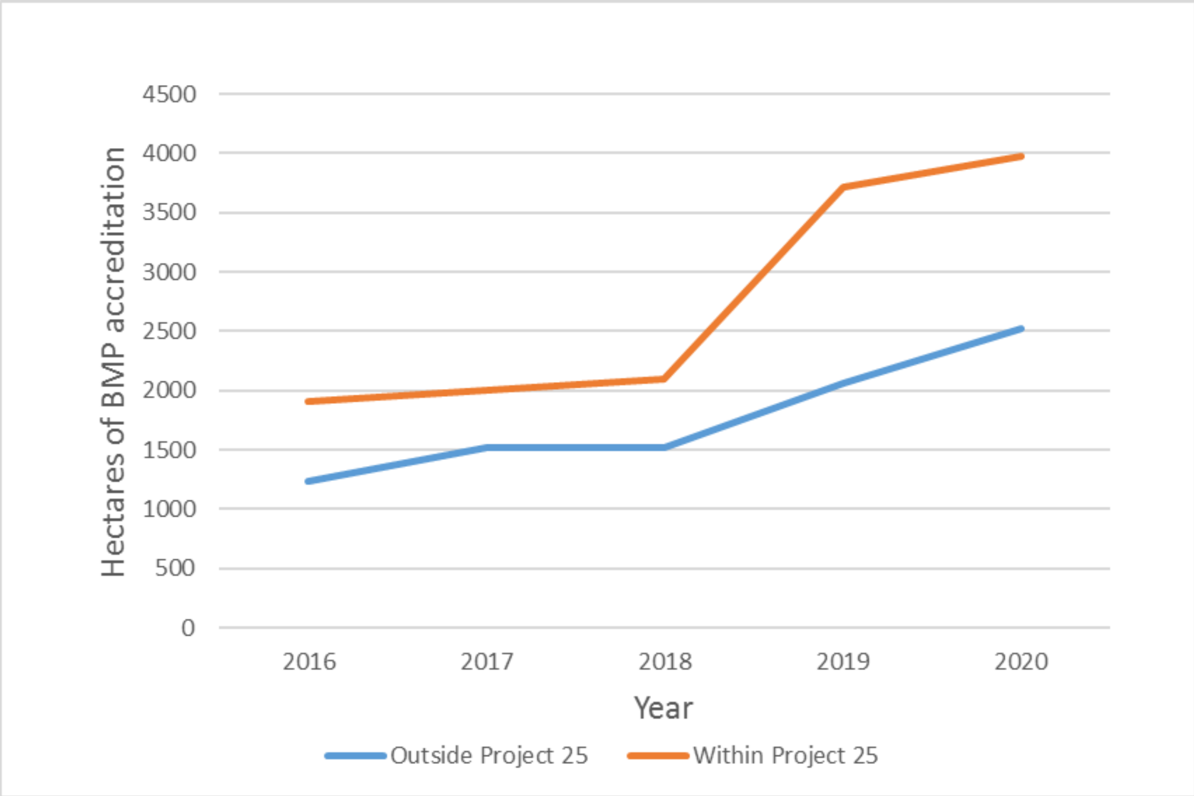

Figure 23: Yearly hectare increases in SMARTCANE BMP accreditation, within and outside Project 25 monitored catchments, in the Russell-Mulgrave (Cairns) CANEGROWERS region since the inception of the project.

Rates of BMP accreditation in terms of grower numbers, as well as land areas under BMP accreditation management (Figures 23 and 24) increased at faster rates within sub-catchment areas receiving Project 25 water quality monitoring and presentation back to industry, compared to grower numbers and land area outside Project 25 focus.

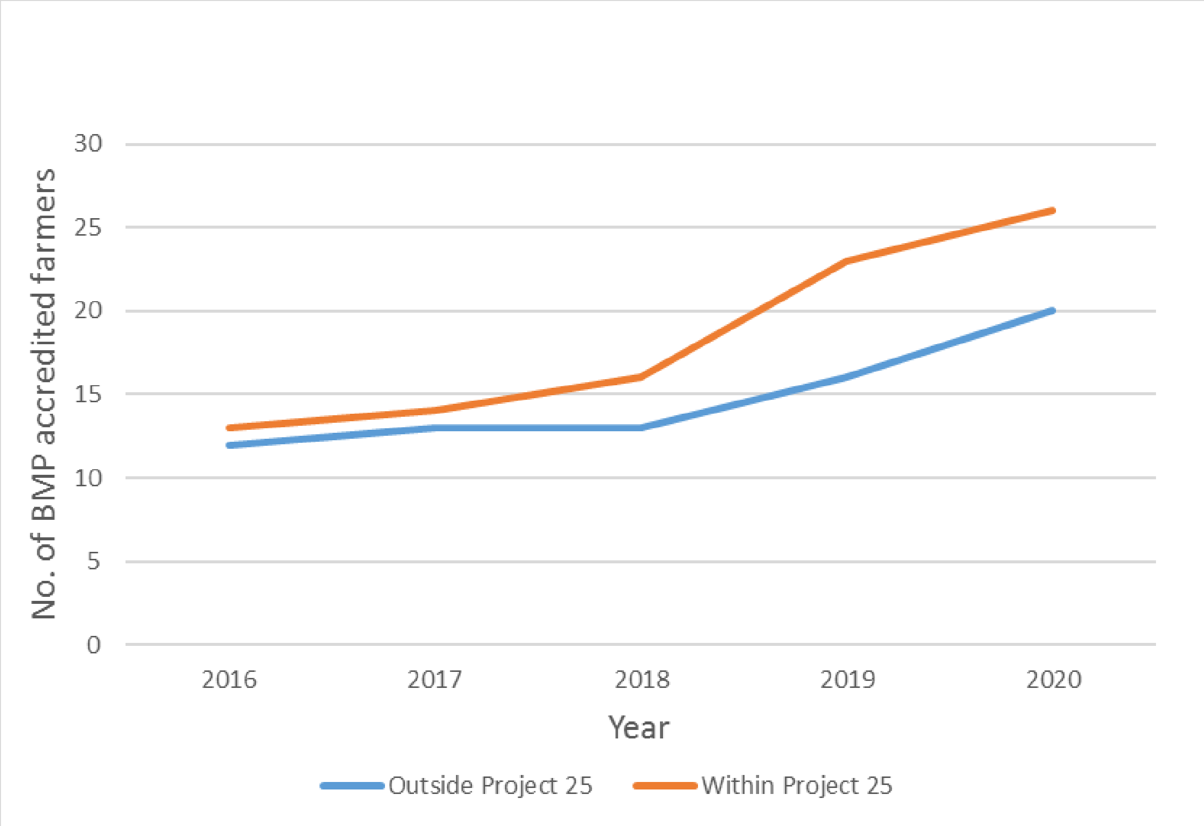

Figure 24: Yearly increases in SMARTCANE BMP accredited canegrowers, within and outside Project 25 monitored catchments, in the Russell-Mulgrave (Cairns) CANEGROWERS region, since the inception of the project.

When looking at these numbers, it should be noted that there is an approximate total cane growing area within the Cairns CANEGROWERS region of ~19,120 hectares, with Project 25 catchment areas (i.e., monitored upstream farming drainage area) making up approximately 8,178 hectares of that total. This equates to ~49% of farming area within targeted Project 25 catchments currently acquiring SMARTCANE BMP accreditation, with ~23% of cane land of the remaining region outside of Project 25 catchments currently BMP accredited.

It is difficult to entirely disentangle the impacts of Project 25 extension, particularly in focus sub-catchments, within the Russell-Mulgrave catchment, as most growers in the region received at least some exposure to the program and its results. Project 25 is also certainly not the only extension-engagement process operating within the catchment, and attributing this BMP uptake data solely to Project 25 should be avoided. Over the course of Project 25, it deserves recognition that other areas (and farmers) within, and outside the Project 25 area, within the Cairns CANEGROWERS region have received support or extension effort from other agencies during the period (i.e., SRA, DAFF). The fact that a number of growers within Project 25 target areas (including identified 'hotspots') have recently engaged significantly with other extension activities for the first time, if anything, underlines the synergies and collaborative extension impacts possible with trust frameworks, locally developed monitoring and extension programs. Indeed, joint extension presentations to farmer groups, between Project 25, and other extension activities, was a frequent, and consistent, aspect of engagement efforts.

3.6.2 Some challenges and opportunities in future finer-scale monitoring programs for 'hotspot' identification in the GBR catchment area.

Limitations of available sensor technologies

Despite the considerable opportunities offered by integration of RTWQM capacity into monitoring programs, limitations do exist, particularly with regard to availability of useable sensors for several of key water quality parameters in GBR sugarcane growing catchments. A number of parameters of direct relevance to the GBRCA such as various forms of inorganic nitrogen (nitrate, nitrite; 'oxidised nitrogen') and phosphorus are already well established constituents in RTWQM initiatives, including in the GBRCA. Recent research at paddock and catchment scale in the GBRCA suggests expanding the monitoring suite beyond oxidised nitrogen forms may, however, be warranted in future RTWQM initiatives, or the analytical limitations or current technologies at least be recognised. Ammonium, rather than nitrate, for example, is often the dominant inorganic nitrogen form leaving canefields and catchments in some major sugarcane growing regions of the GBRCA, particularly in the Wet Tropics (Pearson et al., 2003; Cowie et al., 2013; O'Brien et al., 2013). This is a parameter for which field deployable sensors are available, and which has already been integrated into some RTWQM program designs (see Di Blasi et al., 2013), but has as yet received little practical attention in the GBRCA. Un-degraded fertiliser urea is similarly another 'inorganic' nitrogen form that can dominate dissolved inorganic nitrogen export losses at paddock scales if major rainfall or irrigation occurs soon after fertiliser application (Davis et al., 2016). Urea, as well as total nitrogen, total phosphorus and pesticides do not have currently available sensor technologies. RTWQM cannot be a standalone monitoring effort entirely substituting conventional water sampling approaches, but instead requires integration and support from more traditional methods, and is far from a 'silver bullet solution for comprehensive monitoring.

Sampling frequency

As opposed to end-of-catchment water quality monitoring at a single site, and at relatively large catchment scale, implementation of significant finer-scale, upstream monitoring networks with capacity to identify 'hotspots' do pose a range of methodological, logistical and budgetary challenges for program design. As basin size decreases, high-flow events typically become of shorter duration (i.e., "flashier"), and changes in discharge and pollutant concentrations also occur over shorter periods (Baker et al. 2004; Horowitz, 2013; Zarnetske et al. 2018). Small catchments also appear to exhibit high variability in concentration in relation to flow (Correll et al. 1999), possibly due to variations in extent and pattern of different land use and watershed retention features (Kaushal et al. 2014). Thus, sampling frequency also has to increase to generate acceptable flux estimates and/or concentration ranges to avoid missing the "hot moments" (McClain et al. 2003), episodic events that carry a disproportionate amount of catchment flux. This certainly includes the 'first flush' events documented earlier as common in many Russell-Mulgrave sub-catchments. Without high frequency sampling, episodic events can generate high levels (e.g., 100%) of imprecision and marked underestimation of seasonal or annual loading (Walling and Webb 1985).

These requirements for increased sampling frequency scenarios at smaller catchment scales do pose considerable challenges to automated, and particularly manual discrete sample collection-based monitoring program approaches. Increased discrete sampling frequency engenders greater field/laboratory costs, and eventually, sampling frequencies, either because of system size and/or requisite temporal resolution, are beyond the scope of any discrete sampling approach. With water quality sensor data progressively becoming relatively less expensive per data point as the sampling frequency of discrete samples increases (Table 1), there comes a point where despite initial instrumentation costs, sensor technologies become a more cost-effective option. Due to these considerable inherent limitations of traditional discrete sample collection techniques, many water monitoring programs have shifted towards continuous measurements using *in situ* sensors (O'Flynn et al., 2010; Outram et al. 2014). Continuous real time water quality monitoring is emerging as an attractive and effective water quality monitoring approach, and is being increasingly employed for monitoring of both surface and ground water across multiple spatial scales, and nested catchment monitoring designs (Outram et al., 2014; Pellerin et al., 2016).

These processes are exemplified in some Project 25 data (Figures 21 and 22, panel b), where the streamflow variations and associated nitrate-N concentration fluxes documented in RTWQM data at finer sub-catchment scales are often pronounced, with order-of-magnitude changes occurring in the space of hours. Capturing this data variability in a manual sample collection program would clearly not be pragmatic. The sample collection frequency required even employing an automated discrete water sample collection approach (to accurately quantify the observed variability) would also likely be impractical, as well as cost-prohibitive, particularly with a high number of sampling sites across multiple sub-catchments.

Discharge calculation

Because nitrate-N concentrations alone will not be a reliable indicator of nitrate-N export loads from a sub-catchment (i.e., kg Ha year^{-1}), efficient identification of hotspot catchments will also require the availability of reliable hydrometric data such as stream discharge. The quantification of stream discharge also, therefore, constitutes a major challenge for water quality monitoring programs.

Discharge measurements (traditionally quantified using current meters) are usually required to be made at least several times a year to maintain flow rating curves, which relate discharge to river stage (Wahl et al. 1995), essentially the approach used in Project 25. High data acquisition and maintenance costs are, however, associated with these traditional discharge measurement methods, which are also hazardous to people or equipment during flood measurements, with time-consuming site management requirements (e.g., improvement of cross-sections); and requiring considerable expert-technical knowledge (Davids et al., 2019). In recent decades, new techniques and technologies have played a larger role in streamflow measurement. Advanced electronic sensing equipment, based on acoustic Doppler velocimetry (ADV), have been used to measure one-, two-, and three-dimensional flow fields in natural waterways. Although discharge measurements can be made quickly with ADV, and can provide measurements of complicated flow patterns, contact with the flow is still required, and the equipment is relatively expensive to purchase and operate.

Digital cameras have increasing potential to provide new data streams for environmental science and real-time monitoring applications. Improvements in image quality, power consumption and image processing algorithms mean that it is now possible to utilise camera-based sensing, even to the point of Smartphone and app-based applications, in real-world scenarios such as streamflow discharge calculations (Bradley et al., 2002; Young et al. 2015; Carrel et al. 2020). Discharge estimates using video-based techniques compare well with traditional current meter discharge measurement, with an estimated standard error of ~±10%, and lower (Bradley et al. 2002, Young et al. 2015; Fehri et al. 2020).

Much of this technology to support automated, or real-time, discharge measurements is likely to become available in the very near future. The '*Discharge app*' (already available for Android devices), for example, uses the smartphone's built-in camera and accelerometer to optically measure open channels' water level and surface to derive an estimation of the discharge (Carrel et al., 2019). Such approaches do require some technical field preparation and setup (four markers positioned on both riverbanks, and a geometrical survey of the cross-section of the river encoded into the Discharge app) for usage. Early field testing of these approaches suggest that 'low to moderate discharge' values (<35 m^3 sec^{-1}), the use of the mobile phone application provides good quality data, with and absence of bias and high correlation with true discharges, although reliability suffered at extreme discharge events (Fehri et al. 2020). The capability to remotely quantify discharge events of this scale (<35 m^3 sec^{-1}) in real-time would, however, be likely very applicable to many sub-catchment monitoring programs, such as Project 25.

While edge-of-field/*in situ* data processing requirements still pose challenges, camera-based approaches clearly offer cost-effective capacity for real-time discharge calculations that would be difficult to achieve using methods requiring sensors in or close to the river, or human resourcing during the measurement period. The 1622WQTM app already integrates real-time nitrate-N load calculation at a small number of Project 25 sub-catchment sites (where streamflow discharge rating curves are already available). The capacity to similarly calculate nutrient yields through combination of real-time nitrate-N sensor concentration data with real-time streamflow discharge volumes, offers significant scope and economy to prospective water quality monitoring programs considering catchment nutrient hotspot identification.

4.0 RECOMMENDATIONS AND CONCLUSION

The essentially global disconnections between farmer-landholder perceptions and agricultural water quality impacts highlight that fundamental changes are required in communicating water quality science and information in a medium that is relevant and useful to farmer decision-making.

Project 25 utilised a different principle to traditional 'top-down' water quality monitoring, instead emphasizing a 'ground-up' approach where local canegrowers 'steer' program design and subsequent research and extension efforts in identified sub-catchment hotspots. While existing GBR water quality monitoring programs have tended to focus monitoring at spatial and temporal scales largely removed or irrelevant to farmer decision-making, Project 25 focuses on locally targeted water quality information delivery directly to relevant landholders. While there are clearly divergent over-arching aims for both monitoring program models, there is also clear scope for the two to become more integrated and coordinated programs, each informing the other. This desire for locally relevant information, and solutions was consistently and repeatedly articulated by agricultural stakeholders over the course of the program.

> *"We are often told that a lot of money has already been spent on farmers to improve water quality going to the Reef but there has been very little improvement. We agree – a lot of time and a lot of money has been wasted with some of the programs that the government has put forward… Don't just blame the farmers for this… rarely have the growers themselves had input into how to solve this issue – we haven't been asked about what local solutions are needed. I understand that this approach doesn't often suit the big policy makers in Brisbane and Canberra but one thing is for certain – that unless the strategies are practical and sensible for our region and are well understood by the growers… THEN THE PROGRAM WILL FAIL."*
>
> Canegrower, Babinda

There are well-documented justifications for focussing water quality monitoring and engagement specifically at agricultural producers within catchments. Accepting responsibilities, awareness of environmental damage, positive environmental stewardship attitudes and proneness to adopt agro-environmental and water quality-relevant action programmes are closely related to a sound perception of such problems, particularly at local scales (Vanslembrouck et al., 2002; He et al., 2008; Knowler and Bradshaw, 2007). The willingness of farmers to implement pollutant control practices appears directly related to how land managers perceive the seriousness of the pollution problem (or to pollutants 'they can see'). Control measures to combat highly visible soil erosion, for example, not surprisingly tend to gain greater traction and uptake, whereas communicating the rationale for control measures aimed at more 'invisible' forms of diffuse pollution from agriculture (such as excessive nitrogen or phosphorus losses) have constituted a long-standing challenge to NRM efforts and farmer extension (Blackstock et al., 2010; Osmond et al., 2012). As Project 25 illustrates, the recent confluence of a range of factors, such as new technologies (sensors, IoT, telemetry-connectivity) and greater information and communication technology (ICT) familiarity in farming demographics has opened up significant new opportunities to provide much more locally targeted and timely information on landuse-water quality relationships to key stakeholders.

More than 'just a water quality monitoring program'

The social research results emerging Project 25 clearly underlined the importance of investing in establishing collaborative trust frameworks between stakeholders, the maintenance of open research practice and data transparency, and the critical role of informal learning and training by all stakeholders in achieving impact-based research outcomes. These collaborative and participatory dialogues and relationships are not trivial, and take considerable time to cultivate and develop. The approximate 2-3 years it took for these relationships and trust frameworks to solidify is not atypical, but is also contingent on the intensity and frequency of interaction, agreement on discussion/conversation and personalities interacting (King et al., 2019; Campbell et al., 2015; McKee et al., 2015). And in the case of Project 25, was a "brownfield" rather than "greenfield" project, levering upon the legacy of relationships and local networks existing for some time before the Project itself was formally initiated. But the long-term value in establishing these collaborative relationships is expressed in participating grower sentiments expressed during the 2020 Senate Inquiry;

> *"The whole project is grower driven. A leading group of growers formed it and we control it. We segregated rainforest, caneland and urban land so that we could focus on where the hotspots were and get growers to accept scientific data. Within this project, we focused on five pillars. We get upset when people say it's just a water quality sampling program. It's much more than that. Of course it is sampling and analysis. That's the first thing. That goes from live logging to snap samples. JCU are involved. DAFF is involved.*
>
> *The second part of the program leads on to education. We take those results—what we can get—and educate the growers. But also we've got a collaboration with scientists as well. That's been one of the positives out of this. Where the scientists initially had a top-down approach, telling you what you were doing wrong, this is a bottom-up approach. So we go in it together. It's good to see that actually the scientists have learnt a lot as well along the way from the challenges".*
>
> *The third pillar is that, from that, we go to acceptance and understanding of the results. That's built in with the trust framework. The data is confidential and we educate the growers and everyone about that data. The fourth and most important thing we focus on going through is removing the blame game, because everyone wants to blame everyone else for what's happening. I think that's been a real success of the program. It just eliminates that from the system so that you take ownership of what your impact on the environment is. The fifth and final thing is leading practice change on the ground.*
>
> *So this project, like I say, initially was to validate the modelling. We have found some flaws in some results that were getting attributed to us. We have found those flaws, and I'm willing to talk about that later in my presentation."*

Project 25 Steering Committee Canegrower, Senate Inquiry Hansard transcript.

Awareness of the environmental consequences of fertiliser over-application has consistently emerged, at a global scale, as a consistent gap in farmer's knowledge of the impacts of farming operations on the environment. This suggests that the concept of "awareness of consequences" needs to be further developed for this issue (Floress et al., 2018). Project 25 specifically addresses these types of knowledge gaps within key stakeholder demographics. Demonstration of locally specific farm-scale impacts on the environment, loss of nutrients and capacity for active management may, however, provide powerful landholder motivations for practice change. Moreover, many farming environments are also currently characterized by considerable variability or uncertainty in what are locally appropriate water pollution control measures (Kleinman et al., 2015). In some cases what are prescribed 'best management practices' in one farming context can produce perverse environmental outcomes in others (Kleinman et al., 2015). The capacity for farmers to monitor, adaptively trial and develop their own innovative and locally specific farming practices would provide much of this empowerment and confidence in adopting meaningful practice change.

Simply providing local water quality data is also no guarantee of engendering significant practice change on the part of informed landholders. It is important to manage expectations about what fine-scale, real-time monitoring can truly achieve, particularly in isolation. The fact that provision of genetic data relating to an individual's specific disease-health risks often does little to provoke behavioural lifestyle changes in an individual (Holland et al., 2016) should temper expectations that simply providing local environmental data will automatically result in landholder practice change. The underlying drivers of farmer practice change across most agricultural sectors almost invariably involves a complex interplay between economic, social, risk management and environmental considerations (McGuire et al., 2013; Yang and Fang, 2015). Carefully developed collaborations between farmers, scientists and extension agencies are required to facilitate presentation of information that touches upon all of these decision-making levers.

Community members (and landholders) participating in environmental monitoring, nevertheless, commonly show increased scientific literacy and 'interactional expertise' to discuss with experts; greater awareness and interest in local and wider environmental issues; stronger social networks including engagement with government; and greater overall interest in conservation planning (Storey et al., 2016). With the existing trust frameworks in place, the current Project 25 template and governance in the Russell-Mulgrave, could easily be broadened to address other environmental issues (catchment remediation, carbon sequestration-trading etc.).

The transdisciplinary nature of Project 25

An important point to be emphasised in future potential extension or similar applications of the Project 25 model, is that establishing these collaborative research relationships and frameworks for behaviour change takes considerable time, but is additionally resource intensive and becomes very trans-disciplinary in nature (Figure 25). The increasing differentiation, specialization and fragmentation of science and technology into disciplines in recent decades has undoubtedly accompanied extraordinary advances both in the quantity and quality of knowledge produced. The increasingly specialized cultural, technological and/or organizational structures within scientific disciplines, often coupled with specifically tailored, (discipline-based) scientific questions, often results in science that struggles to address the grand challenges of environmental sustainability, particularly from a societal perspective (Szostak, 2007). The integration of new technologies (such as communicating sensor data to stakeholders), in particular, requires considerable input from a range of very different disciplines (expertise in water quality, sensor-telemetry, ICT, user experience etc.) as well as considerable stakeholder input (Figure 25). Translating this new quantum of data and information into a form accessible, coherent and understandable to target stakeholders such as farmers represents a significant challenge, and require substantial collaboration between water quality scientists, farmers, information systems experts, and extension staff.

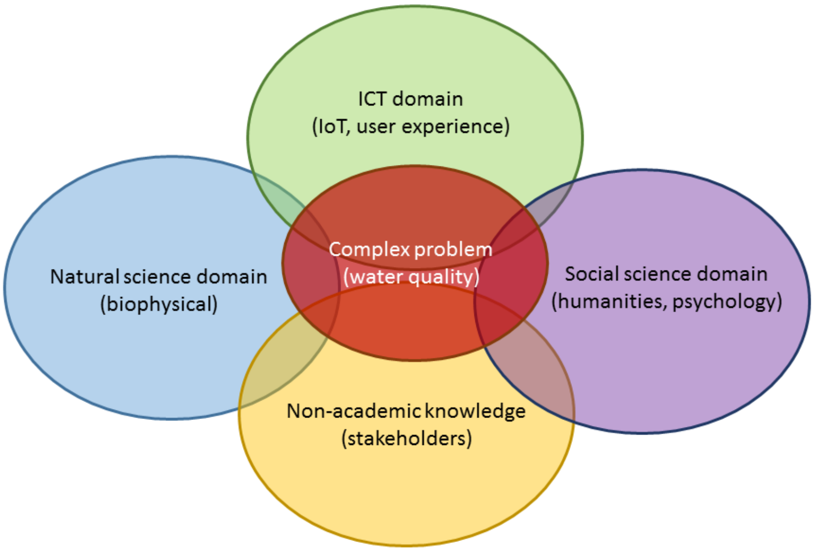

Figure 25: Transdisciplinary nature of Project 25 scientific approach to water quality improvement.

The integration of research from different disciplines in tackling integrated problem-oriented science (particularly collaborative research between natural sciences) is gaining increasing traction, as is recognition of the need for broader societal stakeholders to play a more active role in the definition of research foci and topics and in collaboration with science (Mauser et al., 2013; Polk, 2015). While the overall structure of Project 25 evolved somewhat organically through time, it did ultimately closely parallel some recently proposed frameworks for transdisciplinary integration to tackle similar sustainability challenges (Mauser et al., 2013; Figure 26). The process proposed by Mauser et al. (2013) for co-creation of knowledge — consists of three fundamental steps throughout which both researchers and relevant stakeholders are involved to varying degrees: co-design, co-production and co-dissemination. All of these elements emerged at some point of the Project 25 process, and could provide a useful guide for future research and policy efforts on tackling diffuse water quality pollution;

1. It starts with the **co-design** of the research agenda through sectoral integration between stakeholders and decision makers from the relevant societal sectors (in this case farmers) and science to develop a viable research issue to the point at which it can be handed over to the broader scientific community. The process of co-design starts with the joint framing of the sustainability challenges faced by stakeholders. Important issues to be identified are the scale, both spatial and temporal, of the required

research and the necessary depth of scientific integration. Identification of the stakeholders is also a key element to program design. Large, industry-leading and influential canegrowers were, for example, specifically recruited in Project 25 (Davis et al., 2020). Stakeholders play an important (and possibly dominant role in framing the scope of the scientific questions to be answered). During the co-design phase stakeholders and academic participants work in a coordinated, integrated way to best establish a common understanding of the research goals, to identify the relevant disciplines, participants and the scientific integration steps necessary to approach the topic, and to agree on the roles the different groups have in advancing towards the research goals.

2. The second step consists of the **co-production** of knowledge. Here, the transdisciplinary focus is on scientific integration (and researchers assume a more pronounced role in driving the process). During this phase integrated research is conducted as a continuous exchange among the participating scientists and with the stakeholders. Scientific integration also ensures that the necessary disciplinary research questions are specifically derived from the identified needs of the project and then researched by the respective discipline, and that the scientific quality is maintained in the research process. Finally, ongoing dialogue between stakeholders and scientists ensures the exchange and interaction of their respective knowledge and thereby ensures the societal relevance of the research to the relevant end-users.

3. The last step consists of the **dissemination** of the results among the different societal groups. This includes publication of the acquired knowledge in various forms of accessible language, translation of the results into comprehensible and usable information for the different stakeholders, and an open discussion on the valuation, applicability and relevance of the results among groups of conflicting interests. In the case of Project 25, this involved an active role for farming stakeholders to assume responsibility for advocacy and industry responses to scientific outcomes. This ultimately becomes an iterative process, where the open discussion of the results and the consequential actions taken by stakeholders towards reaching the goal of sustainability leads to new research questions, which will then jointly be framed, which initiates a new transdisciplinary research cycle.

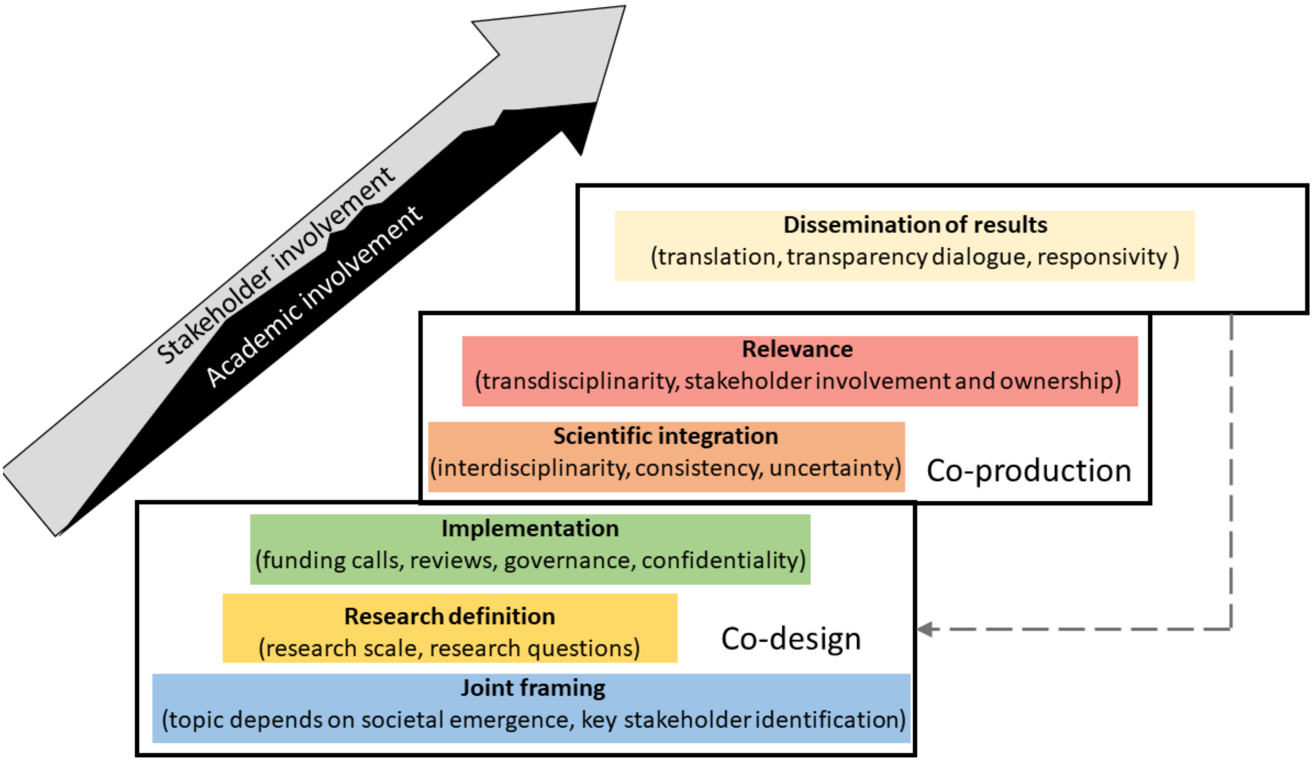

Figure 26: Proposed framework for interdisciplinary and transdisciplinary co-creation of knowledge in integrated research with stakeholders (modified from Mauser et al., 2013; Figure 3).

Conclusions

The grand challenges posed by sustainability issues such as diffuse water quality pollution demand the development of pragmatic approaches to the integration and conduct of transdisciplinary research. Recent experiences advise against policy reliance on single modes of control or management mechanisms (regulated versus voluntary compliance), and small sub-catchment scale monitoring approaches will almost certainly need to be part of, not only lager scale catchment monitoring, but must include a broader, coordinated policy landscape (see Worrall et al., 2009; Osmond et al., 2012). Yet, examples also exist of environmental improvements in the notoriously challenging regions and cultural contexts, where farmer-based groups, water management agencies and conservation organizations have improved environmental quality and redefined the role of agriculture in environmental management (Shoreman and Haenn, 2009). Understanding the motivations and appropriate mechanisms for better engaging catchment stakeholders in ownership of agri-environmental issues should provide a template for more meaningful and cost-effective GBR water quality management into the future.

As noted by the social researchers, without the dedication and enthusiasm of the farmer stakeholders themselves, the evaluation of social impacts and broader Project traction could have been very different. Knowledge production that focuses on more integrative and participatory approaches to harnessing scientific knowledge, particularly that engage non-scientific actors and stakeholders, are increasingly advocated for research and problem solving in 'real-life' (Polk, 2015). This more participatory-based form of knowledge production, where stakeholders outside of academic spheres are seen to hold not only legitimate, but also indispensable knowledge and expertise, played a large role in Project 25 research and development;

> *"Looking at my side and how successful our project has been, I think that's got to be the model going forward. It's actually on ground. It's education. It's giving confidence to growers. It's scientists and the growers working together for a common good. At the end, I don't care about the political games. I don't care about ideologies. I thought the common good was to look after the reef and our impact on the environment.*
>
> *Do we as growers have an impact on the environment? I'm not getting into the Barrier Reef. I'm not a scientist. I'm just looking at our streams. We've got monitors there. Yes, we do—the same as everyone sitting around this table, which everyone forgets. Everyone has an impact on the environment. So the whole idea is: how do we minimise it? We've got to have achievable and realistic targets. People have talked here of a figure of 30 per cent reduction leaving farms. It depends on the rain events et cetera. In the first flush you might get up to six or seven kilos of nitrogen. So to drop that three kilos at 30 per cent doesn't mean you just drop 30 per cent of fertiliser."*

Project 25 Steering Committee Canegrower, Senate Inquiry Hansard transcript.

The water quality monitoring data and results that emerged from Project 25 monitoring conducted in the Russell-Mulgrave catchment were, broadly, very similar to results collected across other GBRCA regions in recent decades. It is increasingly recognised that collaborative efforts between researchers and non-academic stakeholders promises to increase legitimacy, ownership and accountability of environmental sustainability challenges, as well as for the identification of future solutions. In what clearly remains and contentious social and policy landscape, the attitudinal and behavioural changes and sentiments expressed by participating Project 25 canegrowers illustrates that collaborative, participatory water quality remediation programs that establish trust can provide a strong foundation for achieving positive environmental outcomes.

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