2022 Scientific Consensus Statement

Question 4.6 What are the most effective management practices for reducing dissolved nutrient losses (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions? What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices?

Question 4.6.1 What is the potential of Enhanced-Efficiency-Fertilisers (EEFs) in reducing nitrogen runoff and what are the primary challenges in implementation?

Question 4.6.2 What are the implications of mill mud application in influencing nitrogen losses and what are the primary challenges for implementation?

Question 4.6.3 What are the primary factors that influence nutrient losses from irrigated areas and how can these be managed?

Peter Thorburn[1], Kirsten Verburg[1], Marina Farr[2], Tony Weber[3], Maria Vilas[4], Caleb Connolly[2], Rohan Eccles[3]

[1]CSIRO Agriculture and Food, [2]Department of Agriculture and Fisheries, [3]Alluvium, [4]Department of Environment, Science and Innovation

Citation

Thorburn P, Verburg K, Farr M, Weber T, Vilas M, Connolly C, Eccles R (2024) Question 4.6 What are the most effective management practices for reducing dissolved nutrient losses (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions? What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices? In Waterhouse J, Pineda M-C, Sambrook K (Eds) 2022 Scientific Consensus Statement on land-based impacts on Great Barrier Reef water quality and ecosystem condition. Commonwealth of Australia and Queensland Government.

The 2022 Scientific Consensus Statement was led and coordinated by C₂O Consulting coasts | climate | oceans.

The 2022 Scientific Consensus Statement is funded by the Australian Government's Reef Trust and Queensland Government's Queensland Reef Water Quality Program.

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Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

These explanatory notes were produced by the SCS Coordination Team and apply to all evidence syntheses in the 2022 SCS.

What is the Scientific Consensus Statement?

The Scientific Consensus Statement (SCS) on land use impacts on Great Barrier Reef (GBR) water quality and ecosystem condition brings together scientific evidence to understand how land-based activities can influence water quality in the GBR, and how these influences can be managed. The SCS is used as a key evidence-based document by policymakers when they are making decisions about managing GBR water quality. In particular, the SCS provides supporting information for the design, delivery and implementation of the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) which is a joint commitment of the Australian and Queensland governments. The Reef 2050 WQIP describes actions for improving the quality of the water that enters the GBR from the adjacent catchments. The SCS is updated periodically with the latest peer reviewed science.

C_2O Consulting was contracted by the Australian and Queensland governments to coordinate and deliver the 2022 SCS. The team at C_2O Consulting has many years of experience working on the water quality of the GBR and its catchment area and has been involved in the coordination and production of multiple iterations of the SCS since 2008.

The 2022 SCS addresses 30 priority questions that examine the influence of land-based runoff on the water quality of the GBR. The questions were developed in consultation with scientific experts, policy and management teams and other key stakeholders (e.g., representatives from agricultural, tourism, conservation, research and Traditional Owner groups). Authors were then appointed to each question via a formal Expression of Interest and a rigorous selection process. The 30 questions are organised into eight themes: values and threats, sediments and particulate nutrients, dissolved nutrients, pesticides, other pollutants, human dimensions, and future directions, that cover topics ranging from ecological processes, delivery and source, through to management options. Some questions are closely related, and as such readers are directed to Section 1.3 (Links to other questions) in this synthesis of evidence which identifies other 2022 SCS questions that might be of interest.

The geographic scope of interest is the GBR and its adjacent catchment area which contains 35 major river basins and six Natural Resource Management regions. The GBR ecosystems included in the scope of the reviews include coral reefs, seagrass meadows, pelagic, benthic and plankton communities, estuaries, mangroves, saltmarshes, freshwater wetlands and floodplain wetlands. In terms of marine extent, while the greatest areas of influence of land-based runoff are largely in the inshore and to a lesser extent, the midshelf areas of the GBR, the reviews have not been spatially constrained and scientific evidence from anywhere in the GBR is included where relevant for answering the question.

Method used to address the 2022 SCS Questions

Formal evidence review and synthesis methodologies are increasingly being used where science is needed to inform decision making, and have become a recognised international standard for accessing, appraising and synthesising scientific information. More specifically, ’evidence synthesis’ is the process of identifying, compiling and combining relevant knowledge from multiple sources so it is readily available for decision makers[1]. The world’s highest standard of evidence synthesis is a Systematic Review, which uses a highly prescriptive methodology to define the question and evidence needs, search for and appraise the quality of the evidence, and draw conclusions from the synthesis of this evidence.

In recent years there has been an emergence of evidence synthesis methods that involve some modifications of Systematic Reviews so that they can be conducted in a more timely and cost-effective

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[1] Pullin A, Frampton G, Jongman R, Kohl C, Livoreil B, Lux A, ... & Wittmer, H. (2016) Selecting appropriate methods of knowledge synthesis to inform biodiversity policy. *Biodiversity and Conservation*, 25: 1285-1300. https://doi.org/10.1007/s10531-016-1131-9

manner. This suite of evidence synthesis products are referred to as **'Rapid Reviews'**[2]. These methods typically involve a reduced number of steps such as constraining the search effort, adjusting the extent of the quality assessment, and/or modifying the detail for data extraction, while still applying methods to minimise author bias in the searches, evidence appraisal and synthesis methods.

To accommodate the needs of GBR water quality policy and management, tailormade methods based on Rapid Review approaches were developed for the 2022 SCS by an independent expert in evidence-based syntheses for decision-making. The methods were initially reviewed by a small expert group with experience in GBR water quality science, then externally peer reviewed by three independent evidence synthesis experts.

Two methods were developed for the 2022 SCS:

- The **SCS Evidence Review** was used for questions that policy and management indicated were high priority and needed the highest confidence in the conclusions drawn from the evidence. The method includes an assessment of the reliability of all individual evidence items as an additional quality assurance step.
- The **SCS Evidence Summary** was used for all other questions, and while still providing a high level of confidence in the conclusions drawn, the method involves a less comprehensive quality assessment of individual evidence items.

Authors were asked to follow the methods, complete a standard template (this 'Synthesis of Evidence'), and extract data from literature in a standardised way to maximise transparency and ensure that a consistent approach was applied to all questions. Authors were provided with a Methods document, *'2022 Scientific Consensus Statement: Methods for the synthesis of evidence'*[3], containing detailed guidance and requirements for every step of the synthesis process. This was complemented by support from the SCS Coordination Team (led by C_2O Consulting) and the evidence synthesis expert to provide guidance throughout the drafting process including provision of step-by-step online training sessions for Authors, regular meetings to coordinate Authors within the Themes, and fortnightly or monthly question and answer sessions to clarify methods, discuss and address common issues.

The major steps of the Method are described below to assist readers in understanding the process used, structure and outputs of the synthesis of evidence:

1. **Describe the final interpretation of the question.** A description of the interpretation of the scope and intent of the question, including consultation with policy and management representatives where necessary, to ensure alignment with policy intentions. The description is supported by a conceptual diagram representing the major relationships relevant to the question, and definitions.
2. **Develop a search strategy**. The Method recommended that Authors used a S/PICO framework (Subject/Population, Exposure/Intervention, Comparator, Outcome), which could be used to break down the different elements of the question and helps to define and refine the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods[4].
3. **Define the criteria for the eligibility of evidence for the synthesis and conduct searches.** Authors were asked to establish **inclusion and exclusion criteria to define the eligibility of evidence** prior to starting the literature search. The Method recommended conducting a **systematic literature search** in at least **two online academic databases**. Searches were typically restricted to 1990 onwards (unless specified otherwise) following a review of the evidence for the previous (2017) SCS which indicated that this would encompass the majority of the evidence

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[2] Collins A, Coughlin D, Miller J, & Kirk S (2015) The production of quick scoping reviews and rapid evidence assessments: A how to guide. UK Government. https://www.gov.uk/government/publications/the-production-of-quick-scoping-reviews-and-rapid-evidence-assessments

[3] Richards R, Pineda MC, Sambrook K, Waterhouse J (2023) 2022 Scientific Consensus Statement: Methods for the synthesis of evidence. C_2O Consulting, Townsville, pp. 59.

[4] https://libguides.jcu.edu.au/systematic-review/define

base, and due to available resources. In addition, the geographic **scope of the search for evidence** depended on the nature of the question. For some questions, it was more appropriate only to focus on studies derived from the GBR region (e.g., the GBR context was essential to answer the question); for other questions, it was important to search for studies outside of the GBR (e.g., the question related to a research theme where there was little information available from the GBR). Authors were asked to provide a rationale for that decision in the synthesis. Results from the literature searches were screened against **inclusion and exclusion** criteria at the title and abstract review stage (**initial screening**). Literature that passed this initial screening was then read in full to determine the eligibility for use in the synthesis of evidence (**second screening**). Importantly, all literature had to be **peer reviewed and publicly available.** As well as journal articles, this meant that grey literature (e.g., technical reports) that had been externally peer reviewed (e.g., outside of organisation) and was publicly available, could be assessed as part of the synthesis of evidence.

4. **Extract data and information from the literature**. To compile the data and information that were used to address the question, **Authors were asked to complete a standard data extraction and appraisal spreadsheet**. Authors were assisted in tailoring this spreadsheet to meet the needs of their specific question.
5. **Undertake systematic appraisal of the evidence base**. Appraisal of the evidence is an important aspect of the synthesis of evidence as it provides the reader and/or decision-makers with valuable insights about the underlying evidence base. Each evidence item was assessed for its spatial, temporal and overall relevance to the question being addressed, and allocated a relative score. The body of evidence was then evaluated for overall relevance, the size of the evidence base (i.e., is it a well-researched topic or not), the diversity of studies (e.g., does it contain a mix of experimental, observational, reviews and modelling studies), and consistency of the findings (e.g., is there agreement or debate within the scientific literature). Collectively, these assessments were used to obtain an overall measure of the level of confidence of the evidence base, specifically using the overall relevance and consistency ratings. For example, a high confidence rating was allocated where there was high overall relevance and high consistency in the findings across a range of study types (e.g., modelling, observational and experimental). Questions using the **SCS Evidence Review Method** had an **additional quality assurance step**, through the assessment of reliability of all individual studies. This allowed Authors to identify where potential biases in the study design or the process used to draw conclusions might exist and offer insight into how reliable the scientific findings are for answering the priority SCS questions. This assessment considered the reliability of the study itself and enabled authors to place more or less emphasis on selected studies.
6. **Undertake a synthesis of the evidence and complete the evidence synthesis template** to address the question. Based on the previous steps, a narrative synthesis approach was used by authors to derive and summarise findings from the evidence.

Guidance for using the synthesis of evidence

Each synthesis of evidence contains three different levels of detail to present the process used and the findings of the evidence:

1. **Executive Summary**: This section brings together the evidence and findings reported in the main body of the document to provide a high-level overview of the question.
2. **Synthesis of Evidence:** This section contains the detailed identification, extraction and examination of evidence used to address the question.
    - ***Background***: Provides the context about why this question is important and explains how the Lead Author interpreted the question.
    - ***Method:*** Outlines the search terms used by Authors to find relevant literature (evidence items), which databases were used, and the inclusion and exclusion criteria.
    - ***Search Results:*** Contains details about the number of evidence items identified, sources, screening and the final number of evidence items used in the synthesis of evidence.

- ***Key Findings:*** The **main body of the synthesis**. It includes a summary of the study characteristics (e.g., how many, when, where, how), a deep dive into the body of evidence covering key findings, trends or patterns, consistency of findings among studies, uncertainties and limitations of the evidence, significance of the findings to policy, practice and research, knowledge gaps, Indigenous engagement, conclusions and the evidence appraisal.

3. **Evidence Statement:** Provides a succinct, high-level overview of the main findings for the question with supporting points. The Evidence Statement for each Question was provided as input to the 2022 Scientific Consensus Statement Summary and Conclusions.

While the Executive Summary and Evidence Statement provide a high-level overview of the question, it is **critical that any policy or management decisions are based on consideration of the full synthesis of evidence.** The GBR and its catchment area is large, with many different land uses, climates and habitats which result in considerable heterogeneity across its extent. Regional differences can be significant, and from a management perspective will therefore often need to be treated as separate entities to make the most effective decisions to support and protect GBR ecosystems. Evidence from this spatial variability is captured in the reviews as much as possible to enable this level of management decision to occur. Areas where there is high agreement or disagreement of findings in the body of evidence are also highlighted by authors in describing the consistency of the evidence. In many cases authors also offer an explanation for this consistency.

Peer Review and Quality Assurance

Each synthesis of evidence was peer reviewed, following a similar process to indexed scientific journals. An Editorial Board, endorsed by the Australian Chief Scientist, managed the process. The Australian Chief Scientist also provided oversight and assurance about the design of the peer review process. The Editorial Board consisted of an Editor-in-Chief and six Editors with editorial expertise in indexed scientific journals. Each question had a Lead and Second Editor. Reviewers were approached based on skills and knowledge relevant to each question and appointed following a strict conflict of interest process. Each question had a minimum of two reviewers, one with GBR-relevant expertise, and a second ‘external’ reviewer (i.e., international or from elsewhere in Australia). Reviewers completed a peer review template which included a series of standard questions about the quality, rigour and content of the synthesis, and provided a recommendation (i.e., accept, minor revisions, major revisions). Authors were required to respond to all comments made by reviewers and Editors, revise the synthesis and provide evidence of changes. The Lead and Second Editors had the authority to endorse the synthesis following peer review or request further review/iterations.

Contents

Acknowledgements

We are grateful for Dr Phil Bloesch (DES) for his advice on phosphorus cycling in soils, and Mark Poggio (DAF) for his guidance on the economics review for this question. The review benefited from references/evidence sources submitted by Bronwyn Bosomworth (Qld DES), Peter Noonan (Qld DES), and Elisa Westmore (CANEGROWERS). We thank Jody Biggs (CSIRO) for assistance with processing the final reference list and database. Thanks also to Rob Richards (Evidentiary), Jane Waterhouse (C_2O Consulting) and Mari-Carmen Pineda (C_2O Consulting) for guidance in preparing this document and comments on earlier outlines and drafts of this review.

Executive Summary

Questions

Primary Question 4.6 What are the most effective management practices for reducing dissolved nutrient losses (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions?

- **What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions?**
- **What are the production outcomes of these practices?**

Secondary Question 4.6.1 What is the potential of Enhanced-Efficiency-Fertilisers (EEFs) in reducing nitrogen runoff and what are the primary challenges in implementation?

Secondary Question 4.6.2 What are the implications of mill mud application in influencing nitrogen losses and what are the primary challenges for implementation?

Secondary Question 4.6.3 What are the primary factors that influence nutrient losses from irrigated areas and how can these be managed?

Background

This review evaluated the evidence on management practices for reducing dissolved nutrient losses from the Great Barrier Reef (GBR) catchments, focusing on dissolved inorganic nitrogen (DIN) and phosphorus (DIP), also referred to as dissolved reactive P (DRP). Sugarcane, horticulture, banana, irrigated and dryland cropping, and non-agricultural land uses including urban areas were considered on account of these contributing most of the dissolved nitrogen and phosphorus. The focus of the review was on management actions that affect processes generating dissolved nutrients that are subsequently discharged from fields. In agricultural systems, these are:

- Fertiliser amount.
- Fertiliser timing.
- Inorganic fertiliser form and enhanced efficiency fertilisers (EEFs).
- Mill mud and other organic amendments.
- Crop residue management.
- Fertiliser placement.
- Use of fallow legume crops.
- Ground cover.
- Irrigation management (timing, amount, system).

Discharge via both runoff and leaching below the root-zone were considered, as both are pathways by which dissolved nutrients can potentially reach GBR ecosystems. Off-site treatments were excluded for agricultural land uses, including constructed wetlands, bioreactors and irrigation water recycle ponds as these are covered in Question 4.7 (Waltham et al., this Scientific Consensus Statement (SCS)).

For non-agricultural land uses, both structural and non-structural treatment measures were considered (including management and compliance regimes, wetlands, biofilters, swales).

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[5]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has

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[5] Cook CN, Nichols SJ, Webb JA, Fuller RA, Richards RM (2017) Simplifying the selection of evidence synthesis methods to inform environmental decisions: A guide for decision makers and scientists. *Biological Conservation* 213: 135-145. https://doi.org/10.1016/j.biocon.2017.07.004

well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Review method was used.

- Formal search locations included Web of Science and Scopus and informal searches included the Queensland Government database, conference proceedings and author literature collections.
- Four separate searches and appraisals were performed: two for the biophysical evidence on management actions reducing loss of nitrogen (N) or phosphorus (P) in cropping land uses, one for the related economic evidence, and one for the non-agricultural land use.
- The initial keyword and manual searches obtained 1,705 results across the search locations and the four separate searches (including manual additions from, e.g., submissions made to the SCS). Duplicates were removed within each topic area and following initial screening by title and abstract, 670 potentially relevant sources were identified across the four topic areas. After a second screening by scanning the full text for evidence relating to the questions and specific management actions as well as manually adding submitted references and other relevant sources, there were a total of 108 sources with relevant evidence for cropping N loss management, 8 sources for cropping P loss management, 56 sources for cropping-related economics and 119 sources for non-agricultural land uses. Different authors carried out searches for each topic, and therefore some evidence items were used and counted more than once.
- The main source of evidence relating to agricultural land uses came from studies undertaken in the GBR. Evidence from other parts of Australia and other countries often has limited relevance to the GBR because of differences in environment, management and cost structures. However, a small number of studies that were conducted in northern Australia but outside GBR catchments were considered. These were mainly on irrigated cotton and were judged to have high relevance to the GBR on important issues for which there was no equivalent information from studies in the GBR. A number of review papers found in the searches were also included which distilled relevant information from outside the search zone.
- For non-agricultural land uses, relevant studies from across Australia were considered because of the limited number of studies conducted in the GBR related to urban nutrient management.

Method limitations and caveats to using this Evidence Review

For this Evidence Review, the following caveats or limitations should be noted when applying the findings for policy or management purposes:

- Only studies written in English were included.
- Only studies undertaken within the GBR and Queensland were included (with a few exceptions, as noted).
- Only published and peer reviewed sources were considered.
- Almost all studies were post 1990.

Key Findings

Summary of evidence to 2022

Agricultural land uses

Sugarcane is the most widely grown crop in GBR catchments and was the focus of most research identified in this review. Most of that research was relevant to losses of DIN. There was little peer reviewed information found on the effectiveness of management practices for reducing DIN in crops other than sugarcane (with some minor exceptions noted below) or dissolved P in any crops.

In sugarcane production systems, reducing N fertiliser application rates has been shown in both experiments and modelling to be a consistent means of reducing DIN losses via both runoff and leaching, the two pathways by which dissolved nutrients can be transported to GBR ecosystems. This result has also been obtained for cotton and dairy pastures, albeit from a small number of studies.

N applications to sugarcane above industry recommended best practice (SIX EASY STEPS™ shortened to 6ES) result in avoidable N loss, unless crop growth, yields, and hence crop N uptake can be increased (assessing the effectiveness of practices to increase crop uptake of N was beyond the scope of this review). N applications above 6ES recommended rates also increase the cost of production and generally reduce economic returns. However, reducing fertiliser N rates below recommended rates may reduce yields and hence profitability at both the farm and sugarcane mill scales. Further, changing fertiliser rates can involve additional capital expenditure on machinery and increase other business expenses (e.g., labour) which can overshadow cost savings from lowering rates.

A more fundamental problem with trying to implement lower N rates to reduce DIN losses is that the impacts of lower N applications on yields are inconsistent – sometimes there is no yield reduction, other times it is significant. Recent research has clearly shown that this inconsistency is caused by year-to-year and site-to-site variability in climate, soil types and seasonal conditions, and the complex interactions between these factors. There are also other complicating factors. One is that sugarcane crops can start growing and subsequently get fertilised over a wide range of time periods[6], and the time at which crops start growing affects the "optimum" N fertiliser rate (i.e., the rate giving near maximum profitability) of that crop as well as DIN losses. The other factor is that, because the forthcoming seasonal climate cannot be accurately predicted, impacts of lower N applications on yields cannot be predicted. The complex interactions between climate, soils, crop start times, etc., together with the unpredictable seasonal climate effect means that it is unlikely that industry-wide N fertiliser application recommendations will be the same as the optimum N application rate for a particular crop. It also means that experiments, which are normally conducted at a limited number of sites and over a small number of years, may produce contrasting (or conflicting) results.

Despite this complexity, one conclusion that can be drawn from the recent research is that the magnitude of N losses will generally be greater from crops that start growing late in the year (i.e., at the beginning of summer and the wet season). Thus, N management practices to reduce N loss (such as that described below) will likely be more effective for the crops starting later in the year.

Applying N through EEF has the potential to reduce N losses because these fertilisers can maintain N in the soils for longer times and in a less mobile form than with application of conventional (urea-based) N fertiliser, potentially allowing crops to take up N for longer. This uptake may reduce the optimum N rates for EEF, which is attractive to farmers as EEF is more expensive than urea-N fertiliser and the cost savings from applying less fertiliser offset the costs of EEF. However, the benefits of EEF are highly variable across sites and years. The variable benefits can be explained by the three prerequisites needed for EEF to be effective: 1) the length of time that N is maintained within the soil must be close to that over which crops are taking up N; 2) that there must be rainfall events while the N is in the less mobile form that would otherwise cause that N to be lost from the soil; and 3) crop growth must be able to respond to additional N in the soil. Crops will not respond to additional N if, for example, they have already taken up all the N they need, or their growth is constrained by some other factor (e.g., waterlogging).

The third prerequisite is infrequently met meaning that EEF more commonly reduce N losses than significantly reduce the optimum N rates (i.e., result in the same yield at lower application of EEF compared with conventional fertiliser). The application of EEF at similar rates to urea-N fertiliser reduces profitability and is a barrier to adoption. Moreover, the requirement for these prerequisites to be met for EEF to be effective, plus the climate- and soil-driven complexity in the relationship in N application rates and yields described above, means that it is hard to obtain significant benefits of EEF compared to urea-N in single site experiments and/or on-farm demonstrations: clear benefits are often only seen when data, from either experimental or modelling studies, are aggregated across sites and seasons. The difficulty in being able to detect a significant benefit of EEF at a particular site means that a simple industry-wide recommendation for EEF use (e.g., apply EEF at 80% of recommended rate of urea-N) will

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[6] Sugarcane is a perennial crop that is harvested and allowed to regrow. In Australia, the harvest "season" is generally between June and December. Likewise, the crop can be planted over a wide range of times during the year. Thus crops can start growing and subsequently get fertilised over a wide range of times.

likely not be effective under all conditions and growers may not see the benefits on their farm. However, there are some general conclusions arising from the studies on EEF. The benefits are likely greatest for mid- to late-season crops, in the wetter regions of the Wet Tropics, and in wetter seasons. Productivity benefits are more likely on permeable soils, where yield potential is less impacted by the conditions that drive N loss.

There has been less research on the effectiveness of other management practices on reducing dissolved nutrient losses, and so fewer general conclusions can be drawn. For sugarcane, there is little information on the impact of mill mud (a byproduct of sugarcane milling) applications on discharges of DIN and dissolved P, or productivity and profitability. Mill mud contains substantial amounts of N and P suggesting that fertiliser N and P applications could be reduced after mill mud applications, which in turn would reduce losses of dissolved nutrients. However, the one empirical study undertaken showed that mill mud applications did not increase DIN losses in runoff (although leaching losses were not measured) but did increase dissolved P losses. Therefore, the general water quality implications of mill mud applications are currently not known. There is also limited evidence about the effect of mill mud application on farm productivity or profitability, although one study showed increased cane yields (but not sugar yields) following mill mud application in the fallow prior to planting sugarcane.

Likewise, there is little information on the effect of improved irrigation practices on discharges of DIN and dissolved P, or on farm productivity. Well-designed and managed automated furrow irrigation systems on sugarcane farms can be profitable, although the water quality outcomes of these systems are not clear. Limited evidence suggests that converting to a fully automated irrigation system on banana farms may provide economic benefits. Most information on the potential water quality benefits of improved irrigation comes from mechanistic modelling studies. Very high irrigation efficiency resulting from low irrigation application rates is likely to reduce DIN discharges from sugarcane crops, but there is a risk that productivity is also reduced. However, most of these studies do not provide enough detail on the methods or results to draw reliable conclusions about the water quality **and** economic outcomes.

While the secondary questions for this question of the SCS focused on EEF, mill mud and irrigation, there are other practices that can affect losses of dissolved nutrients from cropping systems, namely crop residue management, improved farming systems (growing fallow crops, reduced tillage, etc.) and burying fertiliser. Generally, conclusions cannot be drawn about the effectiveness of these practices with confidence because of the lack of or, in some cases conflicting results within the available literature. For example, legumes grown in the fallow between sugarcane crops (one aspect of improved sugarcane farming systems) can contain high amounts of N, and N fertiliser applications to subsequent crops need to be reduced to counteract the effect of this extra N on DIN losses. Modelling studies suggest yields will be maintained with a 40-50% reduction in fertiliser N. However, empirical information on the amount of N in fallow legumes and the effect on the N fertiliser management and DIN losses in subsequent sugarcane crops is lacking. There are economic as well as water quality implications of moving from bare to legume fallows as the farmers may need to make capital expenditures to enable the farming of legumes. This situation mainly occurs on small properties. Limited evidence shows burying fertiliser reduced discharges of dissolved P; however, the results for DIN discharges are mixed. Also, there is no literature for crops other than sugarcane on the effectiveness of these practices for reducing discharges of dissolved nutrients, nor on the economic outcomes.

Urban/non-agricultural land uses

Compared to agricultural land uses, there are fewer studies on urban/non-agricultural land uses. From these studies it is obvious that structural measures that include vegetation/biological components, such as wetlands, biofilters, algal ponds and existing riparian zones have considerable potential for removal of diffuse dissolve nutrients in runoff. They may also be important for management of wastewaters. Biofilters appear to be the most cost-effective treatment systems in this case, but this is based on limited data and modelling studies.

Improvements in technologies for wastewater management show that systems such as membrane filtration and chemical addition are also likely to perform well.

Non-structural controls for non-agricultural nutrient management (e.g., non-engineered controls such as policy, planning, regulation, compliance, education) appear to work best when implemented as part of an integrated approach. Recycling and reuse of wastewater shows considerable potential, though there are issues with the management of nutrients where that reuse water is applied.

Recent findings 2016-2022

There has been a considerable increase in relevant evidence available for the primary and secondary questions in the period 2016-2022. The main areas of research have been on the potential water quality and economic benefits of applying N as EEF, and the processes that cause those benefits (or lack thereof). There has also been a substantial increase in the understanding of the variability on the relationship between N fertiliser applications and sugarcane yields, the drivers of the uncertainty of this relationship, and the potential water quality benefits that could come from accurate seasonal climate forecasting. These insights also apply to management of EEF and provide a richer understanding of some of the problems associated with focusing on the amount (e.g., application rates) or type (EEF versus conventional) of fertiliser as a way to reduce DIN losses. Evidence for benefits from other management practices (e.g., mill mud and irrigation) and those for other crops is still developing.

In the non-agricultural land uses, there is a trend in the literature towards non-structural approaches to reduce discharges of dissolved nutrients such as policy, planning, regulation and compliance; however, the majority of the literature still focuses on structural approaches in both point and diffuse source nutrient management. In this respect, wastewater management has seen the further development of more technical approaches, often using biological processes incorporating reverse osmosis and/or membrane filtration. For stormwater runoff, vegetated treatment systems dominate the structural controls and still show much promise, though the amount of literature in very recent years, or specifically related to tropical and subtropical climates is very limited.

Significance for policy, practice, and research

As noted above, the water quality benefits and/or productivity and profitability implications of some of the management practices, notably reduction in N rate and use of EEF in sugarcane crops, are variable. Much of this variability comes from the important effect of climate on soil processes and the growth of crops. This variability plays out in practice in a number or ways. One is that the “optimum” amount of N fertiliser for a field varies from year-to-year, which means the production impact of reducing N applications is uncertain. Another implication is that the effectiveness of EEF is variable and an industry-wide recommendation to use EEF at (say) 80% of the recommended rate for urea-N may not result in universal profitability benefits, although water quality benefits are more likely. This uncertainty is a barrier to adoption of reduced N rates and use of EEF. This uncertainty also means that simple, general recommendations will not (and cannot) capture this complexity. A better understanding and representation of this variability would likely provide a basis for more accurate, location and soil specific advice delivered through decisions support systems.

However, given the role of climate in driving this variability, there is (and likely always will be) some degree of unpredictability in the benefits of some management practices. Rather than ignoring this unpredictability, it could be acknowledged, and effort could be spent on developing mechanisms to support growers’ decision-making in the face of this uncertainty. This support could be in the form of tools to characterise and communicate this variability to farmers so they can make more informed management decisions. The support could also be in the form of market-based or financial instruments that address this uncertainty either directly (e.g., insurance) or indirectly (e.g., eco-markets). Examples of these tools and instruments currently exist[7], although describing them is beyond the scope of this review. However, they have attracted considerable interest[8] and monitoring their impact on water

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[7] https://affinitytechnology.willistowerswatson.com/sales/wtwcropinsurance/. https://eco-markets.org.au/reef-credits/.

[8] An example of the interest is: https://www.qld.gov.au/environment/coasts-waterways/reef/reef-credit-scheme.

quality and considering ways in which that might be enhanced will be valuable. (refer to Questions 7.1, Coggan et al., and 7.2, Murray-Prior et al., this SCS for further exploration of this topic).

There are a number of other notable implications for policy, management and/or practice:

- The small amount of information currently available on the trade-offs between water quality benefits and productivity disbenefits of improved irrigation inhibit drawing policy, management and practice conclusions.
- There is little information on management practices affecting loss of dissolved P from cropped lands. However, reducing P fertiliser applications to crops is likely to reduce dissolved P losses.
- N and P fertiliser application rates can potentially be reduced following the application of mill mud to account for the nutrients in mill mud. However, the water quality and economic benefits of reduced fertiliser applications are uncertain. A limitation to the improved management of mill mud is the lack of methods for determining the nutrient loading of the applied mill mud, due largely to variations in nutrient concentrations in mill mud, and the subsequent bioavailability of nutrients.
- There is uncertainty about the water quality benefits of subsurface application of N fertiliser in the few studies published on this topic, with only one (of four) study showing clear evidence of reduced DIN discharges in runoff. One aspect generally not considered is that some N fertiliser will be lost to the atmosphere from ammonia volatilisation following surface application of most conventional forms of N fertiliser. Thus, there will be a greater **net** amount of N entering the soil when N fertiliser is subsurface applied. This factor might account for the variable water quality benefit. There are also differences in methods used in different studies that could add to the uncertainty.
- There is substantial heterogeneity in the cost-effectiveness of improving water quality through improved agricultural management practices, caused by the differences in the practices that needed to be changed to improve water quality, the ease with which these practices could be adopted, and farm size. Better recognition of these factors will improve understanding of the cost-effectiveness of achieving improved water quality.
- Vegetated treatment systems in non-agricultural areas are essential for reducing dissolved nutrient losses for diffuse sources. Conventional nutrient treatment technologies in wastewater management are quite effective, but reuse approaches may provide benefits. Animal processing wastewater management appears to still be somewhat immature compared to domestic wastewater management though similar technologies do show some promise.

Key uncertainties and/or limitations

Agricultural systems

Water quality

One of the key limitations for this question was the small number of studies published in the peer reviewed literature that clearly addressed losses of dissolved nutrients. This was particularly true for EEF, irrigation, mill mud and dissolved P. Likewise, there were few studies on cropping systems other than sugarcane production. For example, the water quality effects of different fertiliser application methods in banana crops are still poorly understood. Quite a few studies quantified the effect of land use (e.g., crop versus forest) rather than crop management and thus were not relevant to this question.

The design of some studies was also a limitation. In some cases, multiple factors were varied between treatments making it impossible to confidently identify the relative importance of each factor in giving the result. Another example was studies in which conclusions were made from measurements of DIN concentrations in soil or runoff. The issue is that the water quality implications of these results are unclear because of the difficulties (or impossibility) of simply relating DIN **concentrations** to DIN **loads** (i.e., kg DIN ha^{-1}) discharged, with the latter being the variable of interest. There were also some studies that made relevant measurements at only a few times during the life of a crop. It is difficult to confidently extrapolate these results to the whole crop because the effect of the treatment (e.g., burying N fertiliser) may vary through time.

Because of the variability in climate in GBR catchments, both in space and time, and the variability in soil types both within and between regions, it is difficult to extrapolate results from experiments to other soil types, the whole district/region and/or other years. In the face of this situation, mechanistic modelling of crop-soil-management-climate interactions has been increasingly used to provide broad scale information. These studies have provided information on both water quality and productivity for sugarcane production systems, and thus facilitated analyses of relative profitability and cost effectiveness of management practices. Mechanistic modelling has not been widely applied in other cropping systems in the GBR, which has limited the insights into the effectiveness of management practices in these systems. While these models have been well developed and extensively validated for sugarcane production, their limited application is due, in some cases, to models either not being well developed or tested. Wider application of mechanistic models would help in identifying management practices that are both effective in improving water quality and cost effective.

Economics

While reducing N fertiliser applications to sugarcane crops is the clearest path to reducing DIN discharges from these lands, the effects of “moderate” (e.g., 20%) reductions of N from historical or recommended rates on productivity and thus economics are uncertain, ranging from non-existent to statistically significant reductions. While more is known about the cause of that variability and uncertainty compared to 2017, how to predict or manage it is still unknown. The uncertainty about the economic outcomes of moderate reductions in N applications limits our knowledge about the cost effectiveness of this DIN reduction strategy. Further, the design of some studies was also a limitation as described in the previous sub-section.

The lack of information on effectiveness of practices for reducing discharges of DIN in crops other than sugarcane and dissolved P for all crops also limits our knowledge about the cost effectiveness of managing these pollutants.

Most modelled economic information on the adoption of practice change was obtained for “representative” farms that have characteristics typical of a region, and much of this information came from modelling. Studies also target major soil types in a region. Farm layout, farm size, rainfall patterns, grower experience, specific soil types, financial situation and farming systems can all influence water quality impacts and farm operating and investment costs, which would in turn impact best management practice adoption and farm profitability. There is also a need to consider specific transaction costs and risk associated with each practice change at the farm scale, although there are few studies on this topic.

Studies of cost and effectiveness are often undertaken for different purposes, and over different timescales within the regions/catchments and audiences. Results are therefore not always directly comparable and do not accurately account for some of the cross sector and regional heterogeneity in abatement costs. Studies should be undertaken for common characteristics that influence costs, production and profitability including property size, soil fertility, land condition, and distance to processing plant or market. Transaction costs, time to adopt practices, program and administration cost, and N export location should be captured.

Many of the past economic studies have obtained information on practices that were assumed, rather than comprehensively demonstrated, to have water quality benefits. The **assumption** of water quality benefits in these studies should not be interpreted as **evidence** of water quality benefits.

Non-agricultural systems

The primary limitations identified in this review for non-agricultural systems are associated with the existence of many experimental and modelling studies, but limited field measurements or on-ground assessments for non-structural controls in particular. Loss pathways following treatment require further quantification, including the flow-on impacts of nutrient losses from reuse of wastewater and potential leaching of nutrients from some treatments. Information on costs and quantified cost effectiveness is also very limited, making comparison between management options challenging.

Evidence appraisal

Overall, the relevance and consistency, and hence the confidence, of the body of evidence were rated as Moderate. However, there was a wide range in the relevance and confidence ratings by topic area (N, P, economics aspects of agricultural land uses, and urban/non-agricultural land uses) and by land use and management practice within them, largely relating to the quantity of studies for these topics (more studies typically increasing the relevance and also typically bringing in more diversity). Diversity, in particular the combination of modelling and experimental results from larger studies occurring over multiple sites proved very valuable in increasing confidence in the findings for some of the management practices in sugarcane (e.g., N rate and use of EEF).

The overall confidence in relation to the secondary question on EEF comes out as High to Moderate. The scores for spatial and temporal relevance keep the formal result as Moderate, but this is due to the larger number of experimental studies and ignores the corroboration provided by experimental and modelling results aligning well. The confidence in the key conclusions was judged to be high. That said, confidence in precise predictions of benefits for a given site and season is still relatively low on account of climate-driven variability, discussed elsewhere in this review.

The confidence that improving irrigation efficiency improves water quality outcomes for DIN losses from sugarcane is Low because the vast majority of published studies do not provide enough detail of the methods, validation or results to draw reliable conclusions about the water quality. Additionally, the confidence that practices that may give water quality benefits can also maintain or improve agronomic and economic outcomes is Low because of the lack of detail on water quality in studies of economic indicators (or parameters relevant to economics).

The confidence in the outcomes of managing mill mud is Low because of the small number of relevant studies. The confidence of the economic outcomes of mill mud management is Low due to very limited research in this area and inconclusive results.

1. Background

The health of Great Barrier Reef (GBR) ecosystems is affected by pollutants that enter the GBR from the adjacent catchment area. Important amongst pollutants discharged from agricultural lands are dissolved nutrients, which are predominantly nitrogen (N) and phosphorus (P). Thus, it is important that agricultural lands are managed to minimise the discharge of these pollutants.

Urban land uses (including industrial, commercial, and residential activities) within the GBR occupy <1% of the total catchment area, however, the intensity of use and large amounts of impervious surfaces results in high unit loading rates for N and P. Remaining non-agricultural land uses such as conservation areas, military lands and mining/extractive activities are likely to have low nutrient contributions requiring management, though point source discharges may exist in land uses such as aquaculture, animal husbandry (e.g., feed lots) and animal processing plants and can be important for management of acute and chronic nutrients loads to the GBR.

1.1 Questions

This review focused on management practices for reducing dissolved nutrient losses from the GBR catchments, focusing on dissolved inorganic nitrogen (DIN) and phosphorus (DIP), with the latter also referred to as dissolved reactive P (DRP). Both agricultural and urban land uses were considered. The primary and secondary questions were defined as follows:

Primary question	**Q4.6** What are the most effective management practices for reducing dissolved nutrient losses (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions? • What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? • What are the production outcomes of these practices?
Secondary questions	**Q4.6.1** What is the potential of Enhanced-Efficiency-Fertilisers (EEFs) in reducing nitrogen runoff and what are the primary challenges in implementation?
	Q4.6.2 What are the implications of mill mud application in influencing nitrogen losses and what are the primary challenges for implementation?
	Q4.6.3 What are the primary factors that influence nutrient losses from irrigated areas and how can these be managed?

Interpretation for agricultural land uses

While dissolved nutrients can be formed in, and discharged from all agricultural land uses, the greatest discharges per hectare occur in cropped lands (sugarcane, horticulture and banana, under both irrigated and dryland production) and intensive pastures (such as in dairy production) because of the additions of N and P, mostly but not exclusively as fertiliser. The application of N and P is a management action that is uncommon in other land uses such as extensive grazing. Hence the focus of this review is on cropped lands where agricultural land uses were concerned.

The questions addressed in Q4.6 focus on management practices that influence the amount of dissolved N and P that are present in fields, and which can subsequently be transported from the field by runoff and/or leaching. The issue of off-site treatment of dissolved N and P once they have been discharged from an agricultural field (e.g., constructed wetlands, bioreactors and irrigation water recycle ponds) were not included in this question as they are covered elsewhere in the 2022 SCS (see Questions 4.7, Waltham et al., and 4.8 Star et al., this SCS).

Leaching is included as well as runoff, because much larger amounts of DIN are leached below the root zone than discharged from fields in runoff. Small amounts of P can be leached too. Leached DIN can move through groundwater aquifers to creeks and rivers, eventually discharging to GBR ecosystems –

this is an important pathway for DIN moving from fields to the GBR. As well as runoff and leaching, DIN can be lost to the environment through the process of denitrification. Some studies reported losses of DIN from fields by runoff, leaching **and** denitrification, i.e., the total losses from all three process, without giving information on losses for individual pathways. These studies were considered because a change in total losses is likely to be reflected in a change in losses from each of the three pathways.

Given that farming is a business pursuit, the cost effectiveness of the management actions relevant to the discharge of dissolved N and P were also reviewed. Cost-effectiveness is defined through the costs of the practice and the resultant income (from crop yield), relative to the reduction in pollutant discharge.

Interpretation for urban/non-agricultural land uses

For urban/non-agricultural land uses, three key pollutant streams for nutrients were considered, point sources related to domestic wastewater generation and discharge, point sources related to animal processing waste discharges, and diffuse runoff sources from urban stormwater. The treatment of infiltrated stormwater into subsurface flows was not directly considered, though often this is characterised as being in the same diffuse runoff as low flows.

1.2 Conceptual diagrams

To answer the primary and secondary questions, three conceptual diagrams were developed to accommodate the different biophysical drivers for the different nutrients (dissolved N and dissolved P) and cropping versus urban land uses.

The frameworks for dissolved N (Figure 1a) and dissolved P (Figure 1b) from cropping lands indicate the different pathways of loss that are of concern, along with the specific attributes that determine these losses. The management actions that aim to reduce losses affect these attributes in different ways. The appraisal of evidence (Section 4.1) is structured around these management actions, considering for each their effectiveness relating to water quality improvements as well as economic and other considerations that may affect the adoption of these practices. The nutrient losses and effectiveness of the management actions in reducing losses are, however, also affected by inherent or natural drivers, such as climate, soil and landscape factors, as well as drivers stemming from human ‘modifications’ of the system.

The framework for non-agricultural land use (Figure 1c) was developed from understandings of different sources and the pathways through which nutrients may be delivered to the GBR. Management actions have been largely grouped into structural and non-structural measures that may be implemented for both point and diffuse source management. Structural measures are those that may be constructed and/or implemented through an engineering approach to place an intervention between the source of nutrients and its release to downstream waterways. Non-structural measures are those which may be implemented through changes to or improvements in policy, regulation, compliance, education and enforcement types of approaches. Appraising the evidence of these has focused on all actions rather than necessarily disaggregating them into structural and non-structural measures, as often these are implemented in combination or in parallel.

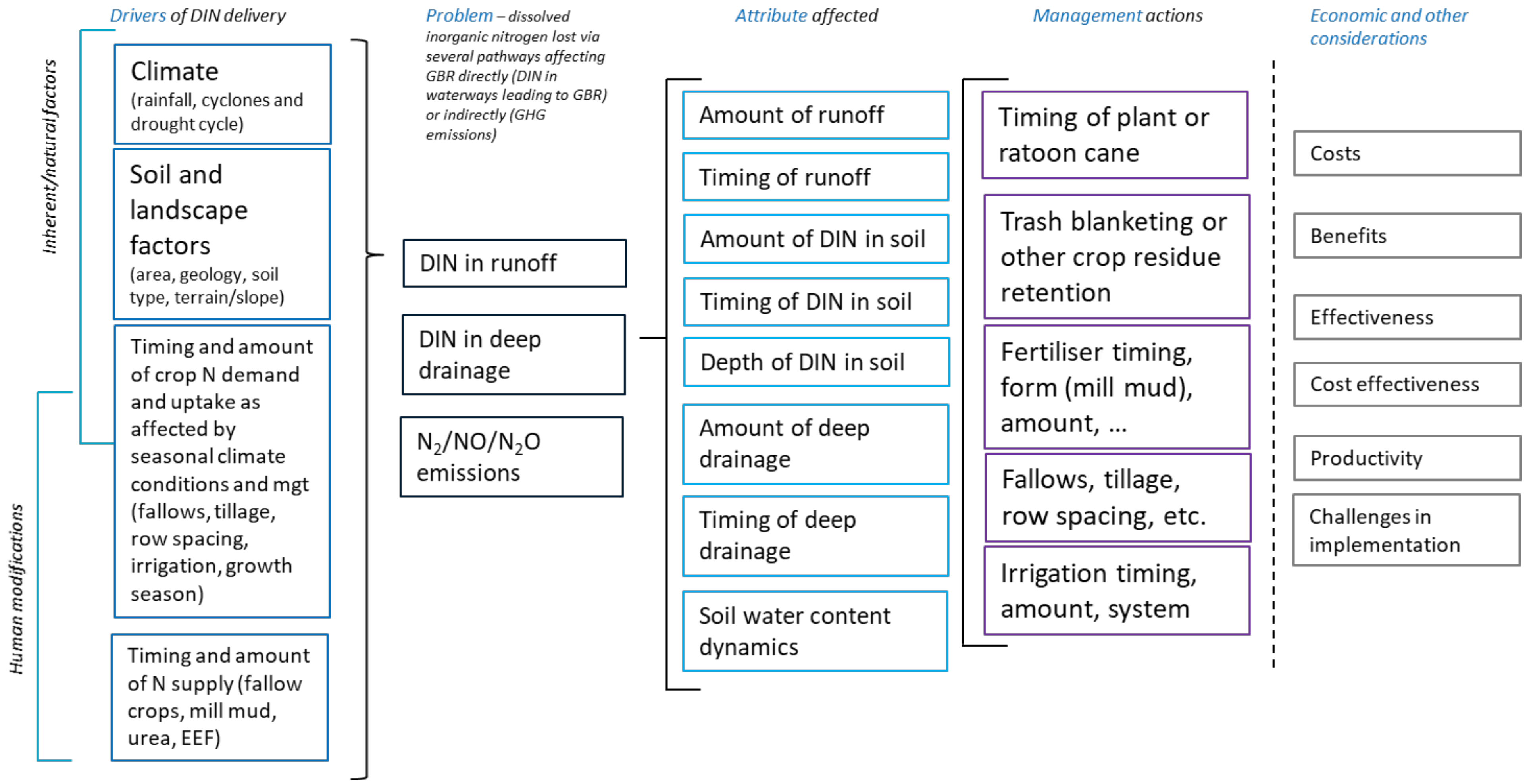

Figure 1a. Conceptual framework for discharge of dissolved inorganic nitrogen (DIN) from cropping lands. The economic aspects of the management actions are also shown. Note: crops include managed pastures.

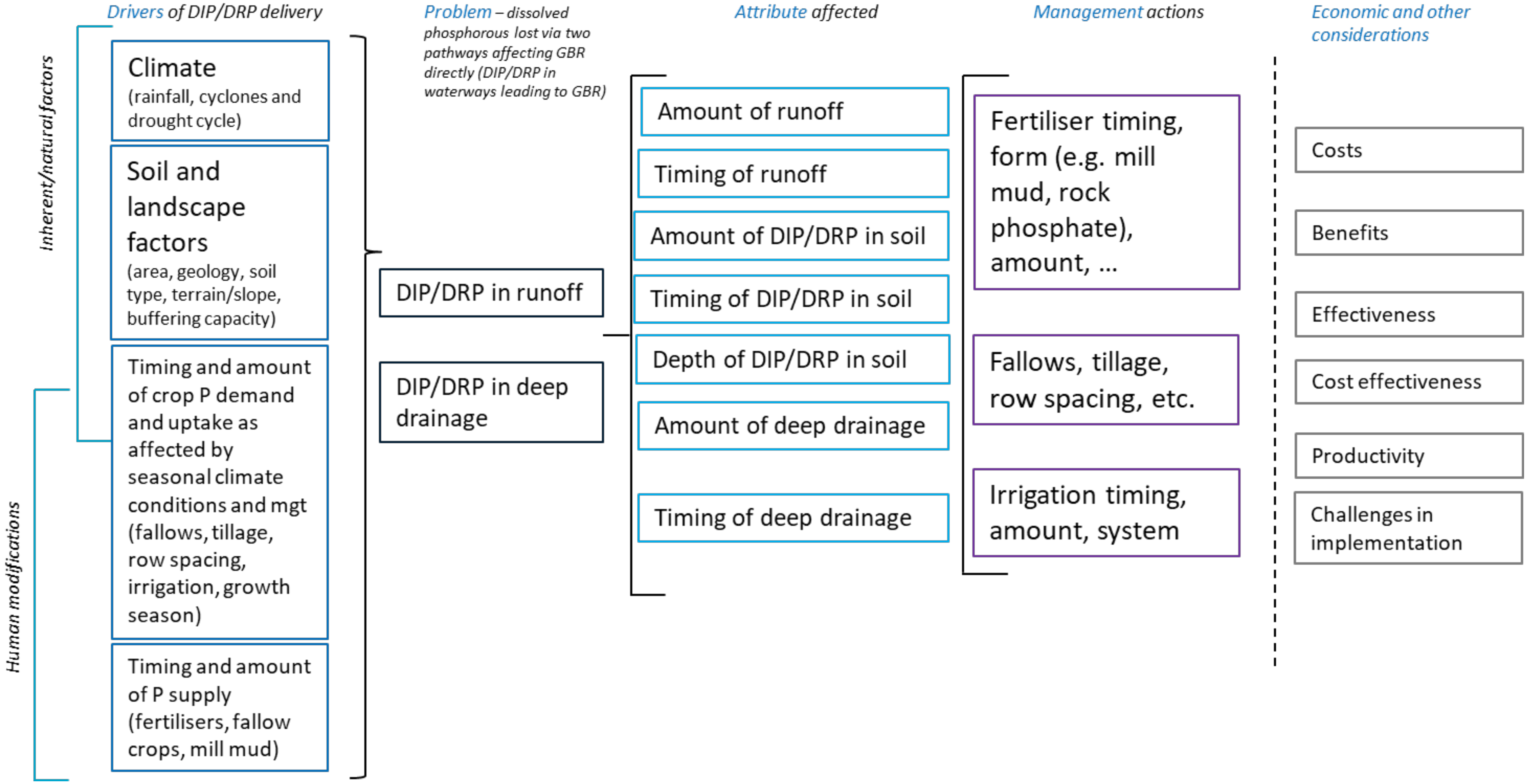

Figure 1b. Conceptual framework for discharge of dissolved phosphorus from cropping lands (commonly referred to as dissolved inorganic P (DIP) or dissolved reactive P (DRP)). The economic aspects of the management actions are also shown. Note: crops include managed pastures.

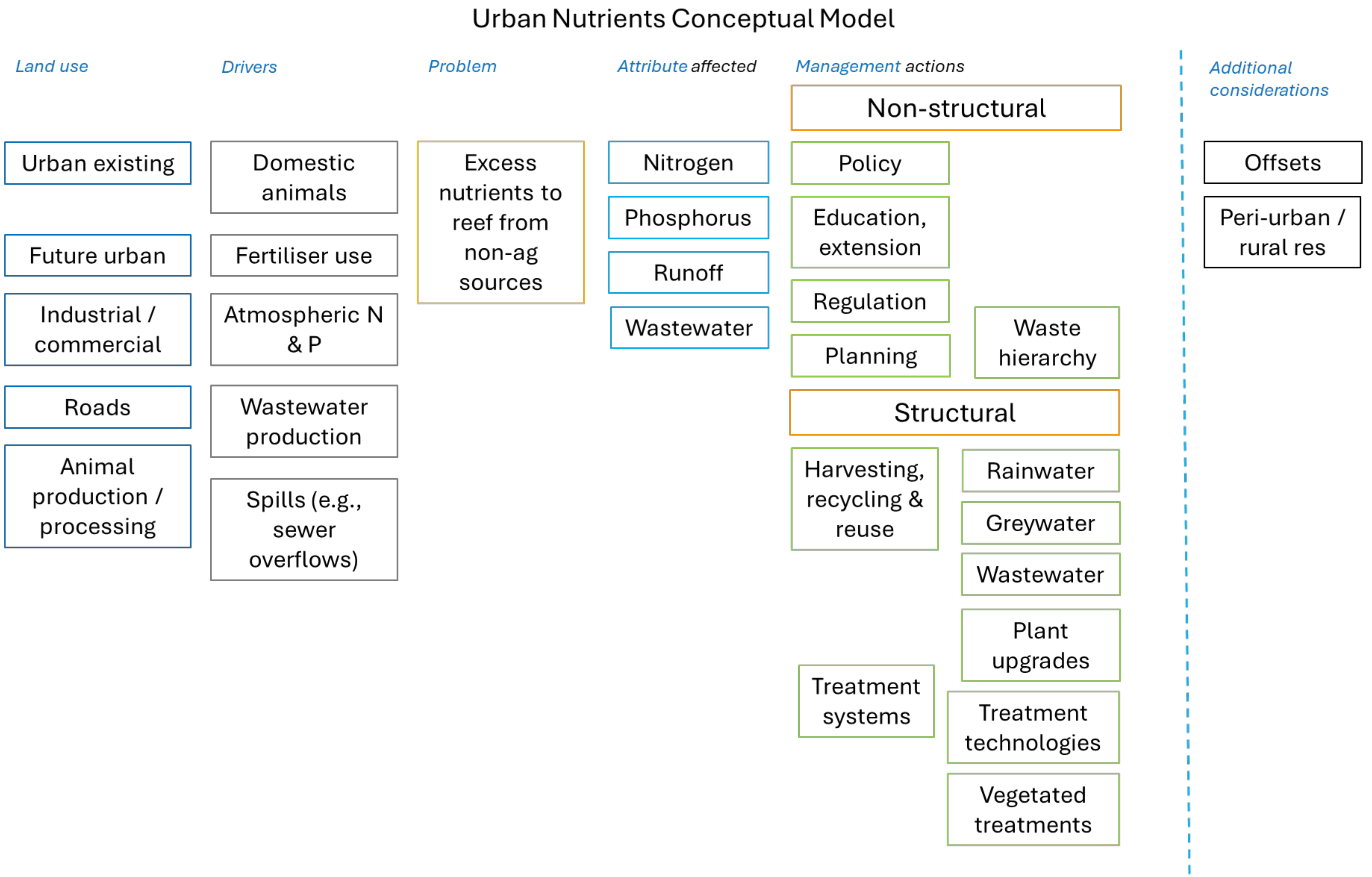

Figure 1c. Conceptual framework for nutrients and their management from urban/non-agricultural sources.

1.3 Links to other questions

This synthesis of evidence addresses one of 30 questions that are being addressed as part of the 2022 SCS. The questions are organised into eight themes: values and threats, sediments and particulate nutrients, dissolved nutrients, pesticides, other pollutants, human dimensions, and future directions, that cover topics ranging from ecological processes, delivery and source, through to management options. As a result, many questions are closely linked, and the evidence presented may be directly relevant to parts of other questions. The relevant linkages for this question are identified in the text where applicable. The primary question linkages for this question are listed below.

Links to other related questions	Management practices relating to reducing particulate nutrient loss from GBR catchments: **Q3.5** What are the most effective management practices (all land uses) for reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, do these vary spatially or in different climatic conditions? What are the costs and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices? Practices relating to off-site treatment of dissolved nitrogen and phosphorus once they were discharged from a field: **Q4.7** What is the efficacy of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality (nutrients, fine sediments and pesticides)? **Q4.8** What are the measured costs, and cost drivers associated with the use of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality? Biophysical drivers of nutrient loss from GBR catchments: **Q4.5** What are the primary biophysical drivers of anthropogenic dissolved nutrient export to the Great Barrier Reef and how have these drivers changed over time? Biophysical drivers of particulate nutrient loss from GBR catchments: **Q3.4** What are the primary biophysical drivers of anthropogenic sediment and particulate nutrient export to the Great Barrier Reef and how have these drivers changed over time? The primary sources of nutrients delivered to the GBR: **Q4.4** How much anthropogenic dissolved nutrient (nitrogen and phosphorus species) is exported from Great Barrier Reef catchments (including the spatial and temporal variation in delivery), what are the most important characteristics of anthropogenic dissolved nutrients, and what are the primary sources?

2. Method

A formal Rapid Review approach was used for the 2022 SCS synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[9]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Review method was used.

2.1 Primary question elements and description

The primary questions were:

- What are the most effective management practices for reducing dissolved nutrient losses (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions?
- What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions?
- What are the production outcomes of these practices?

The secondary questions were:

- What is the potential of Enhanced-Efficiency-Fertilisers (EEFs) in reducing nitrogen runoff and what are the primary challenges in implementation?
- What are the implications of mill mud application in influencing nitrogen losses and what are the primary challenges for implementation?
- What are the primary factors that influence nutrient losses from irrigated areas and how can these be managed?

Question elements derived from these questions are shown in Table 1. Clarifications of some of the terms used are provided in Table 2.

S/PICO frameworks (Subject/Population, Exposure/Intervention, Comparator, Outcome) can be used to break down the different elements of a question and help to define and refine the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods[10] but other variations are also available.

- **Subject/Population:** Who or what is being studied or what is the problem?
- **Intervention/exposure:** Proposed management regime, policy, action or the environmental variable to which the subject populations are exposed.
- **Comparator**: What is the intervention/exposure compared to (e.g., other interventions, no intervention, etc.)? This could also include a time comparator as in 'before or after' treatment or exposure. If no comparison was applicable, this component did not need to be addressed.
- **Outcome:** What are the outcomes relevant to the question resulting from the intervention or exposure?

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[9] Cook CN, Nichols SJ, Webb JA, Fuller RA, Richards RM (2017) Simplifying the selection of evidence synthesis methods to inform environmental decisions: A guide for decision makers and scientists. *Biological Conservation* 213: 135-145

[10] https://libguides.jcu.edu.au/systematic-review/define and https://guides.library.cornell.edu/evidence-synthesis/research-question

Table 1. Description of primary question elements for Question 4.6.

Question S/PICO elements	Question term	Description
Subject/Population	Nutrient loss (in catchments draining to the GBR).	The focus is on dissolved nitrogen and phosphorus. Losses are those resulting from the generation of the nutrient and its transport off the land surface, by moving with runoff or being leached below the root zone.
Subject qualifier	Nutrients losses in crop fields and urban landscapes	Cropped land use includes areas producing sugarcane, horticulture and bananas, both through irrigated and dryland production. Non-agricultural land uses include urban residential, industrial, commercial, mining and extractive industries and potentially military lands. It could be argued that conservation and forestry lands may also be included in non-agricultural lands however these were not examined from a management action perspective.
Intervention, exposure & qualifiers	Management practices that reduce discharge of nutrients.	Practices include fertiliser, crop and irrigation management, as well as the form of fertiliser used (including Enhanced-Efficiency-Fertilisers) and the application of mill mud to cropped fields. For non-agricultural land uses, this includes structural and non-structural actions such as vegetated treatment systems (swales, biofilters, wetlands), proprietary treatment devices (gross pollutant traps, vortex separators, filters), and non-engineered approaches such as planning, policy, education, compliance and enforcement actions.
Comparator	Variability of the management practice effectiveness including challenges.	Varying effectiveness of different management practices in reducing dissolved nutrient discharges. How the effectiveness of the interventions vary spatially or in different climatic conditions. Problems with/limits to implementing the interventions.
Outcome & outcome qualifiers	Reduced dissolved nutrient losses to the GBR.	The difference in nutrient losses from the different interventions. The costs, production outcomes and cost effectiveness of the interventions.

Table 2. Definitions for any terms used in Question 4.6.

Definitions	
Nutrients	Nitrogen and phosphorus in a dissolved form.
GBR	Catchments draining into the GBR.
Enhanced-Efficiency-Fertilisers	Forms of nitrogen fertiliser that either: 1) delay the release of the nitrogen from the applied product into the soil; and/or 2) reduce the rate at which the nitrogen fertiliser is transformed to nitrate in the soil.
Mill mud	A byproduct of the sugar milling process that is commonly disposed of by application to sugarcane fields.
Irrigation	Water applied to cropped fields to reduce crop water stress, coming from surface or ground-water sources.
Economics - Cost	Costs can refer to the variable costs associated with crop production and/or the capital investment required for a practice change, such as the costs associated with purchasing machinery and equipment. There are also more general economic impacts, such as net revenue, gross margin or net present value results. A net revenue (or partial gross margin or partial grower net return) is typically the difference between variable costs and gross revenues. For sugarcane production, it can also be relevant to consider costs and revenue from an industry perspective by, for example, incorporating the net returns that both sugarcane growers and millers would receive into the result calculations.
Economics - Cost effectiveness	Cost effectiveness studies involve the integration of environmental and economic results. Cost effectiveness may be calculated as the present value of costs (private, public, program, maintenance) of a particular intervention divided by the per unit reduction in pollutant (e.g., cost per kg of DIN abated). Some studies report separately on economic and environmental results to give an indication of the cost effectiveness of each management practice change (e.g., if the study includes some changes that improve profit and others that decrease profit). The economic methodologies associated with cost-effectiveness studies can differ between studies.
Urban/non-Agricultural	In this document, urban and non-agricultural land uses are considered together and are defined as those activities which may occur at a high level of intensity, with mixed application of pervious and impervious land surfaces and the generation of both diffuse and point sources of nutrients and other contaminants.
Paddock to Reef (P2R) Water Quality Risk Framework	Water quality risk frameworks have been established for management practices applied in sugarcane, grains and horticulture farming. The 2017-2022 framework[11] categorises risk from high to low risk. Prior to 2017, there were various "ABCD practice frameworks" that defined land condition and subsequent water quality outcomes (Star et al., 2021).
Nitrogen Loss Reduction Index (NiLRI)	A simple metric for assessing the risk of N discharge from sugarcane cropping, defined as the ratio of N fertiliser applied to crops and the cane yield achieved[12].

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[11] https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0017/46106/methods.pdf

[12] Thorburn et al. (2022) https://doi.org/10.1016/j.jenvman.2022.115932

2.2 Search and eligibility

a) Search locations

Searches were performed on:

- Scopus
- Web of Science
- In addition, manual searches included the Queensland Government database, and conference proceedings (where peer reviewed).

b) Search terms

Table 3 shows a list of the search terms used to conduct the online searches in relation to the question elements of Table 1. Separate searches were performed for urban/non-agricultural and cropping land uses. In addition, within the cropping land uses, separate searches were performed for biophysical aspects (separately for nitrogen and phosphorus) and for economics aspects. Manual cross-referencing between the outcomes of the biophysical and economics searches ensured consistency.

Table 3. Search terms for S/PICO elements of Question 4.6.

Question element	Search terms
Subject/Population	*Cropping lands* Sugarcane, horticulture, banana, grains, cotton, crop Queensland, Australia, Australian, Great Barrier Reef *Non-agricultural* Urban, industrial, industry, commercial, roads, aquaculture
Exposure or Intervention	*Dissolved inorganic nitrogen discharge in cropping lands* Fertiliser, mill mud, organic, enhanced efficiency, nitrification inhibitor, controlled release, split *Dissolved inorganic phosphorus discharge in cropping lands* Fertiliser, mill mud, organic, PBI (Phosphorus Buffering Index) *Non-agricultural* Management, action, policy, planning, treatment, measure, reuse, recycling, wetland
Comparator (if relevant)	
Outcome	*Nutrient discharge* Loss, drainage, runoff, water quality, storm, wastewater, discharge *Economics* Economics, profitability, cost effectiveness, benefit, water quality

c) Search strings

Table 4 shows a list of the search strings used to conduct the online searches.

Table 4. Search strings used for electronic searches for Question 4.6.

Search strings
Dissolved inorganic nitrogen discharge ((“sugarcane” OR “horticulture” OR “banana” OR “grains” OR “cotton” OR “crop”) AND (“nitrogen”) AND (“fertiliser” OR “mill mud” OR “organic” OR “enhanced efficiency” OR “nitrification inhibitor” OR “controlled release” OR “split”) AND (“loss” OR “drainage” OR “runoff” OR “water quality”) AND (“Queensland” OR “Australia” OR “Australian” OR “Great Barrier Reef”))

Search strings
Dissolved inorganic phosphorus discharge ((“sugarcane” OR “horticulture” OR “banana” OR “grains” OR “cotton” OR “crop”) AND (“phosphorus”) AND (“fertiliser” OR “mill mud” OR “organic” OR “PBI”) AND (“loss” OR “drainage” OR “runoff” OR “water quality”) AND (“Queensland” OR “Australia” OR “Australian” OR “Great Barrier Reef”))
Economics. ((“sugarcane” OR “horticulture” OR “banana” OR “grains” OR “cotton” OR “crop”) AND (“nitrogen” OR “phosphorus” OR “nutrients”) AND (“fertiliser” OR “mill mud” OR “organic” OR “enhanced efficiency” OR “nitrification inhibitor” OR “controlled release” OR “split”) AND (“economics” OR “profitability” OR “cost effectiveness” OR “benefit”) AND (“water quality”) AND (“Queensland” OR “Australia” OR “Australian” OR “Great Barrier Reef”))
Urban/non-agricultural ((“urban” OR “industrial” OR “industry” OR “commercial” OR “road” OR “aquaculture”) AND (“runoff” OR “stormwater” OR “wastewater” OR “discharge” OR “water quality”) AND (“nitr*” OR “phosph*” OR “nutrient”) AND (“management” OR “action” OR “policy” OR “planning” OR “treatment” OR “measure” OR “reuse” OR “recycling”) AND (“Queensland” OR “Australia” OR “Australian” OR “Great Barrier Reef”) A“D NOT”("w“tland") ”ND NOT (“crop" OR "”ugar“ane")) **Wetland search terms** ((“urban” OR “industrial” OR “industry” OR “commercial” OR “road” OR “aquaculture”) AND (“runoff” OR “storm*” OR “wastewater” OR “discharge” OR “water quality”) AND (“nitr*” OR “phosph*” OR “nutrient” OR “sediment” OR “particulate” OR (“suspended” AND “soli*”)) AND (“wetland” AND (“treatment” OR “measure”)) AND (“Queensland” OR “Australia” OR “Australian” OR “Great Barrier Reef”) AND NOT (“crop” OR “sugarcane”))

d) Inclusion and exclusion criteria

Table 5 shows a list of the eligibility criteria used for accepting or rejecting evidence items. These criteria were used during an initial screening based on study title and abstract and during a secondary screening based on evidence included in the full article against the different management actions in the context of the primary and secondary questions. The initial screening was undertaken via consensus across authors of each topic (nitrogen, phosphorus, economics, urban/non-agricultural).

For the searches on N and P in agricultural land uses the first screening is documented in a separate tab in the appraisal spreadsheet. The secondary screening was documented as part of the appraisal spreadsheet, with excluded studies not contributing relevant evidence noted in the “4. Studies excluded” tab. For the economics search, the detail of both the initial and secondary screening and exclusion of studies is documented on the tab “4. Studies excluded”. For urban/non-agricultural land uses, initial screening based on title and abstract were conducted, with secondary screening undertaken where there were uncertainties, or it was later determined from the article body that it was not directly relevant to the region or question. All studies are listed under the “1. Data Extraction” tab, with column J indicating whether a study was rejected at the first screen or second screen or accepted as evidence. Those rejected in the second screening are also listed on the tab “4. Studies excluded”. Note that for the urban wetlands a separate search was undertaken consistent with Q4.7 (Waltham et al., this SCS) initially, with studies not relating to nutrients excluded in a second screening.

Table 5. Inclusion and exclusion criteria for Question 4.6 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	Nutrients, specifically dissolved N and P. Studies in Australia including Queensland and the GBR related to sugarcane, horticulture, banana,	Studies not on dissolved nutrients, e.g., erosion, particulate nutrients, pesticides. Nutrients other than N and P. International studies.

Question element	Inclusion	Exclusion
	grains, cotton or other crops, urban lands, roads, industrial, commercial or aquaculture land uses.	Other land uses, such as grazing/dairy farms, pastures. Papers published in multiple peer reviewed sources without substantial modification (e.g., duplicate publications). Papers not obtainable. Papers reporting only nutrient concentrations in soils, rather than losses. Old, dated studies for which information was no longer relevant (had been superseded by subsequent studies).
Exposure or Intervention	Practices including fertiliser, crop and irrigation management, as well as the form of fertiliser used (including Enhanced Efficiency Fertilisers) and the application of mill mud to cropped fields. For non-agricultural lands, practices including policy, planning, treatment, reuse, measure, wetland.	Practices not related to applications of nutrients, mill mud or irrigation, or management of the crop.
Comparator (if relevant)		
Outcome	Losses of dissolved nutrients from a cropped field, through runoff or leaching below the root zone, or the total losses (by runoff, leaching and denitrification) or point sources (for non-agricultural land use). Economic measures of costs, benefits, cost-effectiveness and profitability of management practices for reducing nutrient losses.	Losses by other pathways (e.g., denitrification, ammonia volatilisation). Off-field methods of preventing dissolved nutrients being transported to the GBR except for non-agricultural lands where this was included. Economic aspects other than costs, benefits, cost-effectiveness and profitability studies (e.g., transition costs).
Language	English	Non-English
Study type	Peer reviewed and published including technical reports. Studies could be experimental, laboratory, reviews and syntheses, and/or modelling, including mechanistic, empirical or statistical.	Not peer reviewed by independent external reviewers and unpublished studies.

3. Search Results

A total of 1,656 studies were identified through online searches for peer reviewed and published literature. An additional 49 studies were identified manually through expert contact, SCS submissions and personal collection, which represented 3% of the total evidence. 294 studies were eligible for inclusion in the synthesis of evidence (Table 6) (Figure 2). Thirteen studies were excluded due to being unobtainable.

The chosen search strings were deliberately relatively wide and not limited to the GBR as it was noticed that several known relevant publications did not necessarily refer to the GBR in the title, abstract or keywords. Searching outside the GBR was also important to evaluate literature from elsewhere where evidence of studies undertaken within the GBR was limited. For the agricultural land uses, non-GBR studies were mostly excluded during the initial screening, after assessing based on title and abstract whether the study contributed relevant evidence. For topics with limited coverage within the GBR, some studies (just) outside the GBR were included where they reflected relevant conditions. This made the screening process more laborious, but ensured publications were not missed because they were written for a more general audience. A few conference papers were not picked up by the searches, presumably due to database errors as papers presented in the same conference sessions were included. These were added manually. Similar database errors missed a couple of journal publications which were added manually. The manual addition of sources submitted to the SCS as part of the external literature submission process, including several peer-reviewed reports completed in late 2022, contributed valuable other evidence. The authors are confident that the review included most, if not all, peer reviewed research findings on the four topics.

Table 6. Search results table, separated by A) Academic databases, B) Search engines (i.e., Google Scholar) and C) Manual searches. The search results for A and B are provided in the format X (Z) of Y or X of Y (Z), where: X (number of relevant evidence items retained); Y (total number of search returns or hits); and Z (number of duplicates that had already been found in previous searches). Relevant items retained refers to those items left after the ***initial*** *screen.*

Date	Search strings	Sources	
A) Academic databases		Scopus	Web of Science (WoS)
28/11/2022	**Nitrogen**: ((“sugarcane” OR “horticulture” OR “banana” OR “grains” OR “cotton” OR “crop”) AND (“nitrogen”) AND (“fertiliser” OR “mill mud” OR “organic” OR “enhanced efficiency” OR “nitrification inhibitor” OR “controlled release” OR “split”) AND (“loss” OR “drainage” OR “runoff” OR “water quality”) AND (“Queensland” OR “Australia” OR “Australian” OR “Great Barrier Reef”))	88 of 305 (after initial screening)	47 of 266 (after initial screening)
		90 of 571 (Scopus and WoS) after removal of 38 duplicates and 7 sources in second screening.	
28/11/2022	**Phosphorus:** ((“sugarcane” OR “horticulture” OR “banana” OR “grains” OR “cotton” OR “crop”) AND (“phosphorus”) AND (“fertiliser” OR “mill mud” OR “organic” OR “PBI”) AND (“loss” OR “drainage” OR “runoff” OR “water quality”) AND (“Queensland” OR “Australia” OR “Australian” OR “Great Barrier Reef”))	6 of 85	5 of 68
		4 of 153 (Scopus and WoS) after removal of 3 duplicates and 4 sources in second screening.	

Date	Search strings	Sources	
17/11/2022	**Economics:** ((“sugarcane” OR “horticulture” OR “banana” OR “grains” OR “cotton” OR “crop”) AND (“nitrogen” OR “phosphorus” OR “nutrients”) AND (“fertiliser” OR “mill mud” OR “organic” OR “enhanced efficiency” OR “nitrification inhibitor” OR “controlled release” OR “split”) AND (“economics” OR “profitability” OR “cost effectiveness” OR “benefit”) AND (“water quality”) AND (“Queensland” OR “Australia” OR “Australian” OR “Great Barrier Reef”))	208 of 255 (after initial screening)	81 of 227 (after initial screening)
		29 of 482 (Scopus and WoS) after removal of 92 duplicates and 92 other sources in second screening.	
10/11/2022	**Urban/non-Agricultural:** ((“urban” OR “industrial” OR “industry” OR “commercial” OR “road” OR “aquaculture”) AND (“runoff” OR “stormwater” OR “wastewater” OR “discharge” OR “water quality”) AND (“nitr*” OR “phosph*” OR “nutrient”) AND (“management” OR “action” OR “policy” OR “planning” OR “treatment” OR “measure” OR “reuse” OR “recycling”) AND (“Queensland” OR “Australia” OR “Australian” OR “Great Barrier Reef”) AND NOT (“crop” OR “sugarcane”)) And for wetlands: ((“urban” OR “industrial” OR “industry” OR “commercial” OR “road” OR “aquaculture”) AND (“runoff” OR “storm*” OR “wastewater” OR “discharge” OR “water quality”) AND (“nitr*” OR “phosph*” OR “nutrient” OR “sediment” OR “particulate” OR (“suspended” AND “soli*”)) AND (“wetland” AND (“treatment” OR “measure”)) AND (“Queensland” OR “Australia” OR “Australian” OR “Great Barrier Reef”) AND NOT (“crop” OR “sugarcane”))	186 of 450 after first screen 119 of 450 after second screen	
B) Search engines (e.g., Google Scholar)			
	Not used		
	Total items online searches	***1,656 (97%)***	
C) Manual search			
Date	Source	Number of items added	
	Authors personal knowledge and/or collections or arising from cited literature in other sources and sources formally contributed to the SCS process	Nitrogen 18	
		Phosphorus	4
		Economics	27
		Urban	0
	Total items manual searches	***49 (3%)***	

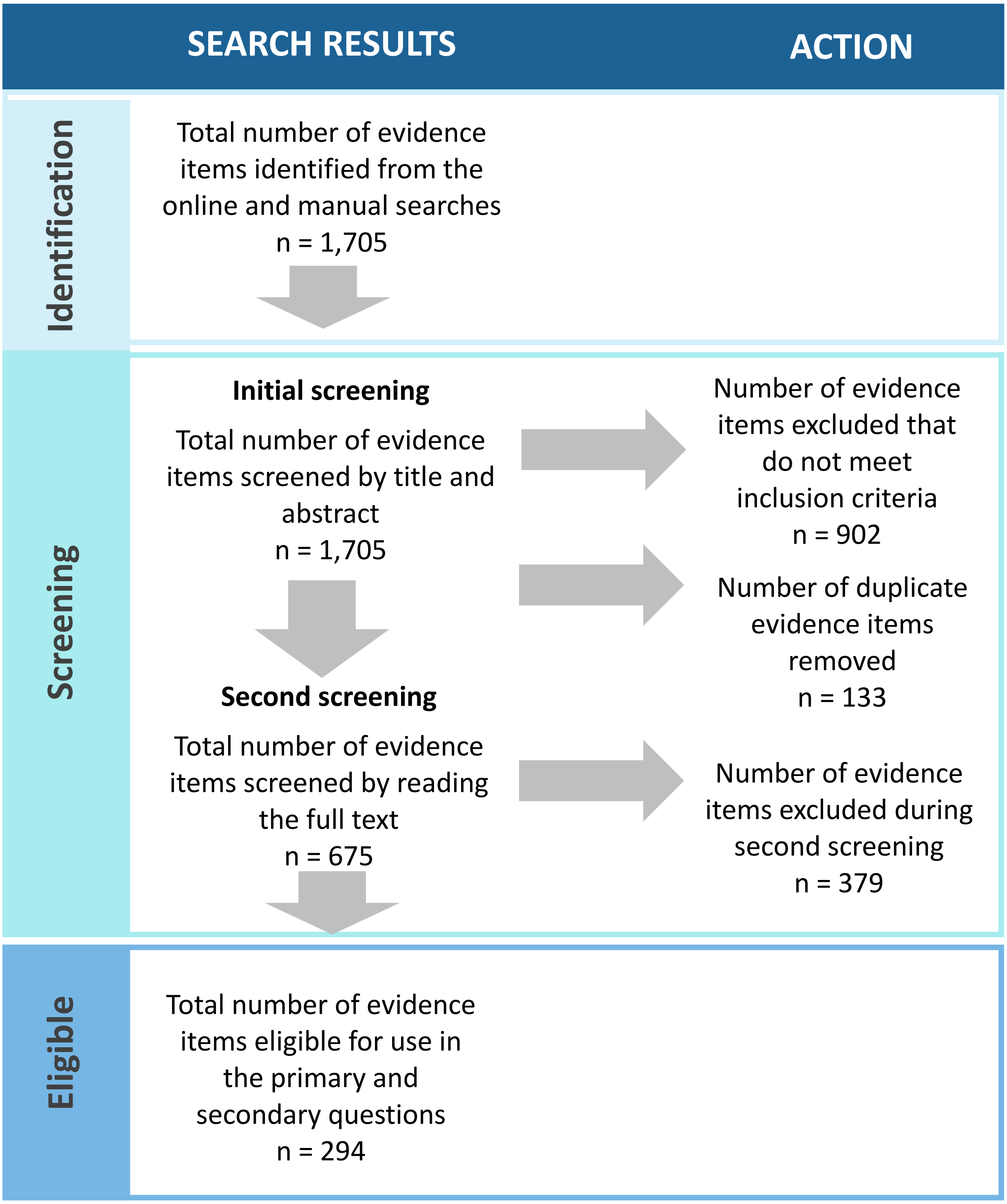

Figure 2. Flow chart of results of screening and assessing all search results for Question 4.6.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

A total of 294 studies were used to answer the primary and secondary questions from different perspectives. In relation to the effectiveness of management practices in reducing dissolved N and P from agricultural land uses, this review focused primarily on studies situated within the GBR. However, for urban land uses, the review included evidence from outside the GBR. The studies included a mix of site or catchment specific studies and studies that included multiple locations across the GBR catchment.

Among the agricultural land uses, the majority of studies focused on sugarcane (e.g., 68% studies from the nitrogen (N) appraisal, 38% of phosphorus (P) appraisal, 71% of economics appraisal). Only a few studies covered multiple crops (e.g., 18 in N search) and most of these were secondary review or re-analysis studies rather than actually comparing effects for crops.

The majority of papers considered were peer reviewed international journal papers (>50%). However, reviewed papers from the Australian Society of Sugar Cane Technologists (ASSCT) also contributed valuable evidence, as did other peer reviewed reports, especially those published in 2022 that were submitted to the SCS as part of the external literature submission process that contributed the latest research findings not yet found in the international journals.

For agricultural land uses, the studies included a mix of experimental (~60%) and modelling (~30%) studies, with some additional secondary studies (~10%) providing reviews across studies or re-analysis of data. For urban there were fewer modelling studies and more observational ones.

For the secondary question on Enhanced Efficiency Fertiliser (EEF), 35 studies were identified as part of the N search of which 57% (20) included quantification of N loss (any pathway) with just over half (13) of these coming from experimental studies. In contrast, only four studies were identified quantifying or relating mill mud treatments to N loss (two of which included modelling).

4.1.1 Summary of evidence to 2022

The results from the four separate searches and evidence appraisals (nitrogen, phosphorus, economics and urban, see Method section) are organised as follows. The evidence relating to **cropping land uses** by ***management action*** is presented first, touching separately on evidence relating to dissolved nutrient discharge (*nitrogen* and *phosphorus*), to productivity outcomes and to costs, cost-effectiveness and profitability (where evidence was available). Evidence is then presented relating to **urban/non-agricultural land uses**, with this separated into non-structural and structural ***management actions*** for domestic wastewater, animal processing wastewater and stormwater runoff (including for some actions several specific treatment types). Costs are included directly as there were insufficient costs to identify specific cost-effectiveness values.

i Cropping land uses

Fertiliser amount

Dissolved nutrient discharge

Nitrogen

There have been many studies on the effect of N fertiliser application rates on discharge of DIN from sugarcane fields. Reducing applications of N fertiliser has consistently reduced discharges of DIN via runoff and/or leaching (Armour et al., 2013; Bell et al., 2021; Cook et al., 2021; Donaldson & Rohde, 2022; Thorburn et al., 2011a; Webster et al., 2012).This empirical result is supported by estimates of DIN discharges from mechanistic (Biggs et al., 2013; 2021; Meier & Thorburn, 2016; Migliorati et al., 2021; Power et al., 2021; Stewart et al., 2006; Thorburn et al., 2011a; Verburg et al., 1998; 2017; 2018; 2022; Vilas et al., 2022; Webster et al., 2022) and empirical (Fraser et al., 2017; Shenton et al., 2010) modelling studies.

Other relevant studies report reduced **total** DIN losses (i.e., sum of losses via runoff, leaching and denitrification) from sugarcane with reduced N fertiliser applications. These studies use a range of techniques, including N balance (Thorburn et al., 2011b), ^{15}N tracing (Takeda et al., 2021) and mechanistic modelling (Verburg et al., 2017; 2018; 2022; Webster et al., 2022). While specific results for runoff and leaching are not reported, the field conditions represented in these conditions mean that a reduction in total DIN losses are likely to have arisen by a reduction in all three pathways that contribute to the total.

In another study, Connellan et al. (2022b) found higher DIN concentrations (averaged over sites, years and in-crop sampling time) at 1 m depth in soils with higher applications rates of N fertiliser at six sites. They interpreted the result as lower N leaching with lower N applications, an interpretation that implicitly assumes the volume of water flowing past the soil sampling point was the same in both treatments. This assumption would not be valid if, for example, crop yields were different in the treatments. Connellan et al. (2022b) also measured DIN concentrations in runoff from six sites. The DIN concentrations tended to be lower with lower N applications, especially in the runoff events earlier in the crops' life. However, as with N leaching, conversion of DIN concentrations to the mass of DIN discharged during a single sampling event or over a whole crop requires the integration of the concentrations data with the volume of runoff water. Therefore, the water quality implications of these results are unclear.

There is less information available for other crops. In cotton, Scheer et al. (2022) reported reduced **total** DIN losses (i.e., sum of losses via runoff, leaching and denitrification) with reduced (by 30 %) N fertiliser applications in a study on the Darling Downs using ^{15}N tracing. While this study was located outside GBR catchments, the results are likely to have relevance to cotton production within GBR catchments. In bananas, lower N applications reduced N leaching (Armour et al., 2013) at a site in the South Johnston region. Reducing applications of N fertiliser reduced DIN discharged in runoff from vegetable production (Nachimuthu et al., 2017a) in an experiment south of Bundaberg, although the treatments with lower N applications had other management changes imposed so the causal link between N fertiliser and DIN in runoff is only implicit. In a dairy pasture at Ravenshoe, Koci and Nelson (2016) found non-significant trends of reductions in DIN losses via leaching with lower N fertiliser inputs. However, for crop such as perennial crops, pineapples, continuous supply crops and mulched crops there is little information on the production-based interactions between nutrients and crop husbandry and the quality of horticultural products (Milbank & Nothard, 2023).

Some other practices related to fertiliser amount have been evaluated on the assumption they could provide water quality benefits, although there is limited published evidence to support those assumptions. An example is variable nutrient application rates. Rust and Law (2016) reported that varying nutrient application across a field may help farmers better match fertiliser applications to a crop's needs and result in reduced average applications of nutrients applied to a field. This is discussed further in relation to costs and productivity outcomes below.

Phosphorus

Adding P fertiliser (20 kg ha^{-1}) increased discharge of PO_4-P (but not Total P (Kjeldahl)) compared with no applied P in runoff from bare soil plots over three applications of simulated rainfall (Cook et al., 2021).

Productivity outcomes

Nitrogen

A large study was conducted on sugarcane crops in the Burdekin region (Connellan et al., 2017) to determine how cane and sugar yields varied between farmers' conventional N application rates, rates higher than conventional rates, and N rates recommended from the industry best practice SIX EASY STEPS™ (6ES). For the Burdekin region, there are two possible 6ES recommendations depending on cane yield potential, one for a potential of 180 t ha^{-1} (6ES-180) and another for 150 t ha^{-1} (6ES-150). Both 6ES rates were included in the study. There were one to five crops grown at each of 23 sites. Across the sites and crops, cane yields in the high and conventional treatments were significantly higher than the two

6ES treatments. However, sugar yields in the high, conventional and 6ES-180 treatment were not significantly different, although sugar yields in the 6ES-150 treatment were.

Reducing applications of N fertiliser below those recommended from 6ES has in some studies been shown to reduce yields of both cane and sugar (experimental studies by Bell et al., 2021; Connellan et al., 2022a; 2022b; Dowie et al., 2019; Wang et al., 2016a and modelling studies by Canegrowers, 2020; Webster et al., 2022). Dowie et al. (2019), in meta-analyses across three seasons and two groups of nine and three sites, respectively, obtained significant reductions in cane and sugar yield when reducing the urea N rate from 220 to 180 kg N ha^{-1} (-18%) on sandy soils, and from 220 to 160 kg N ha^{-1} (-27%) on a sand and loam soil or across all three soil types. The research findings by Connellan et al. (2022a; 2022b) were based on a meta-analysis in which data were pooled across four GBR regions, 54 sites and three seasons. Applying urea at 20% less than the 6ES recommended rates resulted on average in small losses of sugar and cane yield. When analysed as a function of season and soil type, statistically significant cane yield reductions occurred in late-season ratoon crops on clay (2.8 t ha^{-1} reduction) and loam (3.4 t ha^{-1}) soils in seasons with high rainfall conditions (Connellan et al., 2022a; 2022b). Yield losses were also found in combinations of mid-season crops on loam soil and late-season crops on clay soil in seasons with medium rainfall conditions. For other combinations of soil type, season type and crop start there were either no reductions in cane yield or the effects were not statistically significant, indicating that reducing N rate maintained yields in drier conditions.

There have also been mechanistic and statistical modelling studies of the effect of reducing N fertiliser applications below 6ES recommended rates. In a mechanistic modelling study, Webster et al. (2022) found applying urea at 20% less than the 6ES rates resulted in generally small average yield reductions (1.5 t ha^{-1}) over 70 seasons simulated for five soil types in each of 10 regions (i.e., 3,500 season-soil-region combinations) in the Wet Tropics. In contrast, a statistical modelling study by Canegrowers (2020) over five regions (Herbert, Bundaberg, Mackay, Tully and Burdekin) found reductions of 5.0 to 7.5 t ha^{-1} in cane yields and 0.7 to 1.2 t ha^{-1} in sugar yields, depending on the region, from a 30% reduction in N rates relative to 6ES recommended rates. The results and conclusions of this study were based on a single statistical relationship between N fertiliser application and sugarcane yield for each district, derived from an amalgamation of results from trials (7 to 16) conducted in each region.

However, reducing applications of N fertiliser below those recommended from 6ES does not always reduce productivity. The experimental studies of Webster et al. (2012) and Wang and Reeves (2020), and the modelling study of Thorburn et al. (2011b) reported no adverse production effect from reducing N fertiliser applications by up to 40% from the 6ES recommendations.

Other studies have also reported mixed effects on productivity from reducing N rates below those coming from 6ES recommendations. A group of studies were undertaken to evaluate an alternative, the “N replacement system” (Thorburn et al., 2011b), to the 6ES recommendation system. N replacement aims to ensure that the fertiliser N applied to a crop matches the N removed by the previous crop, matching the plant needs, and generally results in lower N applications than 6ES. Cane and sugar yields with N replacement were found not to be significantly different from the farmers‘ conventional N rates in each of 10 field experiments at sites spanning the GBR catchments conducted over 3 to 5 years (Thorburn et al., 2011b; Webster et al., 2012). The N applications with N replacement averaged 72 kg ha^{-1} less than the farmers‘ conventional N rates and 25 kg ha^{-1} less than 6ES recommendations for the experiments. Further, sugar and cane yields increased with N replacement relative to conventional farmer N rates in the third and subsequent crops, potentially due to crops responding physiologically to the variable rather than constant N fertiliser application. Cane and sugar yields with N replacement were also found to not be significantly different from 6ES N rates in two experiments on poorly-drained soils in the Tully region (Skocaj et al., 2012; Table 7) with a 64 kg ha^{-1} reduction in N applied. A modelling study in Mackay (Biggs et al., 2013) also found no difference in yield between the N replacement and 6ES. However, productivity with the N replacement has been found to be lower than with 6ES N rates in some field and modelling studies. Productivity was significantly lower than with 6ES N rates at two experiments on well-drained soils in the Tully region (Skocaj et al., 2012; Table 7), although there was 64 kg ha^{-1} less N applied in the N replacement treatments than 6ES. van Grieken et al. (2014) also found lower productivity with N replacement than 6ES in a mechanistic modelling study across the Wet

Tropics, Mackay Whitsunday and Burdekin. Similar results were reported by Schroeder et al. (2009) based on a statistical model of sugarcane N responses over multiple crops in two experiments, one each in the Herbert and Tully regions. The soil at the Tully experiment was poorly drained, so the modelled outcomes contrast the experimental results of Skocaj et al. (2012). As described above, yields with N replacement may increase relative to conventional N applications through successive crops (Thorburn et al., 2011b). This physiological response is not captured in modelling studies (Biggs et al., 2013; Schroeder et al., 2009; van Grieken et al., 2014).

Some of the variation in results discussed in this section will have arisen because of the effects of climate on sugarcane growth, N uptake and N losses from soils (Thorburn et al., 2018). Biggs et al. (2021) undertook a modelling study to quantify the extent to which optimum N application rates for sugarcane ratoon crops grown in the Tully region varied between years (in response to climatic variation), across soils and harvest times (early-, mid- and late-season harvest). The median optimum N fertiliser rate across the soils simulated was 47% lower than the median N rate from the 6ES for the soils, which resulted in a 1.8% reduction in cane yield (and a 59% reduction to DIN lost to the environment). Generally, median yields simulated at optimum N rate in wet years were lower than that in dry years for the mid and late growing seasons although the interactions between climate, soils and harvest times made optimum N rates almost field-specific. While this study did not develop a new method of recommending optimum N rates for sugarcane crops, it illustrated the potential benefit that could result from a more site and climate specific approach to N fertiliser management in sugarcane.

Phosphorus

There were no studies on the specific effect of P fertiliser applications on crop productivity. In the studies on P applications, the rate of P was varied in concert with other nutrients (N, potassium (K), sulphate) so the specific effect of P could not be determined.

Costs, cost-effectiveness and profitability

Nitrogen

Out of all nutrient management practices (e.g., placement and timing) reviewed by Collier et al. (2015), changing nutrient application rates was identified as the key driver of farm profitability, provided the change doesn't involve additional expenditure on capital or an increase in other business expenses, such as labour (Collier et al., 2015). The importance of nutrient application rates to profitability results in the majority of studies being on that management practice.

The profitability of applying different rates of N was determined in the large study on sugarcane crops in the Burdekin region (Connellan et al., 2017) described in the previous section. One of the two 6ES treatments had the highest profitability in 86% of the individual harvested crops studied. More importantly, across all sites and crops the two 6ES treatments had the highest mean profitability.

Wang and Reeves (2020) conducted six experiments (located in the Innisfail, Tully, Herbert [2 sites], Mackay and Bundaberg regions) over three sugarcane ratoon cane crops. The trials included treatments with urea-N applied at rates 25% above and below 6ES guidelines, although rates were varied by +/- 40% of 6ES at Innisfail, Tully, Herbert, Mackay and Bundaberg in one of the three seasons[13]. Generally, gross margins in the different treatments were not significantly different. However, there were some exceptions. The gross margin of the high N rate treatment was significantly greater than both the 6ES and lower N rate treatment at the one site (Lannercost) in the Herbert in one season. The gross margin of the lower N rate treatment was also significantly greater than the 6ES treatment and similar to the high N rate treatment at the second (Lilypond) site in the Herbert in one season.

In another multi-site study, Harvey et al. (2016) reviewed grower partial net returns from 23 sugarcane nutrient rate strip trials that compared the results of 6ES treatments with: 1) growers' conventional N

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[13] The study also evaluated treatments from the replicated randomised trials with enhanced efficiency fertilisers (not addressed in this section). For details, please refer to Wang and Reeves (2020) (Figure 17). The authors of this review were unable to ascertain from the study whether the reported gross margins are based solely on trial operations (or also on example parameters from Farm Economic Analysis Tool scenarios).

applications; 2) rates from a traditional recommendation system (superseded by 6ES); and/or 3) N replacement treatments. The actual rates applied in the treatments were not reported by Harvey et al. (2016); however, the N rates for treatment (1) and (2) were most likely higher than 6ES rates, and most likely lower in treatment (3). For the majority (20 of 25) of trials with grower and/or traditional treatments, average grower partial net returns were higher for the 6ES treatments than the grower/traditional treatments. The exceptions were located in the Wet Tropics, being two of nine sites in the Johnstone (Brosnan and Mundoo) and three of four sites in the Tully (Murray, Euramo, Riversdale) region.

Eight of the trials reviewed by Harvey et al. (2016) included both N replacement and 6ES treatments. Average grower partial net returns were higher for the 6ES than N replacement treatments, although the difference was negligible (\$3 ha^{-1}) at one site in the Burdekin. There are two notable points about the results from four of these trials. In two (the Macknade trial in the Herbert and Tully 1 in Tully), the N replacement treatments were not actually implemented (Schroeder et al., 2009) and the results came from statistical modelling. As noted above, yields with N replacement may increase relative to conventional N applications through successive crops (Thorburn et al., 2011b) and this response is not captured in modelling studies. Another point is that both grower and industry partial economic returns were previously calculated by Skocaj et al. (2012) for four of the trials. In two of these trials (Murray and Euramo), Skocaj et al. (2012) found there was no significant difference in average economic returns between the 6ES and N replacement treatments. The difference in results could be due to differences in income (i.e., sugar price) and costs (e.g., fertilising, harvesting) used by Skocaj et al. (2012) and Harvey et al. (2016); however, these data were not given by Harvey et al. (2016).

Results from a statistical modelling study of sugarcane production (Canegrowers, 2020) indicate that N application rates below those recommended from 6ES guidelines, could reduce the profitability of farms and mills, and reduce the economic value of sugarcane industry to regional communities and to Queensland (Canegrowers, 2020). Further, blanket applications of N rates below those recommended by 6ES would reduce farm incomes. For example, a 30% reduction (the maximum considered in the study) in N rates from 6ES rate was predicted to reduce crop partial net returns by \$142 to \$266 ha^{-1} depending on the district.

There have also been mechanistic bioeconomic modelling of outcomes of various N management practices for sugarcane production. van Grieken et al. (2014) modelled small, medium and large sugarcane farms in the Wet Tropics, Mackay Whitsunday and Burdekin (BRIA and Delta) regions. Scenarios that included N rates based on the 6ES method produced the higher gross margins than scenarios based on: 1) N replacement method; or 2) N rates based on previous industry recommended rates (with N rates higher than the 6ES method)[14]. Other practice changes relating to fallow management, N application management, N application method, and tillage management were analysed and van Grieken et al. (2014) note that:

> "*…for the combinations of practices analysed in this research, a more targeted nutrient management strategy may prove to have the best cost-effectiveness in improving water quality. The extent to which this affects both financial and environmental outcomes varies between regions, soil types and farm sizes and current management systems.*"

Economic and environmental results indicated that:

- Changing applied nutrient rates from those based on old industry recommendations to those based on the 6ES method provided both economic and overall water quality benefits (in terms of total DIN reduction related to runoff and leaching based on farm gate paddock estimates); and
- While changing nutrient rates from those based on the 6ES method to those based on the N replacement method provided water quality improvements in the Wet Tropics and Mackay

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[14] Specifically the three application rate management scenarios included: AA) Variable rates between blocks (based on N Replacement theory). Calibrates once per season for each fertiliser product; AB) Variable rates between blocks (based on 6ES). Calibrates once per season for each fertiliser product; AC) One rate for plant and another for ratoons based on soil type (based on Old Industry recommendations). Calibration is less than once per season.

> Whitsunday regions and, with limited cases in the Burdekin, such changes resulted in lower gross margins, meaning that the changes came at a cost to farmers.

A management practice that can affect nutrient application rates and profitability of crop production is varying nutrient application rates between management zones. In a study on sugarcane production in the Mackay Whitsunday region, Rust and Law (2016) found variable rate application (VRA) technology may reduce growing costs if linked to a reduction in fertiliser costs, but involves additional costs related to the purchase of a variable rate controller, electrical conductivity (EC) mapping and agronomic advice (Rust & Law, 2016). Rust et al. (2017) note that the long-term yield implications of zonal management systems with VRA are not well established for that region. An investment analysis was completed based on an assumption that there was no long-term change in yield as a result of switching to the VRA system[15]. After the capital outlay required for the system was accounted for, it was found that the VRA system reduced the profitability of the overall farming enterprise.

There were few economic studies for crops other than sugarcane that met the inclusion criteria for this review. Bioeconomic modelling has been undertaken on the impacts of various practice changes on costs and water quality in banana crops for two representative soil types (Dermosols and Ferrosols) and three representative farm sizes (Holligan et al., 2017). The study considered various practice changes relating to crop removal, tillage, ground cover, water control structures, nutrient rates, nutrient application and irrigation. The water quality modelling results found that for the practice changes considered, reducing fertiliser rates was the single most important driver of DIN abatement and resulted in substantial economic benefits (if yields did not decrease). For the Ferrosol soils for example, there was up to 32.2 kg N ha^{-1} yr^{-1} reduction in DIN discharge if N applications were reduced from 450 to 250 kg yr^{-1}, which accounted for 88% of total DIN reduction. Both Holligan et al. (2017) and Harvey et al. (2018) noted that there has been insufficient field research on the effect of various practice changes modelled for banana production to accurately define the production implications for some of the modelled changes. As a result, the economic modelling assumed there were no yield impacts of the practice changes adoption, although it was established that the results are sensitive to changes in yields.

Holligan et al. (2017) also considered changes in applied N rates to bananas in the context of broader nutrient management practice changes. For example, reducing N rates from 450 to 350 kg yr^{-1} applied as granular fertiliser, increasing the frequency of fertiliser applications, and increasing soil testing (together described as a shift from D to C category) had the most positive impact on gross margins on both soils at all farm sizes. A further change that included applying 250 kg N yr^{-1}, additional soil testing and applying N through irrigation (rather than granular fertiliser) for 9 months/year (described as a shift from C to B category) was not as profitable. Holligan et al. (2017) note that some aspects of the nutrient management changes (e.g., applying N through irrigation) were not able to be represented in the water quality model.

Milbank and Nothard (2023) undertook a review of the economic case studies available for various other horticultural crops in Queensland (e.g., perennial crops, pineapples, continuous supply crops and mulched crops), although intensive horticulture/protected cropping was not included. No economic studies were found that “both identify and address barriers to change and practice improvement” relevant to applied N fertiliser rates and water quality impacts.

Long term modelling, across 116 years, was undertaken by Kodur et al. (2019) to explore the interactions of salinity management and other factors on nitrogen leaching for irrigated cotton crops on Vertosol soils on the Darling Downs. While the Darling Downs is beyond the GBR catchment area, this study is mentioned for completeness. Alongside environmental indicators, this work considered net revenues from crops as an economic indicator for an initial scenario with an applied N fertiliser rate of 250 kg ha^{-1}, and a second scenario with a reduced N fertiliser rate of 225 kg ha^{-1} (to minimise N leaching). Results were modelled for various soil conditions, and two irrigation salinity levels. In comparison with the initial scenario, the reduced N rate scenario showed a decrease in net returns

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[15] While Rust et al. (2017) conclude that the VRA system had the capacity to reduce overall nutrient application on the trial farm by 14 percent, associated sugar yields for the base scenario are not reported.

across all irrigation salinity and soil conditions and that reductions in drainage and N leaching were negligible or marginal (<1% for drainage and <3% for N leaching). In a separate paper, Maraseni and Kodur (2019) report on the effect of applied N fertiliser rates, from 0 to 350 kg ha^{-1}, initial soil nitrate N levels and rainfall conditions on financial returns for cotton crops. Results showed that optimising N fertiliser rates to soil N and rainfall conditions increased annual returns by up to \$303 ha^{-1}. Maraseni and Kodur (2019) conclude that these findings suggest that N fertiliser application rates need further refinements specific to prevailing soil and climate variabilities.

While the above discussion has focused on N applied to crops as fertilisers, there have been demonstration trials on how N rates may be refined to account for organic sources of N. Despite most results showing improved or maintained gross margins for refined N rates, there were no significant differences (Nothard & Pfumayaramba, 2021; Pfumayaramba et al., 2022). Pfumayaramba et al. (2022) note that longer-term trials and increased replication across a wider variety of sites are needed to validate refined N management and improve confidence in the results.

Phosphorus

There were no studies on the specific effect of P fertiliser applications on profitability of crop production. In the studies on P applications, the rate of P was varied in concert with other nutrients (N, potassium, sulphate) so the specific effect of P could not be determined.

Fertiliser timing

Dissolved nutrient discharge

Nitrogen

For sugarcane, most research relevant to fertiliser "timing" investigates the effect of the "date" in the year on which fertiliser is applied. Sugarcane is a perennial crop that is harvested and allowed to regrow (or ratoon). In Australia, the crop can be planted in many months of the year and the harvest "season" is generally between June and December. Thus crops can start growing, and subsequently get fertilised over a wide range of times. There is evidence from modelling studies, both mechanistic (Verburg et al., 2017; 2018; 2022; Webster et al., 2022) and empirical (Fraser et al., 2017) that DIN discharged over a whole crop in runoff or **total** DIN losses (sum of losses via runoff, leaching and denitrification) tend to increase when ratoon sugarcane crops are harvested (and thus fertilised) later in the year. Further, there can be an interaction between timing of fertilisation and N rate on DIN losses. Reducing N rate in late harvested crops reduced **total** DIN losses to a greater extent in late than mid-season or early harvested ratoon crops (Biggs et al., 2021; Webster et al., 2022).

Other mechanistic modelling studies considered the effect of timing on long-term average DIN discharged over multiple crop cycles (a crop cycle being a plant crop plus several ratoon crops). When simulations were run with N fertiliser applied in mid to late September, DIN losses through leaching plus denitrification were lower than when N was applied in mid to late November (Migliorati et al., 2021). In another study, DIN discharged in runoff was higher in simulations of crop cycles with a late (August) planting date than early (May) (Vilas et al., 2022). The reasons for the effect of planting date are not clear. It could have arisen because the N was applied later in the year in the later planted crop cycles or because length of the plant crop was different in the two scenarios, presumably shorter for late plant.

Other studies have focused on the length of time between when the crop starts growing (either the date planted or harvested) and when the fertiliser is applied, which can commonly vary from 1 to approximately 40 days. It can be hard to draw definitive conclusions from experiments on this aspect of fertiliser timing because of year-to-year variability in weather and thus the timing of runoff relative to the fertiliser application date (Bell et al., 2021).

Another way to affect the timing of fertiliser application is splitting the application of N across multiple (commonly two) times rather than applying it all on a single occasion. In mechanistic modelling studies, splitting has had little to no effect on the amount of DIN leached (Verburg et al., 1998; Stewart et al., 2006) or DIN losses through leaching plus denitrification (Thorburn et al., 2011c).

The effect of timing N fertiliser applications to sugarcane crops has also been studied in the context of when to apply EEFs as described below.

As described above, Holligan et al. (2017) examined impacts of various practice changes on costs and water quality in banana crops in a mechanistic modelling study. However, the changes included crop removal, tillage, ground cover, water control structures, nutrient rates, nutrient application and irrigation. Some of these affect timing of fertiliser application, e.g., increasing the frequency of N applications by applying N through irrigation rather than as a granular fertiliser. Therefore, the water quality effects of timing could not be isolated from other practices.

No published studies were found on the effect of fertiliser timing for crops other than sugarcane.

Phosphorus

No relevant published studies were identified in the review process.

Productivity outcomes

Nitrogen

There were no significant effects of applying N at 14 or 70 days after planting or harvesting over three sugarcane crops at Mackay (Salter & Kok, 2023). However, there was a non-significant trend for high sugarcane yields with early application. In another experiment at Bundaberg, there were no significant effects of applying 120 kg N ha^{-1} at one time, or that total amount split over three or four application times (Panitz & Schroeder, 2020). The result was the same when applying 120 kg N ha^{-1} or 160 kg N ha^{-1}.

Phosphorus

No relevant published studies were identified in the review process.

Costs, cost-effectiveness and profitability

Nitrogen

There is limited research on the impact of N fertiliser timing on farm economic outcomes. In an experimental study on “typical” Bundaberg sugarcane farm and soil, split applications of urea generally resulted in lower partial net returns (NRs) compared to the standard urea treatment applied at a rate of 120 kg N ha^{-1} in a single application in each of four seasons (plant to 3rd ratoon) (Panitz & Schroeder, 2020).

Phosphorus

No relevant published studies were identified in the review process.

Inorganic fertiliser form and enhanced efficiency fertilisers (Q4.6.1)

There have been a wide range of experiments investigating the potential production and, to a much lesser extent, environmental benefits of enhanced efficiency fertilisers (EEF) in GBR catchments (Verburg et al., 2014; 2016). The effects of EEF on both productivity and losses of dissolved nutrients occur through a number of processes. Nitrate is the mobile form of N in soils (and the main constituent of DIN) that can most easily be discharged from the soil in runoff or leaching. It is also the form of N most susceptible to emitting nitrous oxide (N_2O) during denitrification. EEF act through keeping nitrate concentrations lower in soils for a period of time following application of N and thus “protecting” the fertiliser N from loss. EEF provide this protection through one of two mechanisms, either via inhibiting the conversion of ammonium-N to nitrate (nitrification inhibitor [NI] products) or slowing the release of N from fertiliser pellets (controlled-release products). Different EEFs affect inhibition or release for different lengths of time. Reduced N loss can potentially improve productivity or maintain productivity at lower N application rates (Verburg et al., 2014; Wang et al., 2016b; Wang & Reeves, 2020), and thus improve the fertiliser N use efficiency (NUE).

Dissolved nutrient discharge

Nitrogen

In a 3-year study with unreplicated treatments at two sites, there were small reductions in DIN discharge in runoff from sugarcane with a blend of urea-N (33%) and a nitrification inhibitor (DMPP, 67%) compared with urea-N at one site and variable effects (decreases and increases) at the other (Bell et al., 2021). Connellan et al. (2022b) found significantly higher DIN concentrations at 1 m depth in soils (averaged over multiple years and in-crop sampling times) when the urea-N (33%) DMPP (67%) was applied instead of urea-N at the same application rate averaged over four sugarcane trials in the Wet Tropics; however, they found no significant differences across another two trials in the Burdekin. They also measured DIN concentrations in runoff from these six sites. The relative DIN concentrations in the EEF blend and urea-N treatments (with the same N application rate) were variable across runoff sampling times and sites. From these results Connellan et al. (2022b) conclude that use of EEF would improve “water quality”. However, the water quality implications of soil and runoff DIN concentration results are unclear because DIN **concentrations** do not necessarily relate to **loads** of DIN (i.e., kg DIN ha^{-1}) discharged, and loads are of primary importance to GBR ecosystems.

Glasshouse studies testing the effect of controlled-release fertilisers (CRF) and nitrification inhibitors relative to urea-N found a reduction in nitrate leached from the soil for the CRF but not for the nitrification inhibitors, despite lower soil nitrate concentrations (Di Bella et al., 2017; 2019). Incomplete capture of all nitrate leached may have contributed to this result. Other studies considering DIN loss focused on N_2O emissions (Di Bella et al., 2014; Wang et al., 2016a; 2016b; 2016c) and obtained variable results with both increases and decreases as a consequence of EEF use.

Mechanistic modelling studies have confirmed there is an opportunity for EEF use to reduce **total** DIN loss (combined loss via leaching, denitrification and runoff) from sugarcane cropping relative to urea-N (Migliorati et al., 2021; Verburg et al., 2017; 2018; 2022; Webster et al., 2022). In these studies, the potential to reduce total DIN loss was greater in later-harvested crops compared with early- and mid-season ratoon crops. For early and mid-season ratoon crops, the reduction in total DIN losses were generally small or negligible with the exception of crops simulated in the wettest regions of the Wet Tropics (e.g., Babinda, South Johnstone, North Tully) where EEF could reduce total DIN losses relative to urea-N (Webster et al., 2022). In all situations however, the effect of EEF on total DIN loss reductions varied considerably from year to year.

While these previous studies focus on total DIN loss from sugarcane, there have been investigations of the effects of EEF on DIN lost in runoff. In a simulation study, the DIN lost in runoff was generally a small proportion (<5%; Webster et al., 2022) of total DIN lost and the effect of EEF on DIN discharged in runoff was inconsistent (both decreases and increases). This inconsistency has also been seen in experimental observations (Webster et al., 2022). Increases in DIN discharged in runoff happened when higher DIN concentrations in the soil (e.g., due to later release or delayed transformation from ammonium to nitrate) coincided with runoff events. In the simulations, only at sites with poorly drained soils in the wettest region considered (Babinda) that had a larger percentage of DIN lost via runoff was the net result of EEF a consistent reduction in DIN discharged in runoff. Reductions in N loss via leaching or denitrification were more consistent, likely due to the larger amounts of DIN lost via these pathways.

There is little information on the effect of EEF on N losses for crops other than sugarcane grown in the GBR. In cotton, Scheer et al. (2022) reported reduced **total** DIN losses (i.e., sum of losses via runoff, leaching and denitrification) from use of EEF (DMPP) compared with urea-N at the same application rate in a study on the Darling Downs using ^{15}N tracing. While this study was located outside GBR catchments, the results are likely to have relevance to cotton production within some areas within GBR catchments, such as central Queensland where soils and climate are reasonably similar.

Phosphorus

Most of the product development on EEF has focused on N. Some controlled release forms of P fertiliser are available (e.g., combined N, P, K), however, no published were found on these products in GBR catchments.

Productivity outcomes - sugarcane

Nitrogen

While EEFs can reduce N loss via both denitrification and leaching, this does not always translate into yield increases (Verburg et al., 2018). Indeed, experimental studies have shown variable yield responses to EEF use, both across studies (Verburg et al., 2014; 2016) and within studies (Connellan et al., 2022a; 2022b; Dowie et al., 2019).

Significant sugarcane yield responses were reported by Di Bella et al. (2013; 2014) for trials in the Herbert region in the first two months following application of the CRF. However, trials with blends of urea and CRF in the Herbert, Burdekin and Mackay regions (Di Bella et al., 2014) did not demonstrate consistent treatment effects. Dowie et al. (2019) obtained statistically significant positive responses for the use of CRF for sandy soils and for late harvested crops. There were no significant differences for other soils by crop harvest timing combinations, or the use of a nitrification inhibitor.

Connellan et al. (2022a; 2022b) examined the effect of applying either various EEF formulas (mainly blends of a nitrification inhibitor and CRF) or urea-N to sugarcane crops at 20% below the 6ES rate compared with urea-N at the 6ES rate in 54 trials. The EEF provided some mitigation of the cane yield loss in the reduced rate urea-N treatment. Although the effect of the EEF at the reduced rate was often not significant, there was a clear trend to reduce the yield loss to the extent that there was no significant difference with 6ES anymore particularly for lighter soils in wet seasons. Modelling studies by Webster et al. (2022) and Migliorati et al. (2021) showed the same effects, albeit with larger yield reductions modelled in the latter study which had highly N responsive crops, that also differed markedly in yield between crops harvested in September and November.

Other experimental studies reported no yield benefit in using EEF products compared to conventional fertiliser treatments, applied N rate, split application, in either the sugarcane plant or ratoon crops (Bell et al., 2019; Panitz et al., 2019; Panitz & Schroeder, 2020; Rust & Law, 2016; Wang et al., 2016a; Wang & Reeves, 2020). Verburg et al. (2016) also list several other sugarcane trials, published in the “grey literature”, that failed to obtain statistically significant effects, except for one meta-analysis combining the results of different studies. As well as not showing yield responses, some of these studies did not find that the recovery of N by the crop was improved (e.g., Bell et al., 2021; Wang & Reeves, 2020).

A study modelling sugarcane crops in the Wet Tropics (Tully) confirmed a potential for increased cane yields with the application of CRF for longer season plant crops (Verburg et al., 2017). The cane yield increases were mainly seen at the lower N application rates and demonstrated strong seasonal variability. Maintaining yields at lower N rates, rather than increased yields, was the most common production benefit of using CRF, but the magnitude of the reduction was affected by climate, soil type, timing and seasonality variable (Verburg et al., 2017).

Framework for evaluating likely benefits to water quality and production from the use of enhanced-efficiency fertilisers

The variability in results of experimental and modelling studies for sugarcane in GBR catchments, and indeed crops grown elsewhere (Verburg et al., 2014; 2016; 2022), is not unexpected given the complex factors that determine the effects of EEF. This complexity is explained in a framework that outlines three prerequisite conditions for getting benefits from EEF (Verburg et al., 2022):

1. Sufficient longevity of protection of the fertiliser N.
2. Occurrence of an N loss event during this period of protection and before the N is taken up by the crop.
3. The crop being responsive to the fertiliser N.

To provide reductions in DIN loss, EEF products need to “protect” the fertiliser N (i.e., keeping it in a form other than nitrate) for a sufficiently long duration. Several studies have confirmed that the EEF affects soil nitrate dynamics (Bell et al., 2021; Wang et al., 2016b; Wang & Reeves, 2020,) and provides such protection for some weeks or months. There also needs to be an N loss “event” during this protection period. Thus, the benefits of EEF are affected by **both** the characteristics of the EEF product and weather following application of the fertiliser. This explains the variability in N loss reductions achieved when EEF were used instead of urea-N in the modelling and experimental studies described above, including different effects between early and late ratoon crops and wetter and drier regions. There is more chance of an N loss event in the weeks after fertilisation for late ratoon crops and in wetter regions, hence more opportunity for the EEF to reduce N loss. Although this does not happen every year (as experienced in the study by Bell et al., 2021), the likelihood is higher. Lack of an N loss event during the protection period (e.g., dry weather in the weeks/months following fertiliser application) is also a common reason quoted in relation to individual experiments not showing statistically significant treatment yield effects. The third prerequisite relates to the response of the crop to the extra N made available on account of reduced N loss – does the additional N available allow growth to increase? Crop growth not being responsive to N at the tested N rates is another common reason why experiments do not show statistically significant yield responses.

The magnitude of the EEF effect compared with the variability in measurements is another contributing factor. When results from experiments have been incorporated into combined statistical analysis (e.g., Connellan et al., 2022a; Dowie et al., 2019) small yield benefits of EEF may become identifiable for some soils/conditions.

Phosphorus

No relevant published studies were identified in the review process.

Productivity outcomes – other crops

Nitrogen

There is little information on the effect of EEF on production of crops other than sugarcane grown in the GBR. There was no effect reported on yields in grain crops in a study by Hussein et al. (2018). Scheer et al. (2022) found no significant effect on cotton lint yield from different fertiliser application rates and EEF products. In perennial crops, the usage of CRF could considerably increase the yield while reducing fertiliser application rates. For example, a higher N application rate of CRF in macadamia nut trees produced statistically significantly higher gross yields compared to the control treatment at 16.9% and 33.4% respectively and increased grower incomes (Achilea et al., 2010).

Phosphorus

No relevant published studies were identified in the review process.

Costs, cost-effectiveness and profitability

Nitrogen

Field trials/modelling research produced mixed results in sugarcane crops as both environmental and economic benefits of EEF were highly variable and condition specific (Di Bella et al., 2014; Kandulu et al., 2017). Economic findings can also vary depending on the treatments/scenarios compared, as cost differences are driven by the type of EEF applied, whether it is blended with other products (like urea-N) and the rates of nutrients applied. Revenues depend on factors impacting production outcomes, such as the growing conditions experienced for a particular trial (e.g., rainfall, soil type and the timing of fertiliser application).

Panitz et al. (2019) and Panitz and Schroeder (2020) conducted a study on two EEFs, a nitrification inhibitor (NI) and a CRF, and compared with urea-N for irrigated sugarcane in the Burnett Mary region. Urea-N applied at 120 kg ha^{-1} (called the “standard treatment”) had the greatest mean net return for a whole crop cycle (plant crop and three ratoon crops) (Panitz & Schroeder, 2020). The mean net returns for the NI applied at rates of 120 and 160 kg N ha^{-1} were \$206 ha^{-1} and \$2,016 ha^{-1} less than the standard treatment, respectively. The mean net returns for the CRF applied at rates of 120 and 160 kg N ha^{-1} were \$428 ha^{-1} and \$645 ha^{-1} less than the standard treatment, respectively. Within a randomised block field trial in the Bundaberg and a supporting short-term pot experiment, Panitz et al. (2019) found that partial net returns for two crops were higher with no N fertiliser applied than with an EEF applied.

Wang and Reeves (2020) conducted a range of experiments (located in the Innisfail, Tully, Herbert [2 sites], Mackay and Bundaberg regions) comparing various NI and CRF with urea-N over three crops, with N applied at rates from 6ES recommendations and 25% or 40% below the 6ES rate (40% at Innisfail, Tully, Mackay and Bundaberg in one of the three ratoon crops studied). Compared to the urea-N at the 6ES rate, the gross margins for NI treatments were:

- Significantly greater at a site (Innisfail) in the Wet Tropics, for the NI treatment compared to the 6ES N rates, for the 2017-2018 season.
- Significantly less at a site (Lannercost) in the Herbert district for NI treatments compared to the 6ES N rates and lower N rates, for the 2017-2018 season.
- Not significantly different in all other instances for each season.

Compared to the urea-N at the 6ES rate, the gross margins CRF treatments were:

- Significantly greater than the conventional urea 6ES treatment at Innisfail for the 25% CRF blend at the 6ES N rate, for the 2017-2018 season.
- Significantly less than the conventional urea 6ES treatment at Lannercost for: a) the 75% CRF blend at the 6ES N rate; and b) for all CRF treatments (25%, 50%, 75% CRF blends) at lower N rates, for the 2017-2018 season.
- Significantly less than the conventional urea 6ES treatment at Lilypond (Herbert, Wet Tropics) for the 50% CRF blend at the lower N rate, for the 2018-2019 season.
- Significantly less than the conventional urea 6ES treatment at Bundaberg (Burnett Mary) for the 50% CRF blend at the lower N rate, for the 2018-2019 season.
- Significantly less than the conventional urea 6ES treatment at Mackay for the 25% and 75% CRF blends at the 6ES N rate, and for the 25% and 50% CRF blends for the 2018-2019 season.
- Not significantly different in all other instances for each season.

Gross margins for other comparisons were not significantly different. Wang and Reeves (2020) noted that no individual EEF treatments consistently produced significantly higher or lower gross margins compared to conventional urea at the 6ES N rate (as in, for all seasons).

Dowie et al. (2019) examined the economic performance of EEF (both CRF and NI) in the Burdekin region, based on analyses of the results from 12 trials on furrow irrigated sugarcane with three ratoon crops, harvested over three seasons and covering a range of sugarcane ratoon crops (first, second, third or fourth). The sites were organised into two groups. Group A (nine trial sites with three each on sand, loam and clay soils) included treatments with urea applied at a 220 kg N ha^{-1} (described as the ‘conventional’ N rate), and treatments with product applied at 40 kg lower N rates (180 kg N ha^{-1}) including urea, an NI (DMPP coated urea), a 25% CRF blend (with 25% polymer-coated urea and the remainder as urea) and a 50% CRF blend. Group B (three trial sites with one each on sand, loam and clay soils had the same treatments but with a lower N rate of 160 kg ha^{-1}. Fertilisers were also applied at different times over the season to determine if these factors influence fertiliser efficacy and sugarcane cultivars also varied. Gross margins for the 180 kg N ha^{-1} treatment applied as blend of 50% CRF-50% urea-N (in Group A) were significantly lower than urea-N applied at 180 of 220 kg ha^{-1}, or an NI applied at 180 kg ha^{-1}. Gross margins for urea-N at both rates of the NI treatment were not significantly different. At the other three sites (Group B) gross margins for most of the different treatments were not significantly different. Dowie et al. (2019) noted that the treatment effects varied for different cultivar and soil type combinations.

Additional work evaluating the economic outcomes of EEF products in sugarcane has been completed by Connellan et al. (2022a; 2022b), who conducted field trials on multiple sugarcane farms, spread across all regions of the GBR catchment area. At each site, treatments included N applied as urea-N at the 6ES rate and N applied at 80% of the 6ES rates as urea or a blend of one third NI and two thirds CRF. There was a fourth treatment at each site, which was a different EEF applied at 80% of 6ES rates. The EEF in this fourth treatment was either NI, a blend of 20% CRF/80% urea, or some other EEF. Compared to urea applied at 6ES N rates, grower net revenues were:

- Significantly higher for urea-N applied at 80% of 6ES in low rainfall conditions.
- Similar for the NI and CRF blends (20% CRF/ 80% urea), 80% of 6ES and urea applied at 6ES.

- Lower for EEF blends with high proportions of CRF than urea applied at 6ES N rates.

There was a trend for EEFs to be more profitable in situations of potentially high N losses (e.g., sandy soil, high rainfall, late in season). Connellan et al. (2022b) noted that results from these trials did not include the economic effects of reduced yields on sugarcane mill profitability.

Di Bella et al. (2014) evaluated the results of sugarcane strip trials with CRF treatments in the Herbert (Wet Tropics) and Burdekin regions. Driven by increases in cane and sugar yields, net returns were higher for the CRF treatments (in instances where 15% to 40% of N was applied the CRF form). In contrast to the generally infrequent occurrence of significant differences in profitability of N applied as EEF compared with urea in the Burdekin trials conducted by Connellan et al. (2022a; 2022b), Di Bella et al. (2014) found that farm net returns were increased due to productivity increases, where between 15% and 40% of the N was applied as CRF in experiments in both the Burdekin and Herbert regions.

Kandulu et al. (2017) undertook economic modelling of N applied to sugarcane as CRF and urea across the Wet Tropics. The difference in the cost of EEF and urea was a key determinant of farm profitability from CRF adoption (Kandulu et al., 2017). Economic benefits of CRF varied depending on climatic conditions. If relative costs of EEF drop in the future, either because of increased scale of production or improved manufacturing processes, the economic benefits of EEF use may increase (Kandulu et al., 2017).

Limited published economic studies examining the effect of EEFs in other crops were identified through the literature review. In grain sorghum crops, NI resulted in lower gross margins with urea-N compared with urea-ammonium-nitrate (UAN) applied at an equivalent N rate (Hussein et al., 2018). Those differences were due to the higher cost of the NI. In macadamia nut orchards, higher N application rates of CRF increased grower incomes compared with conventional form and rate of N (Achilea et al., 2010).

Using EEFs in grain crops produced lower gross margins compared to gross margins if urea or urea ammonium nitrate (UAN) were applied to grains. Those differences were due to differences in the cost of fertiliser N, particularly for ENTEC® (Hussein et al. 2018). Higher N application rates of EEFs (CRF) in the macadamia nut trees compared to control treatments increased grower incomes (Achilea et al., 2010).

Phosphorus

No relevant published studies were identified in the review process.

Mill mud and other organic amendments (Q4.6.2)

All the studies on the effects of mill mud on dissolved N and P discharges have been conducted in sugarcane, and no information is available for other crops. The application of mill mud to fallow and ratoons in the sugar industry is a source of N, P, K, sulphur (S), calcium and some micronutrients (Rust & Law, 2016). While mill mud is often blended with ash from the mill and applied as mill mud-ash mixtures, the papers reviewed only reported the application of mill mud.

Dissolved nutrient discharge

Nitrogen

The main empirical information on the effect of mill mud (MM) on DIN discharges comes from an experiment conducted over two crops in the Mackay region (Donaldson & Rohde, 2022). The results show that the application of MM did not have a dramatic effect on DIN discharged in runoff. More specifically, the application of MM did not increase DIN discharges compared with the treatment with no N fertiliser. Applying MM in addition to the conventional rate of N fertiliser (130 kg ha^{-1}) had an inconsistent effect on DIN discharges compared with the application of only N fertiliser, being higher in one year and similar in the other. Applying MM and a reduced rate of N fertiliser (53 kg ha^{-1}) to account for N in MM reduced DIN discharges in comparison with MM plus the conventional N rate, but had an inconsistent outcome compared with the conventional rate N only.

Another empirical study took an alternative approach to assessing the effect of MM application on DIN losses. Thorburn et al. (2022) developed an index – the Nitrogen Loss Risk Index (NiLRI) – to quantify the risk of nitrogen losses for different management practices. NiLRI is related to the N surplus, which is correlated with DIN discharges from GBR catchments (Thorburn & Wilkinson, 2013). NiLRI values were determined for 170,177 ha of cane lands using information reported by sugarcane farmers in Paddock-to-Reef (P2R) evaluation surveys. Those values were then associated with management practices reported in the surveys. Aspects of MM management were the eighth most important of 13 influential variables determining NiLRI values in ratoon and plant cane, meaning the effect of MM management was relatively weak.

There have been two mechanistic modelling studies of the effect of MM on DIN discharges. One study (Vilas et al., 2022) extrapolated the results of Donaldson and Rohde (2022), reporting outputs of long term (70 year) simulations for their site under different MM management. Vilas et al. (2022) found DIN discharged in runoff (average over 70 years) decreased linearly compared with constant N fertiliser applied (630 kg ha^{-1} per crop cycle) as MM applied at the start of the fallow was reduced from 150 to 0 t ha^{-1}. Power et al. (2021) used the model of Vilas et al. (2022) for a broader study of MM management at three sites, one in each of Mackay, the Burdekin and Tully. Similar to Vilas et al. (2022), Power et al. (2021) found DIN discharged by runoff or leaching decreased linearly with decreasing mill mud applications at all three sites. In these modelling studies, the effect of MM was stronger than observed in the field by Donaldson and Rohde (2022), despite the fact that the model used was developed on the data from that field study. The difference in result may have been caused by the difference in timescales – two years in the field study and 70 in the simulation study – with the longer time perhaps reflecting more average weather effects and soil N dynamics than experienced in the two years during the field study.

Phosphorus

Donaldson and Rohde (2022) also studied dissolved P losses in their field study. Applying 5 to 8 times the amount of P in MM compared with fertiliser increased phosphate (PO_4-P) loads in runoff by ~6 to 10 times in 2018/19 (3rd ratoon) and ~12 to 22 times higher in 2019/20 (4th ratoon).

Productivity outcomes

Nitrogen

As part of the Project Catalyst experimental trials, Nothard and Pfumayaramba (2021) and Pfumayaramba et al. (2022) explored the adoption of innovative sugarcane farming practices that were assumed to improve water leaving farms in the GBR catchment area. Those included the impact of refining N rates, accounting for organic sources of N, on farm productivity. The mill mud treatments in Mossman produced higher sugarcane yields.

Another field trial was established in the Mackay Whitsunday region by Rust and Law (2016) to evaluate conventional surface and subsurface application of mill mud and its impact on farm productivity. There were no statistically significant differences between cane yield or percent of recoverable sugar (PRS) treatments (e.g., mill mud as partial nutrition source, application method, application with ameliorants and liquid fertiliser).

Phosphorus

No relevant published studies were identified in the review process.

Costs, cost-effectiveness and profitability

Nitrogen

Economic feasibility of mill byproduct application is a key factor in the distribution of those products, particularly in the case of mill mud application (Qureshi et al., 2007). Three experimental studies relevant to mill mud application produced contrasting results.

Nothard and Pfumayaramba (2021) and Pfumayaramba et al. (2022) explored how refining N rates by accounting for organic sources of N may impact farm productivity and profitability. The mill mud treatments in Mossman (Wet Tropics) had similar gross margins across all treatments due to additional mound operations and cost of the cartage (Pfumayaramba et al., 2022). The subsurface application of mill mud and ash combination in Eton (Mackay Whitsunday) had a \$182 ha^{-1} higher gross margin compared to the surface application. The surface application of mill mud produced a \$27 ha^{-1} higher gross margin compared to subsurface application of mill mud. The subsurface application of mill mud with reduced N rate in Mossman resulted in the highest gross margin in the first and second ratoons and in the overall average gross margin. The difference was \$4 ha^{-1} greater than at the standard 6ES rate. The surface application of mill mud in Sarina (Mackay Whitsunday) had a \$46 ha^{-1} higher average gross margin than subsurface treatment but both treatments produced lower gross margins compared to the control treatment (Nothard & Pfumayaramba, 2021). Pfumayaramba et al. (2022) noted that longer-term trials and increased replication across a wider variety of sites are needed to improve grower confidence in the economic outcomes of applying mill byproducts.

Another field trial (Rust & Law, 2016) was established in the Mackay Whitsunday region to assess conventional surface/subsurface application of mill mud and the viability of building a precision subsurface mill mud applicator. Subsurface application produced a 5% reduction in farm gross margins. The cost of a mill mud applicator was estimated as \$50,000. To break even with this capital expenditure, the subsurface application technology would need to yield 204.45 t ha^{-1} above the yield observed for subsurface treatment. Sensitivity analysis showed that surface (banded) applications of mill mud were relatively profitable (Rust & Law, 2016).

Larsen et al. (2023) reported the results of eight trials investigating the impact of mill byproducts (mill mud, ash and mud/ash mixtures) on sugarcane production and grower net revenues. The replicated, randomised trials occurred on sugarcane farms in the Herbert (four trials), Burdekin (three) and Mackay Whitsunday (one) regions. In summary, treatments included mill byproducts applied at various rates, banded between 35 to 100 t ha^{-1}, or broadcast between 140 to 200 t ha^{-1}. The studies included four to five crops (plant cane and three or four ratoons). Cumulative grower net revenues at the end of the crop cycle were impacted by production outcomes. Cane yields were higher following the application of mill byproducts in the bare fallow, compared to standard grower practice as a control. However, sugar concentrations (CCS) decreased with application of mill byproduct, even at low rates (e.g., 50 t ha^{-1}). CCS decreased as the amounts of mill byproducts applied increased, and this reduced revenues. There was no reduction in fertiliser-applied nutrients when mill byproducts were applied to these trials. Larsen et al. (2023) note that this increased total quantity of N applied to sites that received mud which would reduce CCS. The costs of mill byproducts increased when trial sites were further from the mill, thus reducing net revenues.

Larsen et al. (2023) summarised that, in terms of the byproduct applied, ash had the highest cumulative grower net revenue, followed by mud/ash, and mud respectively. In terms of applications rates, 35-50 t ha^{-1} had the highest grower net revenue, followed by 70-100 t ha^{-1} and 140-200 t ha^{-1} respectively. In particular, banding ash or a mud/ash mixture at 100 t ha^{-1} or less resulted in the grower recovering the cost of the product by the second or third ratoon and "cumulative grower net revenue for mud/ash or ash banded between 35-100 t ha^{-1} were significantly greater than the control on all trial sites, except Clare and Hawkins Creek where they were the same as the control." In light of the findings that mill byproducts applied at rates as low as 50 t ha^{-1} reduced grower net revenues at certain sites and/or reduced CCS, Larsen et al. (2023) concluded that further research is needed to improve guidelines on nutrient and water management so that growers using mill byproducts can maximise their profitability.

Phosphorus

Qureshi et al. (2001; 2007) modelled the costs of mill mud in the Mackay Whitsunday region for scenarios of sugarcane crops receiving various mill mud application rates from various mill-to-farm distances, as well as the costs of inorganic fertiliser. They found that mill mud applied at 150 and 100 t ha^{-1} provided excessive amounts of P, but this was relatively less expensive than commercial fertiliser for distances from mill up to 20 km. Application rates of 75 and 50 t ha^{-1} were less expensive up to 40 km and 25 t ha^{-1} was less expensive at 60 km from mill. The application rate of 12.5 t ha^{-1} was less costly for all mill distances compared to traditional fertiliser applications, thus, more economically attractive. The cost of mill mud application to achieve nutrient balance was lower than the cost of commercial fertilisers if low transportation costs are assumed. Net Revenue (NR) per ha, from each soil type when different mill mud application rates are considered over different mill – farm distances, varied significantly. The NR on alluvial soil was the highest varying from \$598 to \$751 ha^{-1} depending on the distance (e.g., the smaller the distance the greater the NR and vice versa). The NR on grey clay was the lowest and varied between \$168 and \$321 ha^{-1} for the smallest and largest distance farm (Qureshi et al., 2007).

Crop residue management

Crop residue retention has the potential to increase infiltration and reduce surface runoff volumes, therefore, potentially affecting dissolved N and P losses via runoff. Residue retention can also impact on the overall N dynamics of the system and hence impact on DIN losses.

Dissolved nutrient discharge

Nitrogen

In sugarcane, trash retention reduced DIN discharges in runoff of simulated rainfall by 42% (Melland et al., 2022). In that study, simulated rainfall was applied, and DIN discharges measured at only three times during the crop's life, and so the extent to which the trash would reduce DIN discharge over a whole crop or over many years is uncertain. In a mechanistic modelling study, average N losses (through both leaching and denitrification) over 84 years under trash retention were higher than with trash burnt (Meier & Thorburn, 2016). The result reflected the increased N in the soil when trash was retained compared with the loss of N to the atmosphere when trash was burnt. A small proportion of this increased N was stored in the soil, another proportion was taken up by the crop and removed from the field in harvested cane, while the rest was lost to the environment.

Thorburn et al. (2022) investigated the effect of trash retention on NiLRI values. Retaining trash was the tenth and eleventh most influential variable for NiLRI in ratoon and plant cane, respectively, meaning the effect of trash management was relatively weak.

In crops other than sugarcane, one study measured DIN discharged in runoff from vegetable production under a range of treatments that included differences in crop residue management (Nachimuthu et al., 2017b). The main treatment relevant to crop residue management, the "Trash mulch" treatment, combined a surface mulch of cane-trash or forage-sorghum with reduced fertiliser rates and minimum or zero tillage. DIN discharged in runoff from the treatment was less than 50% of that from the conventional treatment. The contribution of the presence of the crop residue mulch to the reduced DIN discharge is unclear.

Phosphorus

No relevant published studies were identified in the review process.

Production outcomes

Nitrogen

Two studies by Nachimuthu et al. (2017a; 2017b) investigated how four sets of management practices would impact not only the off-farm water quality but also the productivity of two vegetable crops (capsicum and zucchini): "Vegetable only" (Rhodes grass or forage-sorghum mulch, minimum or zero tillage, reduced fertiliser rates); "Conventional" (plastic mulch, bare inter-row conventional tillage and commercial fertiliser inputs); "Improved" (improved practice with plastic mulch, inter-row vegetative mulch, zonal tillage and reduced fertiliser rates); and "Trash mulch" (improved practice with cane-trash or forage-sorghum mulch with reduced fertiliser rates, minimum or zero tillage). The "Conventional" system had the highest capsicum and zucchini fruit yields compared to other systems. "Improved" had the second highest fruit yields (80% of Conventional practice). "Trash mulch" was the least productive in both capsicum (45% of Conventional set of practices) and zucchini (43% of Conventional set of practices) (Nachimuthu et al., 2017b). Like zucchini, Vegetable only set yielded 39% of the district average productivity in pumpkin crop. Vegetable yield was dominated by nutrient availability rather than land management (Nachimuthu et al., 2017b).

Phosphorus

No relevant published studies were identified in the review process.

Costs, cost-effectiveness and profitability

No studies have been published on the cost-effectiveness, profitability, and productivity of crop residue management types and their impact on dissolved nutrient discharges.

Farming system (fallows, tillage, row spacing, fertiliser placement, etc.)

The term "farming systems" covers numerous practices including fallow management, different tillage systems, the width between rows for crops like sugarcane and cotton. For the purposes of this review the placement of fertiliser either underground or on the surface of the soil or crop residue is also considered part of the farming system. Each of these practices is reviewed in the following sections.

Fertiliser placement

Dissolved nutrient discharge

Nitrogen

There is mixed evidence of the effect of fertiliser placement on DIN losses from sugarcane crops. In a rainfall simulation study, DIN discharged in runoff was reduced by 64% to 85% for subsurface application compared with surface-applied N in two experiments in the Herbert River catchment (Melland et al., 2022). However, in a similar study at another site in the Herbert River catchment, burying N fertiliser reduced loads of ammonium-N by an order of magnitude but had no significant effects on DIN (Cook et al., 2021). Simulated rainfall was applied three times during the crop's life in all three experiments, and so the extent to which burying N would reduce DIN discharged over a whole crop or over many years is uncertain.

Other studies have measured losses, driven by natural rather than simulated rainfall, over whole sugarcane crops. Webster et al. (2012) measured DIN losses in runoff over three sugarcane crops under two N fertiliser rate treatments over 6 years. Fertiliser was surface-applied in five of the six year N treatment combinations and buried in the second crop of the low N rate treatment. Compared to the five crops with surface-applied N, there was no discernible reduction in DIN discharged from burying the N.

One of the complications with fertiliser placement is that surface applied urea- or ammonium-N can volatilise to ammonia, which is lost to the atmosphere. Volatilisation is enhanced if N is applied on top of crop residues, with losses to the atmosphere as high as ~40% of the applied fertiliser (Prasertsak et al., 2002). Thus, burying N fertiliser can result in a greater **net** addition of N to the soil compared with surface applying N. The higher net addition of N to the soil has been found to increase DIN lost through runoff (1% to 4% of N applied) and leaching (11% to 19%) (see Figure 2 in Thorburn & Wilkinson, 2013) and the combined losses of DIN by leaching and denitrification (22% to 40%) (Prasertsak et al., 2002). Thus, contrasting experimental results may occur because of differences in ammonia volatilisation of surface applied urea- or ammonium-N.

Phosphorus

No relevant published studies were identified in the review process.

Production outcomes

Nitrogen

Nothard and Pfumayaramba (2021) evaluated the results of a field trial in the Mackay Whitsunday region to determine the economic and water quality impact of traditional surface and subsurface application of Bio Dunder® liquid fertiliser (which is byproduct of ethanol and rum production). Subsurface application of Bio Dunder® resulted in similar yields to surface application (Nothard & Pfumyaramba, 2021). Pfumayaramba et al. (2022) noted that longer-term trials and increased replication across a wider variety of sites are needed to validate the practices considered in this body of work since previous trials have shown that subsurface application of BioDunder resulted in yield improvements.

Phosphorus

No relevant published studies were identified in the review process.

Costs, cost-effectiveness and profitability

Nitrogen

A series of experimental trials were established in the Burdekin and Mackay Whitsunday regions to investigate the agronomic and economic performance of fertiliser products (including granular side dressed and stool split fertiliser, and liquid stool split fertiliser) and placement for sugarcane crops (Nothard & Pfumayaramba, 2021). The granular side dressed fertiliser application had a significantly higher gross margin compared to both granular stool split and liquid fertiliser application methods. No statistically significant differences were found between the treatments in other trials. The results suggested that the application method rather than product type may have been the most important factor impacting farm profitability (Nothard & Pfumyaramba, 2021). Subsurface application of Bio Dunder® liquid fertiliser resulted in a reduced gross margin but the differences were not statistically significant. Subsurface application trials have shown mixed results and contradicted previous trials (Nothard & Pfumayaramba, 2021).

Limited research has been undertaken on the cost-effectiveness of management practices on banana farms. Holligan et al. (2017) and Harvey et al. (2018) evaluated and discussed the cost effectiveness of shifts in nutrient **application methods** from class D to C and B on bananas farms in the Wet Tropics[16]. In isolation, improving nutrient application methods from D to C management class would have the smallest contribution to DIN reduction of the three practices that targeted it, assuming yields were held constant (Harvey et al., 2018). Improving nutrient application methods from D to C resulted in economic costs across all farm sizes. An economic return was recorded at the B[17] level only on 40 ha and 100 ha farms (Harvey et al., 2018, p.38). There was no impact of soil types on economic benefits. The lack of economic return could be attributed to the investment on a spreader capable of banded application in shifting from D to C and fertigation infrastructure in shifting from C to B practice classes (Harvey et al., 2018).

Phosphorus

No relevant published studies were identified in the review process.

Use of fallow legume crops

Dissolved nutrient discharge

Nitrogen

In sugarcane production, fallow management is often defined as whether the field is left bare during the fallow or if a crop, commonly a legume, is grown. Legumes can fix N from the atmosphere, which becomes an additional source of N to the field that can subsequently be lost to the environment. For example, Kearney et al. (2019) measured biological N fixation in a soybean crop ranging from 170 to 468 kg ha^{-1}, with an estimated (by ^{15}N tracing) 32% to 45% of that N subsequently lost to the environment. There have also been mechanistic modelling studies comparing differences in DIN losses from long-term sugarcane production which had bare or soybean fallows. Biggs et al. (2013) found soybean fallows increased **total** DIN discharges (aggregated across runoff, leaching and denitrification) by approximately 25% compared with a bare fallow for three soil types in each of three districts of the Mackay region.

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[16] The relevant practice category descriptions are: class B) all fertigation, or a combination of fertigation and banded surface applications is used depending on the weather conditions; class C) banded surface fertiliser applications on row areas only, and; class D) Fertiliser broadcast over rows and inter-row spaces.

[17]

Vilas et al. (2022) found DIN discharges in runoff increased by approximately 75% (averaged over long-term simulations) with soybean fallows compared with bare fallows for a single site in Mackay.

In the above studies, fertiliser N inputs were the same in both the bare and legume fallow treatments. One way to reduce these environmental losses caused by the N fixed by legumes is by reducing N fertiliser applications to subsequent sugarcane crops, and the long-term effect of this management strategy in sugarcane production has been investigated in mechanistic modelling studies. Migliorati et al. (2021) predicted that a 50% reduction in N fertiliser applied to plant cane (equivalent to an approximately 8% reduction in N across all sugarcane crops) reduced median N losses (from denitrification and leaching) by 21% compared to bare fallow **and** “full” applied N. Another study compared differences in DIN losses from sugarcane production with soybean fallows but with different amounts of N fertiliser applied to the sugarcane crops (Biggs et al., 2013). They predicted a 40% reduction in N applied to sugarcane crops would reduce **total** DIN discharges (aggregated across runoff, leaching and denitrification) by approximately 50%.

Phosphorus

No relevant published studies were identified in the review process.

Production outcomes

Nitrogen

Halpin et al. (2015) established a field experiment to investigate if a range of management practices in a soybean/sugarcane farming system would impact sugarcane productivity. This experimental study demonstrated that legume break crops at a N fertiliser application rate of 145 kg N ha^{-1} produced the highest cane yields but sugar yield was not significantly better than any other treatments. There was no productivity improvement in soybean fallow rotation of the subsequent cane crop compared to bare fallow treatment but there was an increase in farm profitability. Additionally, the soybean direct drill technique enabled grain legume cropping to obtain all potential environmental benefits.

Phosphorus

No relevant published studies were identified in the review process.

Costs, cost-effectiveness and profitability

Nitrogen

Legume crop rotation is part of the sustainable sugarcane farming system which can improve farm productivity of the following sugarcane crop and enable N fertiliser application to be reduced for the plant crop (Halpin et al., 2015; Schroeder et al., 2007). Change to legume fallow is highly case specific and has a complex impact on farm profitability (Collier et al., 2015). Gross margins for legume fallows tended to be relatively low in the absence of cane yield improvement. The research findings indicate that moving from bare to legume fallow could results in financial cost to a farmer, particularly on small farms due to required capital expenditure (van Grieken et al., 2014). Extended fallow was found to be not profitable relative to traditional fallow periods in sugarcane (Harvey et al., 2016).

Phosphorus

No relevant published studies were identified in the review process.

Combination of practices

Dissolved nutrient discharge

Nitrogen

Various attributes of farming systems have a major influence on NiLRI values in commercial sugarcane farms (Thorburn et al., 2022). Having a fallow between sugarcane crops and different methods of weed management in the fallow was the second most influential variable for NiLRI values in ratoon crops. In plant crops, fallow type (i.e., bare versus growing a legume) was the most influential. The extent that land is tilled in preparation for planting was the fourth most influential variable for NiLRI values in both plant and ratoon crops.

In crops other than sugarcane, Nachimuthu et al. (2017b) measured DIN discharged in runoff from vegetable production under a range of farming system treatments: “Conventional” (plastic mulch, bare inter-row conventional tillage and commercial fertiliser inputs); “Improved” (improved practice with plastic mulch, inter-row vegetative mulch, zonal tillage and reduced fertiliser rates); and “Trash mulch” (improved practice with cane-trash or forage-sorghum mulch with reduced fertiliser rates, minimum or zero tillage). DIN discharged in runoff from the “Improved” and “Trash mulch” treatments was less than 50% of that from the "Conventional” treatment. The contribution of the different attributes of each treatment to the reduced DIN discharge is unclear.

Phosphorus

Nachimuthu et al. (2017b) also measured Filterable Reactive Phosphorus (FRP) in runoff from vegetable production under a range of farming system treatments (listed above). They found the “Improved” and “Trash mulch” treatments reduced FRP loads by 53% and 27%, respectively, compared to the “Conventional” treatment.

Production outcomes

Nitrogen

As described above (in Crop Residue Management) two studies by Nachimuthu et al. (2017a; 2017b) investigated how a range of management practices would impact the off-farm water quality and productivity of two vegetable crops (capsicum and zucchini). The "Improved” and “Trash mulch” systems were effective in reducing total nutrient losses in the fallow period in both capsicum and zucchini (Nachimuthu et al., 2017a). There was a large reduction in gross margins for all alternative systems of capsicum and zucchini compared to gross margins under “Conventional” practices (Nachimuthu et al., 2017a). Due to yield drop, reduction in grower profitability under “Improved” practices for the zucchini crop was >AUD$6,000 ha^{-1}, or 67% of the expected gross margin in a conventional system (Nachimuthu et al., 2017b). The impact of yield reductions in the “Trash mulch” system suggests that the system may not be financially sustainable, even in the short run (Nachimuthu et al., 2017a). Reduction in grower profitability for the zucchini crop was >AUD$14,000 ha^{-1}, or 24% of the expected gross margin in a conventional system (Nachimuthu et al. 2017b).

Phosphorus

No relevant published studies were identified in the review process.

Costs, cost-effectiveness and profitability

Although studies on N and P have been reviewed separately in this synthesis, when considering “combined practices” it is appropriate to consider the cost-effectiveness of holistic changes to management. Star et al. (2021) reviewed the cost-effectiveness for water quality outcomes of moving from medium risk © management to low risk (B) nutrient management[18], with the majority of the studies included in the review conducted on sugarcane. Their main conclusion was that the cost-effectiveness of moving from medium- to low-risk nutrient management was very heterogeneous, with costs ranging from <$100 ha^{-1} to >$500 ha^{-1}. The heterogeneity came from the differences in the practices that needed to be changed to reduce risk, the ease with which the transition could be made, and farm size. Better recognition of these factors will improve understanding of the cost-effectiveness of achieving improved water quality.

Nitrogen

Various studies exist that consider the outcomes of producers adopting multiple practice changes. As these studies consider suites of changes from a whole of farming system perspective, it is difficult to use them to draw conclusions on which specific practices are the most cost effective for reducing dissolved nutrient losses. These studies do, however, provide broad insights regarding the profitability and cost-

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[18] https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0017/46106/methods.pdf

effectiveness of adopting suites of practice changes, and examples of such studies are provided in this section.

Several combined experimental and modelling studies (Connolly et al., 2018; 2022; Poggio et al., 2018) investigated the farm profitability of the whole farming system and life cycle environmental implications of cane production before and after adoption of best management practice (BMP) by nine growers in the Wet Tropics, Burdekin and Mackay Whitsunday regions. Farm profitability was found to be sensitive to cane yield changes. The economic benefit from BMP adoption (N application rates, soil testing, mill mud application, increased row spacing, GPS guidance, bed forming, reduced tillage, application of ameliorants) was found to be positive on all farms (indicating that each investment was profitable) but varied among the farms (Connolly et al., 2018; 2022). The economic benefits ranged between \$25 and \$220 ha^{-1} per annum indicating beneficial changes towards BMPs for each farming business (Poggio et al., 2018).

A number of bio-economic modelling studies have also considered shifts across various management practice categories. For sugarcane, van Grieken et al. (2014) considered various combinations of practice changes relating to fallow management, nutrient application rate management, nutrient application management, nutrient application method, and tillage management. The modelled results highlight how a grower's existing circumstances can contribute to whether or not a change is cost effective.

Two other modelling studies (Alluvium 2016; 2019) looked at the whole nutrient management shifts in sugarcane. Capital expenditure of shifting from C to B (\$123 ha^{-1} - \$183 ha^{-1} depending on the region) was lower than from D to C change (\$262 ha^{-1}- \$381 ha^{-1} depending on the region). The shift from B to A does not require any capital investment. A shift in nutrient management from C to B[19] produced small positive changes in farm profitability. The most likely life cycle cost for a practice change (capital, operating & maintenance, and program) was from C to B which was relatively lower than the shift from B to A and D to C (highest most likely life cycle cost).

Similarly, in banana crops, the most likely life cycle cost for a practice change from D to C (\$132,098 ha^{-1}) was relatively higher than the cost for moving from C to B in nutrient management (\$22,725 ha^{-1}) (Alluvium, 2019). The most cost-effective nutrient management shifts were from C to B in the Wet Tropics, Mackay Whitsunday and Burnett Mary, and from D to C in the Burdekin region. The least cost-effective was change from B to A in all regions (Alluvium, 2019). The set of nutrient management practices for bananas were found to be the least cost-effective of practices available for DIN reduction due to higher costs and lower efficacy in comparison to nutrient strategies for sugarcane. Shifting from C to B in nutrient management in bananas was the most cost-effective (\$14,730 - \$36,632 kg^{-1} of DIN reduction) option in the Wet Tropics while the same shift was the least cost-effective (\$247,044 kg^{-1} of DIN reduction) in the Cape York region (Alluvium, 2019).

In another study on bananas, Holligan et al. (2017) also considered various combinations of practice changes, and the results of investment analyses revealed that, in general, a transition to improved farming systems (as in, shifting from practices identified by the Paddock to Reef Water Quality Risk Framework as 'high risk' to those categorised as 'moderate risk') showed an overall positive impact on farm profitability, despite some individual practice changes showing a negative impact on farm profitability due to cost increases (and assuming yields were held constant).

While van Grieken et al. (2014) and Holligan et al. (2017) focused on farm level costs of practice changes and farm gate paddock DIN abatement, Star et al. (2021) noted that other studies have been undertaken for different purposes, such as modelling undertaken to predict, for example, the total costs of achieving water quality targets, and this involves broader modelling and extrapolation of available estimates (of the economic and environmental outcomes of practice changes). For completeness, it is noted that examples include modelling by Alluvium for sugarcane and bananas (2016; 2019). Such work

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[19] Class B nutrient management considered for the analysis in sugarcane include use of soil and leaf testing on blocks to be planted. Reduced rate of fertiliser according to recommended rates. Shift towards the use of fertigation, banded surface application and soil ameliorants.

is not directly relevant, however, to assessing which specific practice changes are the most cost effective (on their own merit) to reduce nutrient losses.

Limited studies that considered a combination of practices and water quality were identified for other crops through this review of the literature. Studies by Nachimuthu et al. (2017a; 2017b) investigated how four different sets of management practices would impact off-farm water quality and profitability of capsicum and zucchini crops[20]. For both capsicum and zucchini crops the results indicated that compared to the systems with conventional practices, some alternative systems (with reduced fertiliser rates and various other practice changes) substantially reduced nutrient loads. However, these were accompanied by substantial reductions in gross margin results for all alternative systems, suggesting commercially unacceptable trade-offs between water quality and profitability for the practice changes.

Phosphorus

No relevant published studies were identified in the review process.

Ground cover

Dissolved nutrient discharge

No relevant published studies were identified in the review process.

Production outcomes

No relevant published studies were identified in the review process.

Costs, cost-effectiveness and profitability

Nitrogen and phosphorus

Bioeconomic modelling of banana farming scenarios indicated that a change in ground cover management from the D practice (inter-rows and headlands are sprayed or cultivated bare) to C practice (living or dead, at least 60% cover is maintained in inter-row space and headlands) had a negative impact on profitability, assuming yields are held constant (Holligan et al., 2017). Increasing ground cover on inter-rows and headlands represented a net cost to farming businesses.

Changing “ground cover” from D to C in sorghum cropping resulted in the majority of the water quality benefit, as well as accounting for the negative economic impact. As with “nutrient rate”, the water quality and economic impacts per hectare of changing ground cover management were not affected by farm size or soil type (Hussein et al., 2018).

Controlled traffic

Dissolved nutrient discharge

Nitrogen and phosphorus

Recent studies on farming systems have demonstrated that controlled traffic (CT) could reduce N fertiliser inputs while maintaining or increasing crop yield for a given fertiliser input (Antille & Moody, 2015; Hussein et al., 2018). These reductions in N inputs with similar or higher yields could reduce DIN losses (Thorburn et al., 2022). Crop yield responses to avoid traffic compaction in CT systems were found to be positive ranging from 10% to 190% compared to non-controlled traffic systems with less variability in inter-annual yields (Antille & Moody, 2015; Chamen, 2015; Galambošová et al., 2017; Hussein et al., 2018).

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[20] Practices were described as a) Conventional (plastic mulch, bare inter-row conventional tillage and commercial fertiliser inputs); b) Improved (improved practice with plastic mulch, inter-row vegetative mulch, zonal tillage and reduced fertiliser rates); c) Trash mulch (improved practice with cane-trash or forage-sorghum mulch with reduced fertiliser rates, minimum or zero tillage); and Vegetable only (improved practice with Rhodes grass or forage-sorghum mulch, minimum or zero tillage, reduced fertiliser rates) (Nachimuthu et al., 2017a).

Production outcomes

Nitrogen and phosphorus

In an experimental grain CT system, Hussein et al. (2018) reported grain yield 40% higher compared with yield of the non-CT in all measurements of yield (e.g., thousand-grain weight, total aboveground biomass, harvest index). Due to no effect of fertiliser type on grain yields, it was confirmed that traffic compaction was the key factor affecting crop performance and N recovery in grain and biomass (Hussein et al., 2018).

Costs, cost-effectiveness and profitability

Nitrogen and phosphorus

Controlled traffic in sugarcane farming systems has a complex impact on farm profitability and is highly case specific (Collier et al., 2015).

Hussein et al. (2018) conducted an experimental study to investigate the effect of traffic compaction on sorghum response to N and farm profitability. The experiment was conducted in two adjacent blocks with and without CT. The application of N fertiliser for all treatments was applied in two dressings: 200 and 300 kg N ha^{-1}. The farm gross margin in CT treatment was approximately 34% higher than the non-CT and shallow tillage, and 25% higher with zero-tillage. Differences in gross margins were due to the cost of fertiliser applied, particularly for treatments that involved fertiliser N applied in the form of an EEF and, specifically a nitrification inhibitor (DMPP coated urea). Consequently, the impact of fertiliser cost on gross margin was higher in non-CT treatment compared with CT (Hussein et al., 2018). Hussein et al. (2018) concluded that benefits of using EEFs may not be fully realised if soil compaction is not properly managed.

Tillage management

In sugarcane fields, soil tillage is used to improve physical conditions for cane growth and development (Martini et al., 2021) but excessive tillage may lead to the rapid depletion and loss of soil organic matter (Scarpare et al., 2019). In contrast, no–tillage or zero tillage (ZT) systems minimises soil disturbance and can re-establish soil structure through aggregation, to alleviate soil erosion, supply soil organic matter and to improve water storage in the soil (Martini et al., 2021; Singh et al., 2018).

Dissolved nutrient discharge

No relevant published studies were identified in the review process.

Production outcomes

Nitrogen and phosphorus

There is limited evidence on tillage operations and their impact on farm productivity in both sugarcane and crops other than sugarcane.

A field experimental study (Halpin et al., 2015) was conducted in Bundaberg on reduced tillage in a soybean/sugarcane farming system. They found that implementation of reduced tillage produced similar cane and sugar yields compared to soybean plots that were conventionally tilled.

Other experimental studies looked at zero and strategic tillage operations in grains and cropping (Dang et al., 2018; Thomas et al., 2007). The results showed similar mean values of grain yield for a wheat crop under conventional tillage and zero tillage (ZT). No differences were found in grain protein concentration between conventional and ZT practices. Wheat and barley grain yields increased with increasing N fertiliser rates and N supply. The mean gross margin over four years (calculated using grain prices and costs relating to each year) were similar under conventional and ZT practices while mean gross margins over five years increased with an increase in N supply (Thomas et al., 2007). There were no statistically significant differences in crop productivity between tillage techniques and frequencies of tillage strategies. Strategic tillage improved crop productivity in the first year after tillage but no impact was recorded in the subsequent four years (Dang et al., 2018).

Costs, cost-effectiveness and profitability

Nitrogen and phosphorus

Modelling studies indicate that moving from high tillage to low or reduced tillage on sugarcane farms would typically provide financial benefits with regionally specific and variable water quality benefits. Farm gross margins were found to be relatively higher for low tillage scenarios (van Grieken et al., 2014). Similarly on banana farms, spraying-out fallow (with reduced cultivation and laser levelling), where appropriate, produced economic benefits irrespective of soil type (Harvey et al., 2018).

Experimental studies show that zero and strategic tillage can result in increased farm gross margins in wheat crops (Dang et al., 2018; Thomas et al., 2007).

Irrigation management (timing, amount, system) (Q4.6.3)

Irrigation is an essential part of agricultural production systems in many sugarcane regions in Australia and, like any other agricultural industry, the sugarcane industry is under the pressure to prove that water resources are used in a profitable and sustainable manner (Gillies et al., 2017). Deciding on the optimal use of available irrigation water can be challenging and quite complex, as growers are dealing with conflicting objectives of minimising water usage, maximising productivity and profitability while facing uncertainty about extreme weather events.

Dissolved nutrient discharge

Nitrogen

Irrigation management can have varying effects on DIN discharges. Under-irrigation can restrict crop growth and increase NiLRI values in sugarcane crops, which is an indicator of higher risk of N losses (Thorburn et al., 2022). Relative to this situation, appropriate irrigation will increase crop growth and reduce NiLRI value and water quality risk. Alternatively, application of irrigation can increase the volume of water running off and leaching below a field, which in turn may act as a vector for transporting greater amounts of DIN off a field.

Two experimental studies have reported on the effect of irrigation management on DIN discharges. In cotton, Scheer et al. (2022) found overall N fertiliser losses (determined by ^{15}N tracing) were lower in the overhead irrigated sites (35%) compared to the furrow irrigated sites (51%) over multiple sites and years on the Darling Downs, but this effect was non-significant due to higher N rates used in the furrow irrigated fields. In one year at one of the sites, N fertiliser treatments were the same in both forms of irrigation although N losses were not reported. In that comparison however, crop N uptake was higher and lint yields similar (averaged across all N treatments) with furrow irrigation. This result suggests a tendency for lower N surpluses and thus N losses in the furrow irrigated field. In another study, the addition of polyacrylamide (PAM) to water applied by furrow irrigation to a field in the Ord Irrigation area reduced discharge of DIN in tailwater by ~45% (Oliver & Kookana, 2006).

Both of these studies have limitations. They were conducted outside GBR catchments, although they likely have relevance to furrow irrigation systems in the Burdekin and Emerald irrigation areas. The extent to which the management of irrigation (i.e., amount and time of water applied) influenced the results of Scheer et al. (2022) compared with the type of irrigation systems in unknown. Also, the study on PAM was conducted on a single irrigation event, and thus neither the effectiveness of PAM in successive irrigation events nor on the whole of crop DIN discharges is known.

Other information on the effect of irrigation on DIN discharges comes from long-term mechanistic modelling studies, mostly in sugarcane. Irrigation management had a variable effect on DIN losses by runoff and leaching in a detailed study of furrow irrigated sugarcane at three contrasting sites in the Burdekin Irrigation Area (Thorburn et al., 2011a). For the site with the clay loam soil, reducing the total irrigation volumes applied to the crops throughout their lives reduced DIN discharged through leaching **and** runoff, approximately linearly. At the other two sites which had clay soils, reducing the total irrigation applied reduced DIN discharged through either leaching **or** runoff, but not both. At all three sites, sugarcane yields were reduced by as much as 20% at low irrigation volumes. Another interesting result of this study was that the effect of irrigation amount was similar whether a smaller volume of water was applied more frequently or a larger volume less frequently – the total amount of water was the most important attribute determining DIN discharges and crop yields.

Broadly similar results of the effect of irrigation on DIN discharges from sugarcane fields were obtained in another mechanistic modelling study for one site in each of the Burdekin Delta, Mackay and Tully regions (Power et al., 2021). However, Power et al. (2021) did not separate the losses of DIN by runoff and leaching, nor report the method of irrigation (e.g., overhead or sprinkle) simulated or the impact of irrigation applications on crop yields, nor did they report the yields under the different irrigation management types. Given the potential interaction between irrigation management and yields described above, 'improved' irrigation cannot be assumed to have no effect on production until further data is available.

In a related study, paddock scale modelling within the Paddock to Reef (P2R) program has shown that moving to 'advanced' efficiency irrigation techniques (e.g., drip, overhead or high efficiency furrow irrigation; surge irrigation; optimising furrow in-flow rates; optimising cut-off times using telemetry and automation; skip-row irrigation) combined with the nutrient best management practices could reduce DIN losses by 80% (Alluvium, 2016, p. 117). However, as with Power et al. (2021) few details of the irrigation systems were given, nor the impact on productivity.

A third modelling study simulated applications of varying amounts of overhead irrigation to sugarcane growing on two soils of contrasting permeability in Bundaberg (Verburg et al., 1998). The amount of DIN leached was higher at lower irrigation applications in both soils, because of the effect on decreased crop growth and N uptake.

There have been a small number of studies on the effect of irrigation on crops other than sugarcane. One mechanistic modelling study examined long-term DIN losses through leaching from cotton crops grown on two soils (both Vertosol) on the Darling Downs (Kodur et al., 2019). Increasing irrigation water application increased simulated N leaching.

Bioeconomic modelling studies on banana farms in the Wet Tropics provided estimates of the DIN abatement in tonnes or kg per ha per year under different irrigation practices for two soil types, assuming yields are held constant (Harvey et al., 2018; Holligan et al., 2017). Shifting irrigation practices from C[21] to B[22], D[23] to C and D to B on Ferrosol soil on 40 ha farms resulted in a modelled DIN abatement (3 kg ha^{-1} yr^{-1}, 3.6 kg ha^{-1} yr^{-1} and 8.4 kg ha^{-1} yr^{-1} respectively). Shifting irrigation practices from C to B, D to C and D to B on Dermosol soil on 40 ha farms resulted in DIN abatement (2.5 kg ha^{-1} yr^{-1}, 2.9 kg ha^{-1} yr^{-1} and 7.0 kg ha^{-1} yr^{-1} respectively).

Phosphorus

There is only one experimental study on the effect of irrigation management on dissolved P discharges. The addition of polyacrylamide (PAM) to water applied to a field by furrow irrigation reduced discharge of dissolved P tailwater by ~50% (Oliver & Kookana, 2006). As discussed above, this study was undertaken in the Ord Irrigation area, not in the GBR catchment area. However, it likely has some relevance to furrow irrigation systems in the Burdekin and Emerald irrigation areas, recognising there will be limitations in direct comparison due to variation in soil types and climate characteristics. A limitation of the study is that it was based on a single irrigation event and neither the effectiveness of PAM in successive irrigation events nor on the whole of crop DIN discharges is known.

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[21] Class C irrigation management was described as all irrigation is drip or micro sprinkler system, manually operated. Irrigation schedules are based on capacitance probes or tensiometers and manually operated.

[22] Class B irrigation management considered for analysis include irrigation scheduling based on tensiometers. Manually operated irrigation system under canopy irrigator.

[23] Class D irrigation management was described as some overhead irrigation (4.2% assumed), no soil moisture monitoring tools are used in scheduling irrigation.

Production outcomes

Nitrogen and phosphorus

Better irrigation management practices (e.g., matching irrigation to crop water needs) could improve farm productivity (cane yields) through a reduction in water stress (An-Vo et al., 2019; Wang et al., 2016b).

An Alluvium (2019) modelling study explored two levels of irrigation improvement in the Burdekin Haughton Water Supply Scheme and Delta (Burdekin region) relative to a third (conventional) level (see details below); however, no data were provided showing how an improvement in irrigation may affect production outcomes.

Costs, cost-effectiveness and profitability

Nitrogen and phosphorus

There is limited evidence related to irrigation management in sugarcane and in crops other than sugarcane.

Alluvium (2019) explored irrigation improvements in the Burdekin region (categorised according to a water quality risk framework). Economic data for this assessment were very limited and Alluvium (2019) noted that it should be treated with caution. Additionally, the costs estimated by Alluvium (2019) include the costs of policy interventions to achieve adoption of practice such as extension costs, i.e., the total costs of achieving water quality targets, which involves broader modelling and extrapolation of available estimates of the economic and environmental outcomes of practice changes. Such costs are not directly relevant however, to assessing which specific practice changes are the most cost effective (on their own merit) to reduce nutrient losses but were included for completeness.

Bioeconomic modelling studies on banana farms in the Wet Tropics (Holligan et al., 2017, and discussed by Harvey et al., 2018) provided cost-effectiveness estimates of different irrigation practices (relating to irrigation method and irrigation scheduling) (Holligan et al., 2017).[24] Assuming yields were held constant, improved irrigation practices provided positive economic benefits around \$228 ha^{-1} yr^{-1} shifting from D to C class (Dermosol) on all farm sizes and up to \$854 ha^{-1} yr^{-1} for shifting to B class (Ferrosol) on small farms (Harvey et al., 2018). Converting to a fully automated irrigation system (changing from C to B) delivered the second highest annual economic benefit among the B level practices (among nutrient, fallow, ground cover and water control structures) for Dermosol and Ferrosol soils. The annual economic benefit associated with moving from C to B for irrigation management increases marginally with farm size as the total investment cost was spread over a larger area (Holligan et al., 2017). Shifting from D to C was the most cost-effective change in irrigation management to reduce DIN losses on both soils at all farm sizes. The next cost-effective movement was from D to B and the least cost-effective shift was C to B. As noted previously in this review, the results of the work by Holligan et al. (2017) were driven by cost changes, as yields were assumed to be held constant.

As mentioned previously in the “Fertiliser amount” section of this review, long term modelling of irrigated cotton crops (over 116 years) was undertaken by Kodur et al. (2019) to explore the interactions of salinity management and other factors on nitrogen leaching for Vertosol soils on the Darling Downs. An initial scenario and one with a reduced leaching fraction rate (to minimise drainage and N leaching) were modelled, noting that reduced leaching fraction rates were partly linked to reduced irrigation. Kodur et al. (2019) reported that the economic losses for the reduced leaching fraction rate scenario showed up to “52% higher economic losses than” the initial scenario results and that, compared with

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[24] Irrigation categories are as follows: class B) all irrigation is automated drip/micro sprinkler system underneath trees (method) and irrigation schedules are based on capacitance probes and weather stations and are fully automated (scheduling); class C) all irrigation is drip or micro sprinkler system, manually operated (method) and irrigation schedules are based on capacitance probes or tensiometers - manually operated (scheduling); class D) Some overhead irrigation (method) and no soil moisture monitoring tools are used in scheduling irrigation (scheduling) (Harvey et al., 2018).

the initial scenario, reductions in drainage and N leaching were marginal (3% to 6% for drainage and 2% to 5% for N leaching).

ii. Non-agricultural land uses

This section describes the management of nutrients in non-agricultural lands by focusing on two key components, non-structural and structural approaches. Non-structural approaches consider methods for nutrient management that are implemented through planning, policy, education or behavioural change, capacity building, compliance and enforcement activities. They may or may not result in structural practices being implemented but are often discussed separately from structural (engineered) controls. Of the 119 studies reviewed, 23 specifically focused on non-structural approaches. Structural approaches are usually engineered structures and can include specific treatment processes in wastewater management (e.g., tertiary treatment plants using advanced mechanisms such as reverse osmosis or membrane bioreactors), constructed measures such as gross pollutant traps, wetlands, biofilters or vegetated swales for treating stormwater runoff, or proprietary devices or treatment methods. Based on the literature, non-structural and structural controls have been subdivided further into urban/domestic wastewater, animal processing wastewater and stormwater/diffuse runoff.

The management of urban/domestic wastewater for most built up areas is through centralised sewerage systems where domestic, commercial and industrial (trade waste) wastewaters are passed through a piped network to a wastewater treatment plant, and the treated effluent is then discharged to waterways. Peri-urban and rural residential land uses are often serviced by off-site or decentralised treatment facilities, usually on a household-by-household basis and through small package treatment plants.

Animal processing includes aquaculture, meat processing plants, feedlots, dairy processing plants and other intensive animal processing facilities. Many of these facilities have their own dedicated treatment plants or processes and can often discharge directly into waterways. Management of animal processing waste streams including their nutrient removal potential has been examined separately in the literature to domestic wastewater treatment.

Nutrients in diffuse runoff from stormwater are managed in a different manner to wastewater treatment point sources of nutrients. Typically, this will involve either the minimisation of nutrient generation through planning and design approaches, or through the collection and treatment of runoff through dedicated structural treatment systems. These have therefore been examined separately from domestic wastewater and animal processing sources.

Non-structural approaches

Urban wastewater

In their review of the Healthy Waterways Partnership in South East Queensland, Abal et al. (2006) noted that a partnership model was a demonstratable regional approach that could lead to significant improvements in the standard of wastewater discharged to waterways. The model led to the removal of 80% of N and 60% of P from wastewaters with resultant downstream improvements in water quality. The review focused on achievements to date around wastewater management, but the partnership, now the Healthy Lands and Waterways group, continues to undertake activities for waterway management in the region and continues to demonstrate the value of collaborative approaches.

Harvesting wastewater from homes directly using a methodology called the Urban Harvest Approach was considered in both Australia and the Netherlands by Agudelo-Vera et al. (2012). The approach involves reducing water use and recycling greywater to reduce overall volumes of wastewater exported from a house. Although reductions to wastewater were not quantified, the study highlighted that widespread adoption would reduce overall nutrient export loads.

Another recycling approach was for biosolids from wastewater processes being used in structural fill material in Melbourne, Australia (Arulrajah et al., 2011). The authors noted that leaching of N, P and total organic carbon may require special protection and treatment of the biosolids or specific placement techniques to minimise leaching potential. This highlights that while recycling measures may be useful and help to redirect waste streams from entering waterways directly, there may be implications for waterway impact where the recycled products are applied. This was highlighted in Arunakumaren and Evans (2003) which showed through modelling that reuse of wastewater treatment plant effluent for agricultural irrigation in the Lockyer and Mackay catchments could increase the risk of irrigation induced salinity. While it could provide short-term relief from water scarcity, it could also lead to loss of farms in marginal areas due to rising groundwater increasing soil salinity. The study indicated there were difficulties in assessing N immobilisation in existing sugarcane farming, but it was expected that given the N would be added more gradually than with fertiliser application, the overall nitrate impact on the aquifer was less than the status quo. However, the modelling showed that a significant proportion of the nutrient flux was likely to be sourced during baseflow discharge of nitrate impacted groundwater. The modelling also indicated that P leaching was unlikely to occur.

Brown et al. (2010) assessed a range of options for Melbourne Water's future sewage network including decentralised and onsite options for wastewater management. The study showed that N recovery from irrigation varied from 0.02 to 3.04 kg/household/year but for urine and wet composting systems was estimated at 10.6 and 0.74 kg/household/year. Those options which included urine separation provided the greatest opportunity to recover and reuse N.

Overall, this would indicate that recycling and reuse of wastewater provides significant potential to reduce nutrients entering the GBR. However, at present, it is difficult to estimate by how much, and costs reported were not directly attributed to the recycling and reuse approaches. The location of reuse and recycling approaches needs to be carefully considered in terms of transference of nutrient sources and the overall nutrient balance.

Animal processing

A range of strategies for reducing effluent discharge from shrimp ponds were considered in a review by Brennan (2002) in Queensland. Strategies included reducing production and stocking densities, but also onsite treatment through effluent ponds. The review estimated that using effluent treatment ponds to reduce N would cost between 2002AU$26 and 2002AU$61 per kg of N and that the ponds could also substantially reduce other wastes including sediment.

Burford and Lorenzen (2004) showed that implementing policy that required the ongoing removal of 10-20% of sludge per day from prawn ponds (with no other treatment) reduced remineralisation and total ammonia nitrogen to 20-30% of those ponds without sludge removal. It also substantially reduced NOx concentrations with no change to organic N concentrations.

Changing the feed types for growing red claw crayfish at a Queensland aquaculture operation showed that changing feeding mixes did not make any considerable difference to N water quality in aquaculture ponds but did influence growth rate (Metts et al., 2007).

Generally, this shows that non-structural approaches may not offer significant nutrient removal potential. However, this is based on limited information, especially for the GBR region and for aquaculture species (prawns, barramundi etc.) grown in the GBR.

Stormwater runoff

Non-structural measures, such as strategic land use planning, vegetation retention/buffering, and groundwater controls in stormwater runoff management have seen widespread adoption and been applied across many regions in Australia.

For example, planning controls that may help direct changes in land use to where they may not cause as great an impact were considered by Baginska et al. (2005). The study showed that while urbanisation was generally predicted to increase TN and TP loads in the Tweed River catchment, overall nutrient emissions may be minimised by locating urban developments in areas predominantly used for agriculture. Despite this, the predicted nutrient concentrations from stormwater runoff, especially for TN, were still very high.

Changes in urban design through the use of street trees and urban canopy cover was explored in Melbourne by Baptista et al. (2020). The study used experiments and modelling to show that doubling urban canopy cover in the catchment could reduce runoff, noting that Melbourne is a temperate climate and therefore the same approach may have different results in tropical and subtropical climates. The study demonstrated that an N load removal benefit of 2020AU$200/tree was possible, increasing up to 2020$243/tree for evergreen species. Similarly, work by Middleton et al. (2020) in Perth showed that differences in stream reach scale vegetation cover in urban streams, including woody vegetation and perennial species cover, had significant influences on DIN concentrations, with reductions of an order of magnitude where annual plant cover was 40% compared to if it was 0%. Work by Segaran et al. (2014) also showed that using parks for stormwater filtration was more effective than bioretention devices where those parks were strategically placed. All of these studies highlighted the importance of vegetation and its interception of stormwater as an effective treatment of nutrient runoff.

Groundwater infiltration and reuse was evaluated in a modelling study in Perth, which is noted as having considerable groundwater aquifers available for recharge and reuse (Barron et al., 2011). The models showed that reusing roof runoff provided both water and nutrient benefits while minimising the environmental impacts of increased urbanisation. Expanding on the previous study, Barron et al. (2013) found that urbanisation in areas where there were shallow groundwaters could lead to flushing of legacy solutes in the aquifer towards subsurface drains and that soil amendments may be necessary to prevent leachate from soils reaching groundwater. While not specifically applicable to GBR regions, there are shallow groundwaters known to exist in areas close to agricultural zones such as in the Burdekin Irrigation Area and the nearby delta, and urban development in or near these areas may need to consider changes in groundwater contributions.

Although not directly related to stormwater runoff, De Haas et al. (2012) considered conceptual changes to future water supplies to the Gold Coast in Queensland and evaluated a future water mix that included rainwater harvesting and reuse. While the overall population growth may result in increased eutrophication from increased nutrient loads, there would be reductions on a per household basis and if high quality recycled water was required, this may lead to improved nutrient reductions (De Haas et al., 2012). This integrated approach over a whole of catchment was also considered in an earlier study by Frecker and Cuddy (1994) which showed that combinations of management strategies in a “treatment train” was needed to achieve effective improvement of stormwater runoff quality. Rainwater harvesting and runoff reuse from stormwater ponds was also demonstrated to provide the highest nutrient reductions in modelled case studies in Canberra (Sharma et al., 2008). These studies all highlight that an integrated water management approach is likely to achieve significant nutrient reductions compared to individual treatments.

The application of market-based instruments in urban settings such as offsets and levies were examined by both Baptista et al. (2020) and Greiner (2014). The Baptista study, discussed earlier in this section regarding urban tree canopies, considered the effectiveness and value of tree canopies in N removal through the value of N set by Melbourne Water and offered as an offset for developers that exceed allowable nitrogen loads. Similarly, the Greiner study examined a market-based system for the catchments contributing to Darwin Harbour that considered quantitative pollutant limits and a stormwater offset program for greenfield urban development. They suggested that performance bonds for developments and operations which pose a substantial risk to water quality, including port expansion and dredging may incentivise businesses to comply with their statutory environmental duty and therefore reduce nutrient loads. This study also considered the use of a bubble licensing scheme for nutrient pollution and noted that performance bonds to remedy environmental performance failure would be needed to prevent polluters from shifting remediation costs to the wider community.

Breaking the connection between impervious surfaces and piped stormwater networks through the use of vegetation (e.g., buffers, swales, wetlands, infiltration) to reduce loads of TP, FRP and ammonium was studied by Hatt et al. (2004). They found a strong correlation between loads of all variables and the connection of impervious surfaces, though septic tank density was the dominant influence on NOx concentrations. This highlighted that reducing drainage connection would help to reduce urban-related pollutant impacts on streams. The costs and benefits of stormwater harvesting schemes have also been examined but there was a lack of practical, adequate and widely accepted methodologies to undertake a thorough assessment (Hatt et al., 2006a). Jefferson et al. (2017) reviewed a range of studies of stormwater control measures worldwide and suggested that reductions in mass export of dissolved and particulate pollutants is primarily driven by hydrological mechanisms rather than biogeochemical.

Beckwith and Clement (2013) evaluated best practice fertiliser management and community attitudes in Perth via surveys. The majority of survey respondents did not believe that changing their behaviour would have a significant impact on water quality problems and indicated that they thought farming and industrial practices were the largest contributors. However, respondents indicated that they would be willing to change their behaviour if they learned that their fertilising habits were harmful to the environment.

Combined, these studies of non-structural measures show their importance as a key management approach for managing nutrients from stormwater runoff, though making direct comparisons between the studies is difficult as many are conceptual or modelled studies and there is a distinct lack of on-ground outcome assessment.

Structural approaches

Urban wastewater

Wastewater treatment methods are often characterised as primary (settlement/filtering), secondary (activated sludge) or tertiary (biological nutrient removal, chemical treatment, physical removal), with structural approaches in wastewater nutrient management typically focusing on chemical or biological treatment options.

Biological nutrient removal

Several studies have evaluated the performance of biological nutrient removal in wastewater treatment, including Griffiths et al. (2002) and Kuncoro et al. (2009), both of which considered methods to enhance the biological composition of nutrient removal species by adding carbon (acetate or return activated sludge). The type of biological species was not only dependent on the availability of carbon but the forms of carbon that were provided, for example, return activated sludge resulted in better removal compared to potato starch. Further work by Puchongkawarin et al. (2015) demonstrated that the major bottleneck in enhancing nitrate removal was due to low carbon availability for denitrification. This demonstrates that sufficient carbon of appropriate composition is needed to enhance biological removal.

The impacts of treated wastewater reuse on eucalypt forests by Piper et al. (2011) showed that plant growth was stimulated initially but plants became stressed as the effluent induced acidification of the soils, resulted in high aluminium and manganese concentrations in soils and leaves, and caused waterlogging. This led to the failure of tree species although the study did demonstrate that using a coppice growth (cutting back trees and regrowth) enabled higher levels of water volumes and nutrients to be applied compared to established trees. Another study compared irrigating lettuce with primary effluent and commercial fertilisers using nutrient film technology. While lettuce was effective at removing nutrients from the effluent, there was an unacceptable risk of viruses and heavy metals transferring to the lettuce leaves (Rababah et al., 2000).

An experimental vegetated treatment using a biofilter planted with Giant Reed (*Arundo donax* L.) recorded high biomass production in the biofilter which was irrigated with wastewater. Irrigated systems more than doubled the uptake of organic N and P in plant tissue compared to non-irrigated systems (Willliams et al., 2008).

Young et al. (2019) conducted experiments to evaluate whether additional carbon dioxide from biogas scrubbers would enhance nutrient removal in high rate algal ponds. The study showed that biomass production or wastewater treatment was not meaningfully improved by the addition of CO_2, but wastewater treatment was still effective.

Chemical treatments

Herath (1996) examined methods to remove P and noted that chemical treatment could economically remove 90% of P in wastewater, but physical processes such as ultrafiltration, reverse osmosis and ion exchange may be needed. These all produce reject streams that may need further treatment. Marginal operating costs of 1996AU$219 kg^{-1} of P from 1 mg L^{-1} to 0.3 mg L^{-1} were reported, but this increased substantially to 1996AU$705 kg^{-1} of P removed for reductions from 0.3 mg L^{-1} to 0.1 mg L^{-1}. Chemical treatment of effluent was also evaluated through experiments undertaken by Dwyer et al. (2009) who showed that alum doses of 30 mg L^{-1} were required to achieve maximum dissolved organic nitrogen removal from the effluent.

Physical removal (including settlement ponds and irrigation systems)

Onsite systems for wastewater management were considered by Weaver (1993) who noted that the best management option was to dispose of domestic effluent through the sewer system, as in that period, 45% of dwellings in Perth had onsite soak wells or leach drains. Decentralised treatment systems and technologies have improved significantly since then with Sharma et al. (2013) showing that systems based on membrane bioreactors and ultraviolet (UV)/chlorination disinfection were relatively robust in terms of treatment capacity and showed minimal exceedances of TN and TP approved limits.

Higgins et al. (2009) examined the use of a series of treatment ponds as part of effluent management and noted that there was generally an increase in nutrients over the time spent in the storage ponds, though it was hypothesised that this could have been caused by faecal contamination from birds. There was also a trend for water temperature to be negatively correlated with nitrogenous nutrients.

Removal of nutrients in wastewater effluent through the use of membrane bioreactors (Phan et al., 2015) showed that full scale membrane bioreactors provided sustained high and stable nutrient removal for TN and phosphate from raw sewage in a three-stage process.

Other treatment approaches

Innovative treatments have also been evaluated in the literature, including a proprietary plastic media product (Natrix Major 12/12), trialled at a treatment plant in Brisbane (Münch et al., 2000). The results indicated that it was possible to reduce total inorganic N concentrations to below 12 mg L^{-1} although fluctuations in influent ammonia loads did cause some issues. Based on the results from the pilot plant trial, the study suggested it was possible to reduce input concentrations of total inorganic N by half. Additional work by Toh et al. (2002) showed that the use of simultaneous nitrification/denitrification and annamox could lead to complete N removal at wastewater treatment plants. The use of enhanced control systems for batch reactors at a treatment plant in Noosa, Queensland, resulted in ongoing high levels of performance for total N and ammonia reductions (Tomlins et al., 2002).

In summary, treatment of urban wastewater using structural approaches has been the mainstay of nutrient management of wastewater for a considerable period, with innovations such as improved biological nutrient removal, chemical additions, membrane technologies, proprietary products and effluent polishing approaches showing promise in some applications. This review also highlights the importance of recycling but also the need to consider the downstream impacts of recycled water if not properly applied or managed (e.g., Piper et al., 2011).

Animal processing

The effectiveness of sedimentation ponds in removing N, P and total suspended solids (TSS) from aquaculture effluent was evaluated in Queensland and New South Wales (Jackson et al., 2003). The study found that the ponds were effective at reducing suspended particulates (by 60%), but were less effective at reducing N and P (by 35 and 23% respectively), with residence time in the ponds corresponding negatively with nutrient removal. These ponds were also operated in a batch mode, with N and P removal expected to decrease further if operated continuously due to mineralisation of organic nutrients that may settle out from particulate matter. Jegatheesan et al. (2007) examined technologies to reduce aquaculture pollutant loads in the GBR and found that floating media performs well as pre-filters and can remove significant amounts of N and P from the wastewater. In work by Wormington and McBride (2012), macroalgae was shown to be a successful method for extracting N and P from aquaculture effluent in Bowen, Queensland, with removal rates of 18.2% for nitrate, 50.8% for nitrite, 70.5-93.5% for ammonia, 59% for TN and 26-56% for P. Submerged flow biofilters were trialled by

Abeysinghe et al. (1996) for N and P removal from synthetic fish farm water with complete removal of N obtained in a combined nitrification/denitrification configuration.

The use of soil ameliorants to decrease P leachate from soils and vegetation irrigated by abattoir effluents in Port Wakefield, South Australia, was examined by Seshadri et al. (2014). They found that using flyash or red mud decreased P losses from soil leachate, and that this was associated with increased retention in soils through a rise in soil pH. Animal wastewater treatment using polyacrylamide mixtures (PAM) in a study in Dalby, Queensland, by Entry et al. (2003) focused on the release of N and P through soil leachates when soils were irrigated with effluent. It was demonstrated that a column experiment reduced nutrients when the PAM was applied, but this was not consistent during field trials. Similarly, leaching of surface applied P was noted in application of piggery effluent to different soil types in a study by Phillips (2002), which showed that leaching of P was dependent on the soil type, though conversion of ammonia N to nitrate from the effluent resulted in high mobility of nitrate from the soils.

Grease arrestors receiving tuna processing water in South Australia were shown to remove a proportion of the nutrient load (24% for TKN and 18% for FRP) in a review by Dearman et al. (2001). Aerobic bioreactors were trialled on dairy effluent in a study by Heaven et al. (2012), which showed the ability to reduce TN concentrations by approximately 50% and P concentrations by 24%. Similar technology was evaluated in an Australian study by Jensen et al. (2015) which considered anaerobic membrane bioreactors. This study showed that they were able to consistently reduce 78-90% of N and 74% of P in the wastewater, with the permeate containing ammonia and phosphate that could enable subsequent nutrient capture. Nutrient removal from piggery effluent was evaluated in experiments by Edgerton et al. (2000) which showed that a sequencing batch reactor (SBR) could achieve greater than 99% reduction of ammonia, and 49% reduction of phosphate with oxidised N concentrations not exceeding 7.7 mg L^{-1} as N. Raper and Green (2001) also showed that an SBR could be optimised for treating meatworks effluent if the downstream anaerobic ponds were optimised for nitrification/denitrification. Nitrogen was removed highly effectively (around 95% reduction) from influent concentrations of 150-250 mg L^{-1}.

Animal processing nutrient management still appears to be based on irrigation of treated effluent, though improvements in the use of membrane technologies and vegetated/biological treatment systems have also been considered. In addition, the use of soil ameliorants to reduce the impact of land application of effluent shows promise.

Stormwater runoff

Structural stormwater runoff measures have been widely applied across Australia in response to an increased focus on managing stormwater quality. In this review, these measures have been categorised by treatment type where possible with regards to their performance for reducing runoff nutrient concentrations and loads.

Biofilters

Biofilters are soil filtration systems planted with emergent macrophytes and with underflow collection systems such that stormwater is collected on the surface, then infiltrates through the vegetated soil filter where the treated water is collected through underflow drains before flowing out to receiving waters. Biofilters have been used extensively in urban stormwater management based on their predicted performance in modelling software, though this proliferation of systems has led to inconsistent application and maintenance, and decentralisation of stormwater treatment infrastructure. The literature has improved understanding of their performance, though field studies of operational systems are still somewhat limited.

Denman et al. (2016) evaluated the potential to include trees in biofiltration studies through mesocosm column experiments. This showed that vegetated soil profiles generally reduced NOx concentrations between 2% and 78% and FRP by between 70% and 96% depending on the filtration media. This was consistently greater than unplanted profiles. Plant performance in tropical conditions (Malaysia) were examined by Jhonson et al. (2022) which showed that vetiver outperformed blue porterweed, hibiscus, golden trumpet and tall sedge, with a maximum of 86.4% TN removal, 93.5% TP removal and 90% TSS removal. Ng et al. (2018) considered urban biofilters planted with vegetable crops which showed TN and TP reductions of 47% and 69% respectively. These studies all show that vegetation is a critical component of the treatment process to achieve high N removal.

Hatt et al. completed a number of studies investigating biofilters (2006b; 2007; 2009) examining filter clogging, different media performance, and different climate conditions. Importantly, this work again showed that vegetated systems were more effective than non-vegetated systems, with non-vegetated systems being net producers of N (except for sand media) with variable performance for P. The clogging study showed no changes in effluent concentration generally even when the filters were highly effective at removing particulates, with sediment concentration reducing rapidly through the filter media. TP, heavy metals and then TN followed similar trends associated with particulate forms being removed, but FRP and NOx generally passed through the filter with little to no reductions in concentrations and ammonia was increasingly elevated. From the climate conditions study, they noted that N removal remains a challenge because it is easily transformed to soluble forms and is influenced by wetting and drying of the media. Similarly, Payne et al. (2014) studied biofilter performance in 240 mesocosm columns and found that TN removal was high in the columns during wet periods but much less reliable and effective following a 15-day dry period. They also highlighted that the plant species was of limited importance under wet conditions provided the filter medium was carefully specified to reduce nutrient leaching, though the species selection became a differentiator for performance during extended drying. This may have implications for the design of biofilters in tropical climates in the GBR catchment area if systems are allowed to dry out extensively in the dry season.

In evaluating the performance of sand filters in removing N and P, Kandasamy et al. (2008) showed that two different types of media performed similarly with 61% of TN, 70% of TKN and 53% NOx removed from stormwater runoff. TP showed a 40% reduction and was similar to values reported in the literature.

Long-term performance and potential N accumulation, leaching and denitrification were examined through experiments by Kavehei et al. (2021). This showed that a carbon: nitrogen ratio of greater than 20 is required in the bioretention soil to reduce N leaching and N_2O production. With 25 systems in subtropical Australia being evaluated, they showed that most C:N ratio values were above a value of 25 which was important to promote N immobilisation and the oldest systems showed high C:N ratios with the denitrification potential increasing significantly with the age of the system.

A paired catchment study by Lloyd and Wong (2008) showed that biofilters reduced pollutant loads by retention of runoff and physical and/or chemical treatment processes. Over 10 events, the gross pollutant load was reduced by 100%, TSS by 68%, TP by 68% and TN by 57%. Conversely, Lucke and Nichols (2015) showed variable performance of the treatment of synthetic stormwater including a range of influent concentrations ranging from no added synthetic pollution to five times the typical urban stormwater pollutant loads. Overall, the hydrologic performance was highly variable but positive, with TSS removal being variable and not correlated with influent concentration. For the treatment of 'no-pollution' in the influent, the bioretention systems were shown to have negative removal for TN, however TP was effectively removed across all systems. The field study showed that the performance for biofilters was highly variable and dependent on a range of factors including inflow pollutant concentrations, filter media, construction methods and environmental factors.

Monophasic and biphasic filter media designs were examined in column studies by Macnamara and Derry (2017) for systems proposed to be used in Sydney. The study showed that the columns could achieve a median TN removal efficiency of 84.1% and 89.0% for monophasic and biphasic designs respectively. TP median removal efficiencies were 77.8% and 68.5% respectively.

Collectively, these studies show that the use of biofilters in treating urban stormwater runoff nutrients has considerable value and is applicable to tropical climates, though leaching of nutrients from the media needs to be managed, and the choice of plant species is also an important consideration. The systems appear to improve in performance for denitrification over time suggesting that nutrient removal may improve with system age rather than decline.

Wetlands

Wetland systems in non-agricultural areas are largely constructed vegetated systems with engineered inflow and outflow controls, usually incorporating pre-treatment such as sediment basins, and extensive areas of emergent and floating macrophytes in vegetation zones. In recent years, floating wetland systems have been developed by several proprietary manufacturers and some of the most recent studies have focused on their performance.

Constructed floating wetlands were evaluated by Awad et al. (2022) who noted that while the systems may not be suitable for mitigating peak flows, they accumulate between 0.48-2.0 g of TN per m^2 and 0.04-0.46 g of TP per m^2 when *Baumea rubiginosa* was used in the system, with *Phragmites australis* accumulating between 0.2-2.3 g of TN per m^2 and 0.02-0.2 g of TP per m^2. They also noted that in low level nutrient conditions (TN ≤0.4 mg L^{-1} and TP ≤0.2 mg L^{-1}), *Phragmites* growth was not supported, though *Baumea* species did grow under the same conditions. Constructed floating wetlands were also studied by Schwammberger et al. (2017; 2019; 2023) who observed that pollutant removal was low due to low inflow stormwater pollutant concentrations, but when systems were moved to catchments with typical values for urban catchments in Australia, TN removal was 17% and TP removal was 52%, demonstrating that influent pollutant loads are extremely important in influencing the performance of floating wetland systems. They also showed that constructed floating wetlands remove large amounts of nutrients from urban stormwater through plant uptake. Removal rates of 17% for TN and 52% for TP were also indicated in a study by Walker et al. (2017), but the authors were similar to the Awad et al. (2022) study and therefore the results might be from the same system.

Bourgues and Hart (2007) examined the roles of epiphytic biofilms and sediment processes in 13 urban stormwater wetlands in Melbourne and noted a high degree of heterogeneity across the systems. In systems with a supply of nitrate, low oxygen levels and appropriate redox conditions, high levels of denitrification were observed. They also observed that biofilms on macrophytes were important to shelter bacterial populations able to carry out denitrification at comparable rates than those in adjacent sediments, highlighting the importance of plants to treat nutrient rich stormwater.

Riparian wetlands in an urban area in Calamvale, Brisbane, which were remnants of a larger system of natural channels, showed considerable effectiveness in removing nitrate. The 600 m of remnant channel, lagoons and associated vegetation were reported by Greenway et al. (2002; 2007) as being effective in both wet and dry weather. These wetlands were part of a treatment train including sediment basins, ponds and gross pollutant traps, some of which showed elevated nutrient concentrations at the outlets. Phosphate also reduced in the wetlands.

Wetlands in tropical zones were evaluated by Griffith and Mitsch (2017) for an urban stormwater wetland in Florida, USA which showed that they were net sinks of nutrients with reductions of nitrate from 0.13 mg L^{-1} in the inlet to less than 0.002 mg L^{-1} at the outlet, with N removal expected to increase over time as denitrification processes increase with increased organic carbon in the soils, whilst TP was expected to reduce.

Riparian wetlands in Durham, North Carolina, USA were evaluated and showed that N removal was not just a function of surface area, but also hydrologic length of contact between the riparian zone and stream sources of nutrients in work by Richardson et al. (2011). Although not climatically similar to GBR regions, it does highlight one of the key design elements that needs to be considered for wetland systems. Similarly, pollutant removal was noted as being directly related to hydraulic residence time by Headley et al. (2001; 2005). Sakadevan and Bavor (1999) showed through five experimental wetlands in Richmond, NSW, that low hydraulic loading and greater retention times enhance the removal of N and P, though this was for wastewater rather than stormwater runoff.

Headley et al. (2001; 2005) also observed that nutrient uptake by plants was important and accounted for greater than 70% of the nutrient removal initially. Denitrification was low initially, from 17-22% of the removal of TN, increasing to greater than 49% after 17 months. The role of denitrification improving over time was also demonstrated in experiments by Lund et al. (2001) who showed that plant biomass uptake was important initially, with sediment becoming increasingly important as a sink. Denitrification was also shown to be a dominant nutrient reduction process by Rahman et al. (2019a; 2019b; 2019c) with organic carbon and high nitrate concentrations being important factors in the favouring of denitrification over nutrient recycling by bacteria.

Three lake/wetland systems which were used as recreational systems showed nutrient export from Lake Pertobe in Warrnambool, Victoria in a study by Howitt et al. (2014), though it did show some improvement for other contaminants (e.g., heavy metals, *E. coli*). Kasper and Jenkins (2007) examined a wetland system in Brisbane, Queensland and noted that the activities of birds, resuspension of inorganic sediments and growth of organic matter could all influence the determination of background concentrations, though they also noted that vegetation plays a significant role in the capture of suspended solids and nutrients and limits the resuspension of these into the water column. Variable performance was also noted in a secondary review study by Mitchell et al. (1995) that showed the potential for water quality amelioration, but not consistently under day-to-day operating conditions with hydraulic short-circuiting and the role of plants under different operating and weather conditions being seen as important factors. Nguyen et al. (2018) also noted only slight reductions in TN and TP loads when modelling wetlands along the Torrens River in Adelaide, South Australia, suggesting that combining wetlands with buffer zones and stabilised riverbanks may be necessary.

Yang et al. (2021; 2022) showed that most Councils do not monitor the stormwater treatment effectiveness of wetlands over time in Melbourne, Victoria, but the quality of water in wetlands receiving industrial stormwater runoff showed serious accumulation of heavy metals. Ziajahromi et al. (2020) also identified the possible origin of synthetic rubber in wetlands indicating that they act as a sink for tyre particles, and this may show that they receive proportions of road runoff which can also be important sources of nutrient pollution.

In summary, these studies show that wetlands for urban runoff nutrients are applicable in GBR catchments and denitrification processes are the dominant form of N removal over time. Vegetation is important for harbouring bacteria responsible for denitrification processes and systems with limited vegetation show relatively poor or variable performance. Wetland performance is also strongly related to hydraulic loading rates and retention time. Floating wetlands show some potential for nutrient removal but this may be limited either by the treatment system or by low influent stormwater concentrations.

Swales

Vegetated swales are linear drainage structures that may contain grass or emergent macrophytes that interact with stormwater flows to promote sedimentation and infiltration. They are typically incorporated with other treatment measures in a “treatment train” and studies on them as individual treatments are limited.

Vegetated swales were extensively studied in field experiments by Fletcher et al. (2002) in Brisbane, QLD, which showed them to be an effective stormwater treatment measure, with 44% to 57% removal of TN, and 58% to 72% of TP concentrations, with similar ranges for load reduction (40-72% for TN and 12-67% for TP). Treatment performance diminished with increasing flow rate, though this was less important for TN and TP, reflecting the likely influence of rapid chemical processes.

Conversely, Kachchu Mohamed et al. (2014) showed only limited effectiveness of swales for removing nutrients which they thought may be due to leaching of N and P from the swale as their results were inconsistent with previous research findings.

Green roofs

Green roofs are roofing structures that contain plants and drainage to intercept rainwater and slow down flows to drainage pipes. They can also be used as part of water recycling schemes.

Overall, both Beecham and Razzaghmanesh (2015) and Razzaghmanesh et al. (2014) showed that green roofs exhibited export of nutrients due to leaching from the growth medium, though this was lower in vegetated roofs than non-vegetated roofs, indicating that plant uptake was occurring. Recycling of roof water from these systems may be possible though extensive green roofs did show some nutrient removal.

Proprietary devices

Proprietary devices include manufactured treatment systems that are typically modular so they can either be constructed off-site and installed at the place of interest, or constructed *in situ* to a common design.

Gross Pollutant Traps (GPTs) have been noted to both remove pollutants from urban stormwater runoff and contribute to them, with Ball and Ara (2010) showing that N and P release could occur from systems with wet sumps that were installed in Sydney, NSW, with 50% of the P in trapped leaf litter released in 22 days, with the remainder in the following 150 days, though N release was less than that of P. Birch and Matthai (2009) showed removal rates of TP, TKN and NOx of 4%, 10% and 74% respectively for a Continuous Deflection Separator in Sydney NSW, though they also stated that mean concentrations were slightly reduced and the system was not efficient for removing nutrients.

Drapper and Hornbuckle (2015) evaluated both pit baskets and cartridge filters independently in installations in Brisbane, QLD, and showed that the pit basket removed 38% for TN and 37% for TP, with the cartridge filter removing 42% TN and 55% TP. A later study also by Drapper and Hornbuckle (2018) using a larger dataset than the 2015 work indicated removal by the pit basket to be 45% for TN and 28% for TP, with the cartridge filter removing 42% of TN and 59% of TP. They also noted that higher inlet concentrations produced better performance.

A SPEL Stormceptor equipped with a coalescer unit in Nambour, Queensland, was evaluated by Hornbuckle and Drapper (2018) for treating nutrients in addition to treating hydrocarbons and TSS. This showed that the unit would remove 23% of TN and 11% of TP using the Efficiency Ratio method from 18 complying events evaluated. They also noted lower levels of influent concentrations and that the device was not exporting pollutants over time.

Nichols and Lucke (2016) considered the performance of a Humegard system installed on the Sunshine Coast, QLD, with removal rates of 26.6% for TN and 40.6% for TP though the results were highly variable which may also be related to low concentrations pollutant inflows.

Other systems (including combined treatment trains)

Infiltration systems in Sydney, NSW, were evaluated by Birch et al. (2005) showing that TP was able to be reduced by 51% and TKN by 65%, but the concentration of NOx in the effluent of the system was 2.5 times greater than the influent with it being proposed that travel time through the sand filter component enabled bacteria to oxidise organic N. In a separate study, the same authors examined a detention basin next to a major motorway which showed that while TKN and TN removal was high, the system exported NOx and sometimes TP (Birch et al., 2006). Pezzaniti et al. (2012) also conducted experiments on an infiltration/detention basin receiving road runoff and showed that both TKN and TP were reduced by 64% and 77% respectively, though speciated nutrients were not evaluated.

Permeable pavements were found to significantly improve stormwater quality with regards to nutrients and other contaminants by Beecham et al. (2012), with TN removed by 58% and TP by 33% respectively and the average effluent concentrations were less than ANZECC (2000) trigger values. Bratieres et al. (2012) also evaluated a proprietary permeable pavement using the Enviss system in Melbourne, Victoria, which showed TN concentration reductions of 25-75% for one configuration and 38-83% for another. TP removal appeared to be related to particulate P removal as dissolved P removal levels varied greatly. They also noted that performance reduced over time. Yong et al. (2011) considered removal of nutrients in addition to studying the clogging behaviour of three different pervious pavement types through experiments. TP removal was shown to be 20% for all flows except low flow, with leaching of TN observed from all flows except high flows but removals averaging around 15%. Again, as per the Birch study on infiltration systems, leaching of TN was expected to be related to longer detention times breaking down trapped sediment in the clogged layers of the pavement with subsequent increases in outflow TN concentrations.

The performance of rainwater tanks for nutrient removal was examined by Coultas et al. (2011) using a stochastic modelling approach and this showed only minor nutrient savings were possible.

Modelling of combined treatment trains was considered by Imteaz et al. (2012; 2013; 2015) where they evaluated the use of the MUSIC software to consider removal of nutrients and other pollutants, including costs of treatments. They noted that systems may be possible to achieve an efficiency of 100% though there is a threshold size beyond which higher treatment efficiencies cannot be achieved without very high costs. They also showed that bioretention systems provided the highest removal efficiency in lower costs ranges and that the MUSIC software could simulate flow conditions with good accuracy, though the removal efficiency predictions for TP and TN were variable with both under and overestimation.

Overall, structural controls for stormwater treatment show that they are generally effective for nutrient removal, especially where vegetation is a key component of the process. Leaching of nutrients from filter media does appear to be an issue if not properly managed, especially from systems that do not contain vegetation. Release of nutrients from wet sump gross pollutant traps is also an issue for consideration.

4.1.2 Recent findings 2016-2022 (since the 2017 SCS)

- For agricultural land uses there has been a considerable increase in evidence relating to the primary and secondary questions since the 2017 SCS with 79% of studies in the nitrogen appraisal and 71% of those in economics appraisal published between 2016 and 2022. Recent studies for the phosphorus appraisal accounted for 50% of the total. For the urban appraisal, the percentage of recent studies was much lower (15%), although 50% for the urban wetlands.
- Research undertaken and published since the 2017 SCS has clarified the potential benefits relating to use of EEF.
- A major advance since the 2017 SCS has been the understanding and quantification of the role of climate variability, both year-to-year and within years in driving water quality and production outcomes of different N fertiliser management practices (notably different N rates and use of EEF). The possible benefits of incorporating seasonal climate forecasting into N fertiliser management decisions has also emerged.
- Recent research on the water quality benefits of burying N fertiliser has shown that benefits are possible under some conditions. However, limitations to the methods used in these studies mean that previous research showing that there may be few water quality benefits from burying N are still valid.
- Research on mill mud and irrigation management is generally recent and still developing (or needs further development).
- Denitrification is a key process for nutrient removal in vegetated treatment systems.
- Non-structural approaches have some merit but limited evidence for potential reductions.
- Recent economic studies have produced research findings consistent with the results reported in the past. Building on previous knowledge, recent studies put more emphasis on expanding research to different forms and application rates of EEFs and nutrient management practices in all sugarcane areas adjacent to the GBR. This makes the research findings more robust.

4.1.3 Key conclusions

The following key conclusions are based on the evidence presented above.

4.6 What are the most effective management practices for reducing dissolved nutrient losses (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions? What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices?

- In sugarcane systems reduction in N application has been shown in experiments and modelling to be a consistent means to reduce N losses via all pathways. This result has also been obtained for cotton and dairy pastures, albeit from a small number of studies.

- N application rates above the best practice result in increases to the cost of production and in loss of potential economic returns.
- N loss that occurs as a consequence of an oversupply of N can only be alleviated by reduction of N rate, unless there is scope to improve crop performance and hence the crop's demand for N.
- When fertiliser N rates are reduced "too much" there can be an impact on productivity and profitability at the farm and sugarcane mill levels. The challenge is that both the reduction in N loss and the possible impact on productivity and profitability are variable, affected by climate, soil and seasonal conditions. As a result the "optimum" N fertiliser rate (i.e., the rate giving near maximum profitability) is both unknown and unpredictable for a specific sugarcane crop.
- Nutrient application rates are a key driver of farm profitability. However, changing rates can involve additional expenditure on capital or an increase in other business expenses (e.g., labour) which can overshadow cost savings from lowering rates.
- Timing of the crop start (either the date planted or harvested for ratoon crops) has been shown to have a big effect on N losses under sugarcane, with losses likely to be higher for crops later in the season (i.e., in early summer and the commencement of the wet season). This result indicates that N management practices to reduce N loss will usually be more effective for the later crops.
- The time during a crop cycle when fertiliser is applied (e.g., soon after harvesting or several weeks later) has not been studied in detail, even though delaying fertiliser applications for plant crops and early (July and August) ratoon crops is common in several regions. Given the findings for EEF, some of which effectively "mimic" delayed fertilisation, further research into delayed and split applications would be warranted to clarify the currently sparse and mixed findings.
- Legumes grown in the fallow between sugarcane crops can contain high amounts of N, and N fertiliser applications to subsequent crops need to be reduced to counteract the effect of this extra N on DIN losses. Modelling studies suggest yields will be maintained with a 40-50% reduction in fertiliser N. However, empirical information on the amount of N in fallow legumes and the effect on the N fertiliser management and DIN losses in subsequent sugarcane crops is lacking.
- There are economic implications of moving from bare to legume fallows as farmers may need to make capital expenditures to enable the farming of legumes. This situation mainly occurs on small properties.
- The evidence on the effectiveness of other management practices is less clear on account of fewer studies, mixed results and them being tested as part of farming systems involving multiple practices, which makes it difficult to conclude with certainty the role of individual practices due to possible offsets or interactions between them.
- Moving from high tillage to low, reduced or zero tillage can provide financial benefits.
- For urban/non-agricultural land uses, it is obvious that structural measures that include vegetation/biological components, such as wetlands, biofilters, algal ponds and existing riparian zones have considerable potential for removal of diffuse runoff nutrients and may also be important for management of wastewaters. Biofilters appear to be the most cost-effective treatment systems in this case but this is based on limited data and modelling studies.
- Improvements in technologies for wastewater management also show that systems such as membrane filtration and chemical addition are likely to perform well.
- Non-structural controls for non-agricultural nutrient management appear to work best when completed in an integrated approach and recycling and reuse show considerable potential, though there are issues with the management of nutrients where that reuse water is applied.

4.6.1 What is the potential of Enhanced Efficiency Fertilisers (EEFs) in reducing nitrogen runoff and what are the primary challenges in implementation?

- Applying N through EEF has the potential to reduce N losses because these fertilisers can maintain N in the soils for longer times and in a less mobile form than with application of conventional (urea-based) N fertiliser, potentially allowing crops to take up N for longer. However, the results are highly variable across sites and years and clear benefits are often only seen when data, from either experimental or modelling studies, are aggregated across sites and seasons.

- The variable benefits of EEF mean that growers who evaluate EEF on their own farm may not obtain or see the benefits at individual sites and/or in individual years.
- The variable outcomes can be explained by the three prerequisite conditions needed for an EEF to be effective: 1) The longevity of protection provided by the EEF must be long enough to bridge the time for the crop uptake of N; 2) The timing of N loss must be early in the season during the protection period; and 3) The crop must be able to respond to the “saved” N in context of overall N supply and other crop growth constraints.
- The benefits of EEF are, however, linked with the likelihood of N loss being experienced early in the growing season during the period that the EEF keeps N in a less mobile form. Therefore, benefits are greatest for mid- to late-season crops, in the wetter regions of the Wet Tropics, and in wetter seasons. Productivity benefits are more likely on permeable soils, where yield potential is less impacted by the conditions that drive N loss.
- On account of the third prerequisite condition, benefits of EEF in the form of reductions in N loss are more frequently obtained than productivity or gross-margin benefits, resulting in an implementation challenge where growers may not always see a return.
- The dependence of benefits on soil, climate, timing of crop and other factors affecting crop growth potential results in an implementation challenge. Further work on adoption would need to consider whether it is more effective to develop an industry-wide recommendation (e.g., use EEF at 80% of recommended urea rate) that is simple but may not have an effect under all conditions (hence growers may not see the benefits on their farm) or to develop more complex, location and soil specific advice.
- There is limited evidence on the effects of EEF on DIN discharged in runoff. The limited experimentation and modelling that has been performed suggests that the effects can be variable, including increasing N loss slightly usually during later events when the EEF action has diminished. The latter is not an issue where N loss via runoff is a large component of N loss (under late crops on relatively impermeable soils in wetter regions of the Wet Tropics), as in that case the earlier reductions in N loss offset the possible small increases later. However, it does challenge experimental outcomes where the N in runoff amounts is smaller.

4.6.2 What are the implications of mill mud application in influencing nitrogen losses and what are the primary challenges for implementation?

- Mill mud contains substantial amounts of N and P suggesting that fertiliser N and P applications could be reduced after mill mud applications, which in turn would reduce losses of dissolved nutrients.
- However, there is generally little information on the impact of mill mud application and management of discharges of DIN and dissolved P. Thus, no strong conclusions can be drawn.
- The application of mill mud seems to have little effect on DIN discharges in runoff.
- Dissolved P losses are quite large and P inputs should be accounted for in nutrient management of crops following application of mill mud.
- There is limited evidence on the effect of mill mud application on farm productivity, or on costs or cost-effectiveness of N reduction. Experimental studies produced contrasting results.

4.6.3 What are the primary factors that influence nutrient losses from irrigated areas and how can these be managed?

- There is little information on the effect of improved irrigation practices on discharges of DIN and dissolved P or on farm productivity. Most information comes from mechanistic modelling studies. However, most of these do not provide enough detail of the methods or results to draw reliable conclusions about the water quality and economic outcomes.
- High irrigation efficiency resulting from low irrigation application rates is predicted to reduce DIN discharges from sugarcane crops, but there is a risk that productivity is also reduced.

- Well-designed and managed automated furrow irrigation system on sugarcane farms can be profitable, although the water quality outcomes of these systems are not clear.
- Limited evidence suggests that converting to a fully automated irrigation system on banana farms may potentially provide economic benefits.

4.1.4 Significance of findings for policy, management and practice

As noted above, the water quality benefits and/or productivity and profitability implications of some of the management practices, notably reduction in N rate and use of EEF in sugarcane crops, are variable. Much of this variability comes from the important effect of climate on soil processes and the growth of crops. This variability plays out in practice in a number of ways. One is that the "optimum" amount of N fertiliser for a field varies from year-to-year, which means the production impact of reducing N applications is uncertain – it might have no effect on yield/profitability in one year and reduce yield in the next. Another implication is that the effectiveness of EEF is variable and an industry-wide recommendation to use EEF at for example 80% of the recommended rate for urea-N will likely not result in universal water quality and/or profitability benefits. This uncertainty is a barrier to adoption of reduced N rates and use of EEF. This uncertainty also means that simple, general recommendations will not (and cannot) capture this complexity. A better understanding and representation of this variability would likely provide a basis for more accurate, location and soil specific advice delivered through, for example, decisions support systems.

However, given the role of climate in driving this variability, there is (and likely always will be) some degree of unpredictability in the benefits of some management practices. Rather than ignoring this unpredictability, it could be acknowledged, and effort could be spent on developing mechanisms to support growers decision making in the face of this uncertainty. This support could be in the form of tools to characterise and communicate this variability to farmers so they can make management decisions being informed about the uncertainty of the outcome. The support could also be in the form of market-based or financial instruments that address this uncertainty either directly (e.g., insurance) or indirectly (e.g., eco-markets). Examples of these tools and instruments currently exist[25], and discussing them is beyond the scope of this review. However, they have attracted considerable interest[26] and monitoring their impact on water quality and considering ways in which that might be enhanced will be valuable (refer to Questions 7.1, Coggan et al., and 7.2, Murray-Prior et al., this SCS, for further exploration of this topic).

There are a number of other notable implications for policy, management and/or practice:

- The small amount of information currently available on the trade-offs between water quality benefits and productivity dis-benefits of improved irrigation inhibit drawing policy, management and practice conclusions.
- There is little information on management practices affecting loss of dissolved P from cropped lands. However, reducing P fertiliser applications to crops is likely to reduce dissolved P losses.
- N and P fertiliser application rates should be reduced following the application of mill mud to account for the nutrients in mill mud and provide water quality (notably for dissolved P) or economic benefits. A limitation to the effective implementation of this practice is the lack of methods for determining the nutrient loading in mill mud applied, due largely to variations in nutrient concentrations in mill mud, and the subsequent bioavailability of nutrients.
- The water quality benefits of burying N fertiliser compared with surface application are uncertain. Some of the N fertiliser is lost to the atmosphere from ammonia volatilisation following surface application of N, and so burying N likely increases the **net** addition of N to the soils which may contribute to the uncertainty in water quality benefits. Different methods are used in different studies, also potentially contributing to the uncertainty.

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[25] https://affinitytechnology.willistowerswatson.com/sales/wtwcropinsurance/. https://eco-markets.org.au/reef-credits/.

[26] An example of the interest is: https://www.qld.gov.au/environment/coasts-waterways/reef/reef-credit-scheme.

- Vegetated treatment systems in non-agricultural areas are essential for reducing nutrients in diffuse sources, with conventional nutrient technologies in wastewater showing that they are quite effective, but reuse approaches may provide benefit. Animal processing wastewater management appears to still be somewhat immature compared to domestic wastewater management though similar technologies do show some promise.

4.1.5 Uncertainties and/or limitations of the evidence

Agricultural systems

- The effect of EEF on N in runoff needs further clarification as the evidence is sparse with mixed findings.
- Reducing N fertiliser application rates is the clearest path to reducing DIN discharges from cropped lands. However, the effects of "moderate" (e.g., 20%) reductions of N on productivity are uncertain, ranging from nonexistent to statistically significant reductions. While more is known about the causes of that variability and uncertainty compared to 2017, there is still limited understanding about how to predict or manage it
- There is little information on management practices affecting loss of dissolved P from cropped lands and the role of mill mud in N and P dynamics needs to be further clarified.
- The evidence relating to different management practices for crops other than sugarcane is very sparse and often involved testing of multiple practices at once. More studies, including modelling, to tease out the effects of individual practices as well as the effects of soil, climate and seasonal conditions are warranted.
- Spatial and seasonal variability is a challenge – demonstrating consistent effects on farm in individual years as opposed to trends in meta-analyses and modelling and the challenge this may pose for adoption.

Non-agricultural systems

- Limited on-ground assessments for non-structural controls.
- Impacts of reuse.
- Potential leaching of nutrients from some treatments.
- Many experimental and modelling studies but limited field measurements.
- Costs are difficult to come by.

Economics

- Most of the modelling studies examined the impact of practice change on representative farms that have characteristics typical of a region. As such, the results provide a representation of farm profitability and water quality impacts in each district and are, by no means, representative of every paddock or indicative of a particular farming business. The modest variation in farm Gross Margins within regions highlights the need to consider any specific transaction costs and risk associated with each practice change (van Grieken et al., 2014). Farm layout, rainfall patterns, grower experience, specific soil types, financial situation and farming systems can all influence the farm operating and investment costs, which would in turn impact BMP adoption and farm profitability (Harvey et al., 2018; Holligan et al., 2017).
- The water quality effect of the N application methods such as broadcast, banding and fertigation in banana crops could not be represented in the modelling due to a lack of data on the implications for off-site loss. The impact of management practice changes on DIN in deep drainage is still poorly understood (Harvey et al., 2018).
- The results for cost changes vary depending on the nature of the change in management practice and the particular parameters. Investment risk needs to be included. The impact of management practice changes on soil health, yield and the number of profitable ratoons in a production cycle warrants further consideration, as these factors may have a considerable impact on the economic outcome (Poggio et al., 2018).
- Cost and effectiveness estimates vary across different sugarcane farming systems, soil and land types, regions and catchments. Studies are often undertaken for different purposes, timescales

within the regions/catchments and audiences. Estimates usually depend on an implementation of specific measures, environmental conditions, spatial and temporal scales, baseline/reference scenario, types of land use and management practices. An inclusion of different costs and/or elements of costs significantly contribute to variations. Thus, the estimates are not directly comparable and do not accurately account for some of the cross sector and regional heterogeneity in abatement costs. Costs considered should be appropriate for the scale at which they are assessed. Common characteristics that influence costs, production and profitability include property size, soil fertility, land condition, and distance to processing plant or market. These aspects should continue to remain a focus of future work. Transaction costs, time to adopt practices and for costs and benefits to accrue, program and administration costs and N export locations should be consistently captured depending on the scale of assessment and purpose of the research study (Farr et al., 2019).

- Many of the past economic modelling studies investigated the cost-effectiveness of management practice change for a major soil grouping in each region. Although a major soil grouping represents a large proportion of the farming area within a region, the water quality implications (and abatement of pollutants) will likely change when investigating different soil types and climatic locations, hence impacting on the cost-effectiveness calculations.
- Many of the past economic studies have obtained information on practices assumed, rather than comprehensively demonstrated to have water quality benefits. The assumption of water quality benefits in these studies should not be interpreted as evidence of water quality benefits.

4.2 Contextual variables influencing outcomes

The contextual variables for the outcomes of Question 4.6 are summarised in Table 7.

Table 7. Summary of contextual variables for Question 4.6.

Contextual variables	Influence on question outcome or relationships
Climate variability, both seasonal and interannual, and climate change	Climate variability affects the likelihood of DIN losses from sugarcane. The effects occur because the timing and amount of rainfall affects the volume of water running off and leaching below a field, which are the vectors for transporting greater amounts of DIN off a field. They also occur because rainfall, solar radiation and temperature determines crop growth (and nutrient uptake). Rainfall can result in waterlogged soils which in turn reduce crop growth and nutrient uptake. Thus climate variability affects many processes which interact to produce the resultant water quality and production outcome in a given season. While there has always been an understanding about the role of climate variability driving DIN discharges (e.g., Thorburn et al., 2011c), a much clearer understanding has recently emerged about how and why climate affects the optimum amount of N fertiliser for sugarcane (Thorburn et al., 2017; 2018) and the possible water quality and product benefits if we were able to match N fertiliser applications to climate (Biggs et al., 2021). Much of this understanding has come from research in the Wet Tropics. Climate variability also affects the benefits from EEF because of all the factors and processes described, as well the actions of EEF themselves being sensitive to soils water content and/or temperature. As with conventional N fertilisers, a much clearer understanding of the effect of climate variability on EFF has recently emerged. Benefits are more likely in the Wet Tropics than other regions and more likely in seasons with rainfall during the early weeks/months of the ratoon crop (Verburg et al., 2022; Webster et al., 2022). There is limited understanding of the impact of climate change on discharge of dissolved nutrients from GBR catchments.

Contextual variables	Influence on question outcome or relationships
Timing of sugarcane ratoon crop	The timing of sugarcane ratoon crop is a strong factor in determining the likelihood and magnitude of DIN losses from sugarcane due to rainfall in the early weeks or months after fertilisation being more common in late ratoon crops (Biggs et al., 2021; Migliorati et al., 2021), consequently this affects the effectiveness of EEF use in reducing DIN losses (Verburg et al., 2022; Webster et al., 2022).
Soil type	Soil type affects the pathway of DIN losses and affects benefits from EEF, with productivity benefits more likely on permeable soils where the crop potential is not limiting the crop's N response (Verburg et al., 2018).
(non-agricultural) Land use type	The non-agricultural land uses vary considerably so one of the key contextual variables will be the land use and its intensity, both in terms of the generation of stormwater runoff or for wastewater production. For the former, the amount of impervious surface appears to correlate with the loads for diffuse runoff, whereas for point sources, it is often directly related to wastewater volume.
(non-agricultural) Nutrient source	Whether the nutrient source is from a wastewater discharge (point source) or via runoff (diffuse source) dictates the management actions that are most likely to be effective and there is little overlap in treatment mechanisms, though occasionally some treatments (e.g., wetlands) may be effective across both sources albeit using different configurations to reflect the nature of both the nutrient load (point sources typically being higher in concentration with lower variability in flows, diffuse sources having lower concentrations but highly variable flows).

4.3 Evidence appraisal

The results of the evidence appraisal for the components of Question 4.6 are presented in Table 8.

Relevance

Relevance of the overall body of evidence to the questions was Moderate, but on the high side. The rating for relevance to Question 4.6 was highest, ranging from a rating of 3 in the Urban appraisal to a rating of 2.2 in the Economics appraisal. The lower score in the economics appraisal was likely due to inclusion of a wide range of studies, some of which provided only information on certain aspects, and fewer studies specifically targeted at the question.

Within agricultural land uses, there were considerably fewer studies considering phosphorus, so that its ratings for questions on agricultural land uses reflected the evidence relating to nitrogen. There was also variation between crops, with crops other than sugarcane having a limited number of studies. Thus the ratings reflect the dominance of sugarcane studies. Spatial relevance was interpreted to mean that the evidence captured evidence from a wide range of regions or sites, representing soil and climatic differences. This rating tended to be moderate across the Wet Topics stemming from a mix of single site and multiple site studies. However, the number of multiple site studies appear to have increased in recent years. There was a smaller number of mostly single site or regionally constrained studies in other regions, so the spatial relevance was lower for these regions. The spatial relevance for the body of evidence as a whole was Low to Moderate (or listed as not applicable). Modelling studies generally covered greater spatial scales to scored high on this aspect. The temporal relevance rating tended to be lowest, balancing low scores for most experimental studies and high scores for modelling studies.

For the questions on the effect of reducing N rate or of using EEF in sugarcane land use, combining modelling and experimentation provided a more complete picture – i.e., modelling compensating for the lower temporal relevance of individual experiments. In relation to the biophysical aspects of the secondary question on EEF, the relevance of the body of evidence for the question was high (2.8 out of

3.0) on account of most studies being specifically focussed on evaluating the environmental or agronomic benefits of EEF. The spatial relevance was Low to Moderate (1.5) with many studies limited to one site, although in recent years a number of larger studies included several sites across the GBR, including the large experimental study by Connellan et al. (2022a; 2022b) on 74 farms across the GBR and the Webster et al. (2022) modelling analysis for 10 climates x 5 soils each across the Wet Tropics. Temporal generalisability scored low among the experimental studies, but high for the modelling studies, for a moderate rating of 1.8. The overall relevance was Moderate (6.1).

For the management of mill mud there were a small number of highly relevant studies, but they were limited to a single site. Another study modelled mill mud in more regions but provided little detail about the methods. Thus, for mill mud the spatial relevance is Low.

The relevance of research on irrigation is Low because few studies reported both water quality and production outcomes. The spatial relevance is also Low because the vast majority of insights come from one region.

The evidence for non-agricultural land uses was reasonably extensive when searching across Australian studies, but only limited studies for Queensland and very few for the GBR region. There is also a lack of recent studies in the stormwater runoff field in the last five years, with many of the studies occurring prior to that period. Similar to the agricultural evidence, the spatial relevance is Low to Moderate with the temporal relevance also being Low to Moderate.

Table 8. Summary of results for the evidence appraisal by topic for Question 4.6. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency.

Aspects	Relevance to the question (out of 3.0)				Quantity of items	Diversity of items	Consistency	Confidence
	To the Question	Spatial	Temporal	**Overall**				
Agriculture								
Primary question	1.5 Moderate	1.1 Low	1.5 Moderate	4.2 Moderate	70			
Use of EEF to reduce N loss	2.9 High	1.5 Moderate	1.8 Moderate	6.1 Moderate	21	High	High	Moderate
Effect of mill mud on N and P loss under sugarcane	2.8 High	2.0 Moderate	2.5 High	7.3 High	4	High	Low	Limited
Effect of N rate reduction on N loss	2.8 High	1.5 Moderate	2.4 Moderate	6.7 High	29	High	High	High
Other practices and in other crops	1.5 Moderate	1.1 Low	1.5 Moderate	4.2 Moderate	0-5 per practice/crop	Low	Low	Limited
P studies	1.8 Moderate	1.0 Low	1.3 Low	4.0 Moderate	8	Low		Limited
Economics	2.2 Moderate	2.2 Moderate	1.4 Low	5.8 Moderate	56			Moderate
Non-agricultural								
Non-agricultural	3 High	2 Moderate	1.5 Moderate	5 Moderate	119		High	Moderate
Stormwater runoff – wetlands & biofilters	2.2 Moderate	2.4 Moderate	2 Moderate	8 High	26		High	High

Consistency, Quantity and Diversity

Based on the authors' experience and knowledge of the potential total pool of available evidence on agricultural land uses for this topic, it is considered that a high proportion of evidence has been used to answer the question. This is evidenced by only 3% of the studies being added manually by the authors.

The quantity and consistency of studies varied widely by topic, management practice and land use for both agricultural and non-agricultural land uses, so that its overall Moderate score only reflects that it sits between low and high. For several topics for sugarcane land use, e.g., the effect of N rate and use of EEF, the quantity and consistency ratings were High (in the case of EEF thanks to a rapid increase in studies since the 2017 SCS). The quantity rating of these management practices was much lower or not even explored for other crops. For other management practices, e.g., effect of mill mud and irrigation management the quantity and consistency of studies was much lower, even for sugarcane. A particular example is studies on the water quality benefits of burying fertilisers. Two recent studies (Cook et al., 2021; Melland et al., 2022) found contrasting effects of burying N fertiliser on the amount of DIN discharged in runoff of simulated rainfall applied three times during the year. Results of an earlier study (reported by Thorburn & Wilkinson, 2013, Figure 2) also show no benefit of burying N fertiliser. Studies on crops other than sugarcane often studied the combined effects of management practices, rather than providing an understanding of the effects or benefits of single practices.

The biophysical aspects of the secondary question on EEF were characterised by a high score for quantity (30% of all biophysical studies on N), although the quantity of studies characterising N loss was lower, lacking solid extrapolatable evidence from experiments. Its score for diversity was High on account of a mix of experimental and modelling studies whose results reinforced each other. The score for consistency was rated High, although this is a high consistency in inconsistent outcomes of EEF in individual trials. However, the drivers affecting the variability (climate, soil, management including timing aspects) are now understood. This does, however, not mean that implementation is straightforward. The variability and economic aspects are challenging for adoption.

Additional Quality Assurance (Reliability)

The internal validity of studies was generally high, with concerns on quality only noted for a few studies (e.g., lack of replication, sampling of subset of events or only at snapshots in time, measurements of N concentrations instead of N loads limiting the conclusions that could be drawn), many of which still provided some evidence with their limitations noted.

Confidence

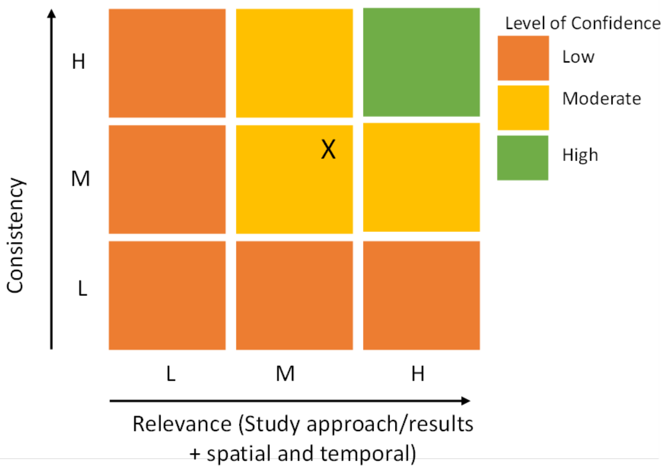
The overall confidence rating, stemming from relevance and consistency, was rated as Moderate, but varied across different topics (Table 8, Table 9).

The overall confidence in relation to the secondary question on EEF comes out as High to Moderate. The scores for spatial and temporal relevance keep the formal result as Moderate, but this is due to the larger number of experimental studies and ignores the corroboration provided by experimental and modelling results aligning well. The confidence in the key conclusions was judged to be High. That said, confidence in precise predictions of benefits for a given site and season is still relatively low on account of the noted climate-driven variability.

The confidence that improving irrigation efficiency improves water quality outcomes for DIN losses from sugarcane is Low because the vast majority of published studies do not provide enough detail of the methods, validation or results to draw reliable conclusions about the water quality. Additionally, the confidence that practices that may give water quality benefits can also maintain or improve agronomic and economic outcomes is Low because of the lack of detail on water quality in studies of economic indicators (or parameters relevant to economics).

The confidence in the outcomes of managing mill mud is Low because of the small number of relevant studies. The confidence of the economic outcomes of mill mud management is Low due to very limited research in this area and inconclusive results.

Table 9. Summary of results for the evidence appraisal of the whole body of evidence in addressing the primary question. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency. The final row summarises the additional quality assurance step needed for questions using the SCS Evidence Review method.

Indicator	Rating	Overall measure of Confidence
Relevance (overall)	Moderate - High	
-To the Question	Moderate - High	
-Spatial (if relevant)	Low - Moderate	
-Temporal (if relevant)	Low - Moderate (or N/A)	
Consistency	Moderate - High	
Quantity	Moderate (range Low - High) (294 studies)	
Diversity	High (46% experimental, 21% modelling or conceptual, 15% reviews and secondary analysis, 13% observational and 5% other including mixed studies, social and behavioural)	
Additional QA (Reliability)	High	The internal validity of studies was generally high, with concerns on quality only noted for a few studies, many of which still provided some evidence with their limitations noted.

4.4 Indigenous engagement/participation within the body of evidence

None reported.

4.5 Knowledge gaps

Nitrogen and phosphorus

- The climate-driven (and thus unavoidable) variability of water quality and productivity/profitability benefits of some of the management practices, notably reduction in N rate and use of EEF, pose challenges for implementation. Methods for seasonal climate forecasting continue to improve and more information on the extent to which this information reduces the uncertainty of the outcomes would be beneficial. Developing new methods, or more detailed evaluation of current methods for farmers to manage the 'downside' economic risk of achieving improved water quality would be valuable.
- For N in sugarcane production, modelling has proven effective in extrapolating insights into water **and** production (and hence economic) results from experimental studies in sugarcane to

provide an understanding of spatial and temporal variability. This cannot yet be done for other crops or nutrients as the modelling frameworks are either not as comprehensive as for N in sugarcane, or do not exist. The current modelling capability can handle grain crops and, to a lesser extent cotton, based on model verifications in other environments. However, to extrapolate the sparse experimental findings for bananas and horticulture, further quantification of N losses as well as crop N uptake and response are required.

- To clarify the current mixed findings of the effect of EEF and mill mud on dissolved N and P in runoff and to ensure models have a robust basis for extrapolation of experimental results, further quantification of dissolved N and P in runoff, and the effect of EEF and mill mud on it, is required.
- To better inform the required adjustments to fertiliser N and P and give growers confidence on that, further quantification of the timing of N and P release from mill mud as a function of its composition is needed. Climate is likely to have a substantial effect on nutrient release, so ways of coping with climate-driven (and thus unavoidable) variability in N and P release should also be considered.
- There is little comprehensive or reliable published information on the water quality and associated production outcomes of different irrigation systems (e.g., furrow versus trickle) or management or irrigation within a system (e.g., improved scheduling of irrigation). Some studies report water quality benefits, but not production outcomes. Others **assume** water quality benefits and focus on production. Further, many modelling studies do not describe the modelling in enough detail to understand how the results came about. More detailed modelling studies could be undertaken and published. Further field studies would add important confirmation to these studies.
- There is little comprehensive or reliable published information on the water quality and associated production outcomes for agricultural land uses other than sugarcane production.
- There is little comprehensive published information on the water quality and associated production outcomes of burying N fertiliser.

Economics

- There is a lack of economic information on mill mud, legume break crop, fallow length in rotation with cane, variable application rate strategies and their impact on water quality and farm economic outcomes.
- There is limited research on exploring the economic and environmental implications (e.g., losses of DIN and P) of applying mill mud in different locations. There is a paucity of information on the environmental costs such as costs in the form of leaching or odour due to stockpiling, erosion or groundwater contamination due to over-fertilisation, or costs of heavy metal contamination in the existing studies (Qureshi et al., 2001; 2007). Comprehensive mill mud management strategies should also consider locational characteristics of farms, such as soil types and paddock layouts, and other geographic features that can be efficiently incorporated within a spatial regional analysis (Qureshi et al., 2001).
- Limited research on the cost of changing irrigation practices, particularly in conjunction with nutrient management. No studies were found that assess costs, profitability and cost-effectiveness of irrigation shifts to the lowest (L) water quality risk management practices.
- There is limited information on the ideal timing of EEFs application in a ratoon crop. Fertiliser delivery methods (e.g., side-dressing) could be tested to help distribute EEFs more evenly across the plant bed at the desired depth with sufficient slot closure. The objective of further testing would be to maximise the effectiveness of EEFs at lower N rates. Benefits of the EEFs could not be achieved in every climate, crop class, soil type, season, and timing of fertiliser application, thus, those factors should be accounted for. EEF products with higher longevity could provide relatively greater environmental benefits and require further research.
- Integrated approach (e.g., a combination of field trials, biophysical and economic modelling) would benefit future research as it would provide more accurate information on economic and

environmental benefits of nutrient management practices for water quality outcomes. Virtual trials should be complemented by field trials.

- There is a lack of emphasis on farm heterogeneity across individual growers and regions.
- Economic and environmental assessment studies do not include a transaction cost. However, transaction cost and time to adopt practices for costs and benefits to accrue, program and administration costs and N export locations should be consistently captured depending on the scale of assessment and purpose of the research study.
- There are a limited number of studies that applied any form of statistical analysis.
- More realistic variability could be introduced into future simulation models such as a greater number of soil types, allowing soil organic C, N and water to change over time and a wider variety of management practices (e.g., timing of fertiliser applications, precise harvesting dates).
- Climate change is one of the key contributing factors to the decline in health of the GBR but it is poorly captured in cost-effectiveness studies.
- Research should consider the likelihood of combined pollutant reductions. Management actions, that potentially focus on a single pollutant reduction, may fail to capture cost-effectiveness reductions in other pollutants.
- Very few experimental field studies related to farm economics included a water quality outcome component.
- Consideration and inclusion of a wide range of variables in N_2O estimation are highly desirable for further improvements to N_2O mitigation (Maraseni & Kodur, 2019).
- An inclusion of ground water nitrate tests that can be linked to alternate application rates of N should be included in future trials that are under conditions where ground water contributions of nitrates are significant (Nothard & Pfumayaramba, 2021).
- There is a lack of comprehensive studies integrating environmental, economic and social information for all land uses.
- Limited research on economic benefits of moving to management practices in banana crops (e.g., nutrient management) for water quality improvement.
- Limited research on economic, agronomic and environmental benefits to water quality in horticulture. The value of horticultural production per hectare varies considerably, and this can influence how crops are grown and risks approached (e.g., less consideration of input cost impacts when crops are higher in value). Limited work on measuring horticultural risk impacts in the GBR. No economic studies that both identify and examine barriers to practice improvement or practice change. No research on economically viable improved management practices for the industry. No clear understanding of the exact economic relationships between soil, pesticide and nutrient risks in excess rainfall conditions/events (Milbank & Nothard, 2023).
- Controlled traffic and reduced tillage operations are under-explored in horticulture. In crops such as sweet potato, haul-out tractors intermittently drive on top of the seedbed creating long term compaction issues. Economic and environmental outcomes should be explored for crops with the highest potential water quality impact. These include new macadamia plantations, avocados and pineapples, mulched crops (due to environmental management requirements of micro-plastic pollution and the intensive cycling of continuous supply root crops) (Milbank & Nothard, 2023).

Urban/non-agricultural land uses

- There is very limited evidence on the costs of management practices available in the literature and this would need to be evaluated through further examination of the grey literature, though it is understood that this is also limited.
- While there is a considerable body of evidence around the use of biological and vegetated treatment systems, there was a lack of spatially relevant literature which would mean there is some uncertainty around the applications in the tropics and subtropics, though studies have focused on the effects of climate variability and some studies were undertaken in those climates.

- There is a lack of evidence around the ongoing implementation of a range of treatment systems, especially where vegetated and biological systems are used, particularly in relation to their longevity, maintenance and renewal requirements over time. There are a wide range of these systems implemented across the region, but a lack of a systematic assessment of their performance or whether they are achieving the outcomes anticipated through design and modelling.

The management context of some key knowledge gaps is summarised in Table 10.

Table 10. Summary of knowledge gaps for Q4.6.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
The climate-driven (and thus unavoidable) variability of water quality and productivity/ profitability benefits of N fertiliser management, including EEF.	Determine the extent that forecasts of seasonal climate, based on recent forecasting methods, can reduce uncertainty in the water quality and production outcomes of conventional and EEF N management. Develop and/or further test ways of reducing the negative economic outcomes to farmers of implementing practices to reduce discharge of dissolved nutrients.	Reduces barriers to, and thus greater adoption of practices to reduce discharge of dissolved nutrients from agricultural lands.
Understanding the trade-offs between water quality benefits and productivity dis-benefits of improved irrigation.	Conduct studies, both experimental and modelling, that qualify both the nutrient discharges (in both runoff and deep drainage) and crop yields of different irrigation systems (e.g., furrow versus trickle) and different irrigation scheduling used in a system (e.g., high versus low efficiency of furrow irrigation).	Clear understanding of the extent to which improved irrigation management and/or improved systems can reduce nutrient discharges and the cost effectiveness of any water quality benefits arising from these interventions.
Best practice management of nutrients of crops after mill mud application and the economics of these practices. Bioavailability of nutrients in mill mud.	Studies, both experimental and modelling, on discharges (in both runoff and deep drainage) and bioavailability of nutrients, following the application of mill mud, and the management and economics of nutrients for crops after mill mud application. Management will be aided by developing methods for determining the nutrient loading in mill mud applied, which can be affected by both variations in nutrient concentrations in mill mud and the amount of mill mud applied.	A limitation to the effective management of mill mud is the limited understanding of nutrient discharges and crop growth following mill mud application.
Studies on the management of dissolved P discharges in all cropping systems.	To what extent does reducing P fertiliser application rates reduce dissolved P discharges, and are there other management practices that can provide similar or greater benefits at similar or lower cost.	Understanding the cost effective reduction of dissolved P discharges.

5. Evidence Statement

The synthesis of the evidence for **Question 4.6** was based on 294 studies, undertaken across the Great Barrier Reef catchment area and wider Australia for non-agricultural/urban-related evidence and published between 1990 and 2022 (plus a few older references dating back to 1976 for non-agricultural/urban evidence). The synthesis includes a *High* diversity of study types (46% experimental, 21% modelling or conceptual, 15% reviews and secondary analysis, 13% observational and 5% other including mixed studies, social and behavioural), and has a *Moderate* confidence rating (based on *Moderate* consistency and *Moderate* overall relevance of studies).

Summary findings relevant to policy or management action

Reduced application of nitrogen fertiliser is a consistent means of reducing dissolved inorganic nitrogen exported from fields via all pathways (runoff, leaching and gaseous losses) in different agricultural land uses, climates and management contexts in the Great Barrier Reef catchment area. In sugarcane, nitrogen application rates above industry best practice can result in avoidable nitrogen loss, increase the cost of production and reduce economic returns. However, reducing fertiliser nitrogen rates “too much” can impact on productivity and hence on profitability at the farm and sugarcane mill, although the definition of “too much” is variable. Enhanced-efficiency fertilisers may reduce both dissolved inorganic nitrogen export via leaching and mitigate risks of productivity losses when nitrogen fertiliser applications are reduced. However, the results are highly variable across sites and years and consistent benefits are often only seen when averaged across sites and seasons. There are limited studies that assess the effectiveness, productivity or cost-effectiveness of other sugarcane management practices including mill mud application, subsurface application of fertiliser, improved irrigation, crop residue management and various attributes of improved farming systems (e.g., tillage, fallow legumes) in reducing dissolved inorganic nitrogen export. There is little peer reviewed evidence on the effectiveness of management practices for reducing dissolved inorganic nitrogen export in crops other than sugarcane, or on the management of dissolved phosphorus exports. For urban/non-agricultural land uses, structural measures that include vegetation or biological components, such as wetlands, biofilters, algal ponds and existing riparian zones have considerable potential for removal of diffuse runoff nutrients and may also be important for management of wastewater. Non-structural controls for nutrient management in non-agricultural land uses including policy, planning, regulation, compliance and education, appear to work best when completed as part of an integrated approach. Recycling and reuse of wastewater shows considerable potential, provided that there is careful consideration of the location of water reuse.

Supporting points

- The possible impacts of reducing nitrogen fertiliser rates on productivity and profitability in sugarcane are variable and can be affected by climate, soil and seasonal conditions. As a result, the optimum nitrogen fertiliser rate (i.e., the rate giving near maximum profitability) is both unknown and unpredictable for a specific sugarcane crop. Reducing fertiliser rates reduces the cost of production for crops; however, there may be additional costs such as expenditure on capital or an increase in other business expenses in doing that and there is a risk that productivity will be reduced.
- Reducing nitrogen rate (or applying enhanced-efficiency fertilisers) is likely to provide greater water quality benefits for crops starting later in the year, as the magnitude of dissolved inorganic nitrogen losses will generally be greater closer to the start of the wet season and first rainfall events. This timing may also affect the productivity impact of reduced nitrogen applications.
- Enhanced-efficiency fertilisers act by reducing the concentration of the mobile form of inorganic nitrogen (nitrate) in soils which helps to reduce leaching. Benefits of using enhanced-efficiency fertilisers are likely to be greatest for crops starting in mid- to late-season, in wetter regions and wetter growing seasons. Increased productivity will only occur if dissolved nitrogen leaching is reduced and crop growth at that time is responsive to the additional nitrogen available in the

soil. These conditions are more likely on permeable soils. There is limited evidence quantifying the benefits of enhanced-efficiency fertilisers in reducing dissolved inorganic nitrogen losses.

- There is some evidence that applying mill mud to sugarcane can increase losses of dissolved phosphorus, but not nitrogen. Reducing fertiliser application rates in crops following mill mud application seems prudent to reduce risk of additional dissolved phosphorus and nitrogen losses; however, the benefits of these interactions have not been quantified. In addition, the extent to which fertiliser applications can be reduced following mill mud without impacting on crop productivity is unclear.
- The effect of improved irrigation practices on dissolved nutrient losses or on farm productivity in the Great Barrier Reef catchment area is uncertain, with most information derived from mechanistic modelling studies in sugarcane. The available results indicate that high irrigation efficiency resulting from lower irrigation application rates, is predicted to reduce dissolved inorganic nitrogen losses from sugarcane crops, but there is a risk that productivity is also reduced. While there is evidence that well-designed and managed automated furrow irrigation systems on sugarcane farms can be profitable, the water quality outcomes of these systems are not clear. Limited evidence suggests that converting to a fully automated irrigation system on banana farms may potentially provide economic benefits.
- There is limited evidence on the effectiveness of management practices for reducing dissolved inorganic nitrogen export in bananas, horticulture and grains. Mechanistic cropping systems models, that have been useful in providing insights in sugarcane production, are not well developed or tested for these crops.
- Factors that influence the cost-effectiveness and productivity of nutrient management practices in cropping include farm size and layout, rainfall patterns, soil type, landholder experience and distance to a processing plant or market. Program and administration costs, transaction costs and the time taken to adopt practices and for benefits to accrue are also important. Better recognition of these factors and more consistent monitoring and reporting will improve understanding of the cost-effectiveness of achieving improved water quality.
- In non-agricultural areas, planning and regulatory requirements are driving innovation in nutrient treatment. The use of planning and regulatory approaches continues to support the application of suitable nutrient management actions (both structural and non-structural) and are most effective when considered in conjunction with specific treatment controls. Biofilters appear to be the most cost-effective treatment systems in this case, but this is based on limited data and modelling studies. Improvements in technologies for wastewater management also show that systems such as membrane filtration and chemical addition are likely to perform well.

6. References

The 'Body of Evidence' reference list contains all the references that met the eligibility criteria and were counted in the total number of evidence items included in the review, although in some cases, not all of them were explicitly cited in the synthesis. In some instances, additional references were included by the authors, either as background or to provide context, and those are included in the 'Supporting References' list.

Body of Evidence

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Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 4.6

Theme 4: Dissolved nutrients – catchment to reef

Primary Question 4.6: What are the most effective management practices for reducing dissolved nutrient losses (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions? What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices?

Secondary Question 4.6.1 What is the potential of Enhanced-Efficiency-Fertilisers (EEFs) in reducing nitrogen runoff and what are the primary challenges in implementation?

Secondary Question 4.6.2 What are the implications of mill mud application in influencing nitrogen losses and what are the primary challenges for implementation?

Secondary Question 4.6.3 What are the primary factors that influence nutrient losses from irrigated areas and how can these be managed?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Peter Thorburn	CSIRO	Farming systems, N, P, mill mud	Lead author	All sections except urban and editing role economics sections, N and P searches and conceptual model.
2. Kirsten Verburg	CSIRO	Farming systems, N, EEF	Contributor	All sections except urban and editing role economics sections, N search and conceptual model.
3. Marina Farr	DAF	Economics	Contributor	Economics sections and conceptual model, economics search, all text in other sections relating to economics.
4. Tony Weber	Alluvium	Urban and wetlands	Contributor	Urban/non-agricultural sections, urban and wetland searches and conceptual model, all text in other sections relating to urban/non-agricultural.
5. Maria Vilas	DESI	Farming systems, N, P, mill mud	Contributor	P searches and conceptual model, review of P and mill mud text.
6. Caleb Connolly	DAF	Economics	Contributor	Economics sections and all text in other sections relating to economics.
7. Rohan Eccles	DESI	Urban	Contributor	Urban searches and appraisal.