# 2022 Scientific Consensus Statement

## **Question 8.1** What are the co-benefits e.g., biodiversity, soil carbon, productivity, climate resilience, of land management to improve water quality outcomes for the Great Barrier Reef?

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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

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# Executive Summary

## Question

**Question 8.1 What are the co-benefits e.g., biodiversity, soil carbon, productivity, climate resilience, of land management to improve water quality outcomes for the Great Barrier Reef?**

## Background

Water quality improvement is important for the health of the Great Barrier Reef (GBR) and requires a range of management actions to reduce land-based runoff and the associated impacts of sediments, nutrients, pesticides and other pollutants to the GBR. Of primary interest is the effectiveness of land management practices for improving water quality runoff from agricultural land uses (reviewed elsewhere in the 2022 Scientific Consensus Statement (SCS), primarily Questions 3.5 Bartley & Murray, 3.6 Brooks et al., 4.6 Thorburn et al., and 5.3 Davis et al.), and there is growing interest in understanding the co-benefits of these practices such as economic and production outcomes, reduced carbon emissions, increased biodiversity, and improvements to soil health. In this Question, co-benefits are the additional positive environmental and social outcomes from adoption and implementation of practices for water quality improvement.

This Question reviews potential on-farm co-benefits of implementing practices for water quality improvement in the GBR catchment area. The major agricultural land uses considered are grazing, sugarcane, horticulture and grains. The primary direct co-benefits examined in this review are improved biodiversity, better soil health, reduced greenhouse gas emissions and beneficial outcomes for Indigenous communities. While economic and production outcomes are clearly recognised as co-benefits, they were not included in this review as they are integral components of other SCS Questions (noted above) and these questions are cross-referenced where appropriate. Assessment of the 'downstream' effects of the co-benefits on GBR ecosystems is also outside of the scope of this Question. Furthermore, indirect or 'expected' co-benefits such as reduced gully erosion as a result of ground cover management in grazing lands, were not within scope.

## Methods

- 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[5]. 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 Summary method was used.
- Search locations included Scopus and Google Scholar.
- While this Question follows the formal 2022 SCS Method for the Synthesis of Evidence, it was delivered in two phases, with the second phase completed following preliminary peer review. This is described further in the Methods. The initial scope of the review included consideration of the potential co-benefits of land management practices with water quality benefits in the grazing, sugarcane and horticulture industries. The second phase extended the search to include grains and added criteria to refer specifically to the agricultural management practices generating water quality outcomes in the Paddock to Reef Water Quality Risk Framework, and the subsequent paddock scale co-benefits including biodiversity, reduced greenhouse gas emissions, increased soil carbon and opportunities for benefits to Indigenous communities. From the initial keyword search, 354 literature items were identified through online searches. Following secondary screening of the full-text, 30 were eligible for inclusion in the Evidence Summary. An additional 16 items were manually added through either personal collections,

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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

peer networking, or identifying other potentially relevant studies from key evidence items. A total of 46 studies were included in the initial synthesis.

- Following preliminary peer review, a further 258 items were screened and an additional 51 studies included in the synthesis.
- Therefore, a total of 612 studies were evaluated for this Question with a total of 97 included in the body of evidence for the synthesis, with one study used for grazing and grains land uses.

### Method limitations and caveats to using this Evidence Summary

A deviation from the standard process was necessary for this review based on the initial peer review feedback to include a wider scope of studies in answering the question. This involved an additional set of literature searches being conducted by another author resulting in more evidence being included in the review.

While there are a broad range of co-benefits that can accrue from land management techniques to improve water quality, this Question focuses on a subset that represent both public and private co-benefits and offer opportunities to demonstrate the potential for co-benefits to be achieved across agricultural sectors in the GBR catchment area.

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

- Only one academic database was searched.
- Only studies written in English were included.
- Only peer reviewed publications were included.
- Only studies published from 1990 were included.
- Separate authors assessed evidence items for the two searches. The second author conducted the initial search and prepared most of the grazing section. The first author was engaged following preliminary peer review and conducted the additional search, wrote the sections covering sugarcane, grains, horticulture and bananas, and addressed the second round of peer review.
- Water quality benefits of land management were not included in the scope of the review because these are covered elsewhere in the SCS (e.g., Questions 3.5 Bartley & Murray, 3.6 Brooks et al., and 4.6 Thorburn et al., this SCS).
- Downstream effects (e.g., for streams, rivers, and wetlands) were not included because these are covered elsewhere in the SCS (e.g., Questions 3.2 Collier et al., 4.2 Diaz-Pulido et al., and 4.9 Waltham et al., this SCS).
- Potential indirect co-benefits or likely benefits from the ‘flow on’ effects of a management action intended for water quality improvement were out of scope.

## Key Findings

### Summary of evidence to 2022

The available literature clearly supports the proposition that there **may** be significant environmental and social co-benefits from land management practices designed to improve water quality in the GBR. The existence, and the extent, magnitude and duration of these co-benefits are however extremely variable, and depend on many contextual and site factors, as well as how the management actions are designed and implemented. Moreover, the evidence is equally clear that these benefits are not automatic, proportionate or inevitable, but will depend on careful design for each specific context. These conclusions are supported by the following key findings:

- Co-benefits occur where a specific land management practice implemented to improve water quality for the GBR has additional positive secondary impacts such as improving economic and production outcomes, reducing carbon emissions, increasing biodiversity and improving soil health.
- There are existing policy mechanisms such as the Land Restoration Fund and Australian Carbon Credit Unit scheme that are relevant to supporting co-benefits (environmental, socio-economic

and First Nations) flowing from GBR water quality management practices. While these existing mechanisms could offer opportunities for water quality benefits to be included with other co-benefits over the same area, differences in the guidelines, timelines, measurements and specific practices of the programs currently impede this.

- Key considerations for successful policy and program design to encourage greater adoption of practices yielding co-benefits include the characteristics of the specific co-benefit being sought, the capacity to accrue multiple benefits, the framework that is applied to measure the co-benefit and to achieve additional co-benefits, the timescale expected to achieve co-benefits and the monitoring and maintenance frameworks required to demonstrate their achievement.
- The Paddock to Reef Water Quality Risk Framework defines management practices within four categories related to the risk posed to water quality outcomes, ranging from low to high risk practices. The land uses in the framework include grazing, sugarcane, bananas, horticulture and grains. While many of the management practices outlined in the framework have the potential to generate co-benefits, further work is required to align these practices with related policies and programs.
- There are very few studies in the GBR catchment area that have directly measured the co-benefits of land management practices which are intended to improve water quality outcomes for the GBR. Most studies have focused on a single benefit, limiting the ability to fully assess the potential co-benefits of water quality improvement practices in agricultural land uses.
- The limited evidence indicates that the co-benefits of land management practices to biodiversity, soil carbon and carbon emissions vary spatially, based on the bioregion, land use and practice.
- The ways in which land management practices and climate warming interact will affect co-benefits. For example, grazing practices that increase tree cover, ground vegetation cover and soil carbon are likely to trap more water on the property and thus improve vegetation productivity, reducing the impacts of droughts.
- Non-agricultural land uses (such as urban), conservation areas and wetlands were outside of the scope of this review.
- Further work is needed to understand the potential co-benefits associated with water quality improvement actions in the GBR catchment area, and to identify appropriate mechanisms to encourage adoption of practices that have additional co-benefits.

*Grazing*

- There are opportunities to achieve positive carbon and biodiversity outcomes in grazing, however not all frameworks align. For example, woody weeds are a characteristic associated with poor land condition in some frameworks but are regarded as important for some forms of biodiversity elsewhere.
- The relationship between grazing management strategies and soil organic carbon over the short and long term is complex. Stored soil organic carbon (to a depth of 30 cm) appears to be influenced by various combinations of grazing intensity, land condition, rainfall and land/soil type, and it is difficult to establish evidence for a strong link between livestock management and soil organic carbon content. Studies to date indicate that the benefits of maintaining ground cover and/or reducing stocking rates for soil health can take many years.
- Improved riparian and vegetation management in grazing (and cropping) lands has resulted in positive changes for several bird, insect and other invertebrate species, with evidence of increased species richness and abundance, and changes to community composition.

*Sugarcane*

- A critical Paddock to Reef Water Quality Risk Framework management practice to reduce the risk of nutrient runoff from sugarcane is to apply less fertiliser to match industry recommended rates. Reducing the amount of fertiliser applied can reduce emissions of nitrous oxide (a greenhouse gas), however nitrous oxide can still be lost through other pathways including deep

drainage and runoff. Nitrous oxide emissions vary with soil type, temperature, and soil water which also vary across sugarcane growing regions.
- Maintaining sugarcane trash on paddocks after harvesting, or green cane trash blanketing can both minimise soil erosion and runoff, and improve soil health. The use of soybean break-crops to inhibit monoculture fungus and pests has also shown benefits for soil health. However, there is limited evidence that trash blanketing is beneficial for soil carbon.
- There is some evidence of downstream benefits to biodiversity from maintaining streambank vegetation in sugarcane areas.
- The methods for measuring co-benefits in sugarcane vary between studies, with additional variability in temporal and spatial characteristics, making it difficult to compare benefits between studies.

*Horticulture and bananas*

- There was only one study specific to horticulture, but many of the principles, practices and outcomes are similar to those of other cropping systems. As with sugarcane, reducing the amount of fertiliser applied in horticulture and bananas reduces the risk of nutrient runoff and potentially, nitrous oxide emissions. Nitrous oxide emission rates linked to the amount of fertiliser applied have been compared among horticulture crops, with emissions varying across plots. Increased monitoring will help to understand these potential co-benefits.

*Grains*

- There are potential improvements to soil health from crop rotation and fallow management, which reduce sediment erosion, break monoculture and reduce disease pressure.
- Grain cropping systems have the most long-term comprehensive datasets to assess the various co-benefits flowing from water quality improvement practices, and to understand the impacts of different climate cycles and climate change. However, these data do not necessarily align with different environmental benefits. For example, a number of soil carbon recordings were made at different depths from those required for credit by the Australian Carbon Credits Unit.

### Recent findings 2016–2022

While there are few studies that directly measure the co-benefits of land management practices to improve water quality, there is growing interest from policy, government and landholders to recognise and deliver additional benefits. These benefits are increasingly being recognised in Australian environmental markets. For example, green markets are a relatively new mechanism in Australia with Australian Carbon Credit Units designed for the *Carbon Credits (Carbon Farming Initiative) Act 2011* established in 2015 as part of the Emissions Reduction Fund. Currently, only the Land Restoration Fund in Queensland permits the ‘stacking’ of benefits (e.g., carbon and biodiversity).

Monitoring and the accompanying science behind co-benefits is relatively new and continues to be explored. Careful program design, including consideration of additionality and timescales to achieve different co-benefits, is required to ensure that different co-benefits can and do occur.

## Significance for policy, practice, and research

Co-benefits are complex in nature and in some instances are mutually exclusive, making it difficult for policy and program design. Not all of the identified co-benefits have approved methods for measuring benefits and, therefore, participation in some programs and enviromental markets is limited. The review identified that there is limited and varied measured data for the co-benefits that could be derived from water quality improvement practices. There are also large variations in findings, suggesting that the establishment of projects to generate multiple benefits would require specific planning and monitoring to assess their achievement.

There is limited direct evidence about whether specific land management practices for water quality improvement support co-benefits in the GBR catchment area. Studies investigating the potential co-benefits of land management in grazing, horticulture, sugarcane and grains rarely mentioned water quality improvement. The broader literature does, however, indicate that certain land management practices can lead to other benefits from water quality improvement actions. There can also be synergistic benefits that have a flow on effect from the initial co-benefit, however, these were deemed out of scope and highlight the need for clear policy regarding the co-benefits being sought. An integrated synthesis of this evidence in addition to the economic and production co-benefits of practices through biophysical improvements is needed to guide future management opportunities.

Careful policy and program design will be critical to consistently measure, and achieve co-benefits. Key considerations for policy include clear identification of the co-benefit or co-benefits that are being targeted, the capacity to accrue multiple benefits, the framework used to measure and achieve co-benefits, the timescale expected to achieve co-benefits, and the monitoring and maintenance frameworks required to demonstrate their achievement. Further work is needed to understand the potential co-benefits associated with water quality improvement actions in the GBR catchment area, and to identify appropriate mechanisms to encourage adoption of practices that have additional co-benefits.

## Key uncertainties and/or limitations

- This is a relatively new field of research in terms of specific quantification of co-benefits (as opposed to potential or conceptual inferences) so the criteria for inclusion of peer reviewed literature only may have limited the scope of available data.
- The focus on land management practices to improve water quality in the search terms is likely to have excluded studies where a land management practice implemented for reasons other than to improve water quality, but may have resulted in co-benefits.
- The management of invasive species in conjunction with achieving co-benefits was not explored, representing a limitation to the review. Invasive species have the capacity to diminish public and private benefits; a landscape-level strategic outlook is required to address these issues. For example, while Indian couch provides ground cover, it provides very little additional benefit to biodiversity or any private benefits.
- Potential disbenefits of management actions were outside of scope but would be an important consideration for water quality improvement programs.

## Evidence appraisal

A total of 97 studies were used in this Evidence Summary with one study relevant to grazing and grains land uses. These studies represented multiple lines of evidence including experimental, observational, and modelling.

For grazing, 57 studies were used to address the question. The overall relevance of the body of evidence to the question for grazing land uses was rated as High, but Consistency was classed as Low resulting in a Limited Confidence rating. For sugarcane, 21 studies were used. Based on a Moderate overall relevance to the question and Moderate Consistency, the Confidence rating for sugarcane was Moderate. For grains, 19 studies were used to address the question. The overall relevance of the body of evidence to the question for grains was rated as High and Consistency was scored as High which gave a Confidence rating of High for grains. For horticulture and bananas, the quantity of studies was Low as only a single study was found to address the question. This resulted in a Limited Confidence rating for horticulture and bananas.

# 1. Background

To support the health of the Great Barrier Reef (GBR), targets for end-of-catchment load reductions of total suspended sediments (TSS), dissolved inorganic nitrogen (DIN), particulate phosphorus (PP), particulate nitrogen (PN) and pesticides have been developed for each of the 35 basins adjacent to the GBR under the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP; Australian & Queensland Government, 2018). These targets are based on end-of-catchment anthropogenic loads and, therefore, linked to the relevant land uses in each catchment. Targets for the adoption of land management practices that improve water quality are also defined. Actions in grazing and grains are primarily linked to TSS and particulate nutrient reductions; and in sugarcane, bananas, and horticulture the actions are primarily linked to DIN and pesticide reductions, but TSS and particulate nutrients are also relevant in some locations.

In the context of this Scientific Consensus Statement (SCS) Question, co-benefits are the additional positive environmental or social outcomes from the adoption and implementation of practices for improved water quality outcomes. Production and subsequent economic co-benefits may also be derived from these practices; however, these benefits are not covered here as they are within the scope of Questions 3.5 Bartley & Murray, 3.6 Brooks et al., 4.6 Thorburn et al., and 5.3 Davis et al. Co-benefits can be direct where the land management practice leads to improvements in agricultural production, or indirect through, for example, changes in vegetation structure and composition leading to benefits for biodiversity or carbon sequestration in the soil. They can be private benefits such as productivity benefits, or public such as positive environmental outcomes or benefits to Indigenous communities. Assessment of the 'downstream' effects of the potential co-benefits on GBR ecosystems is outside of the scope of this Question.

## Policy mechanisms for co-benefits in the context of the GBR

A key factor for the consideration of the co-benefits associated with water quality management in the GBR is the range of likely drivers or barriers to adoption, including the current policy context. While this is not specifically within the scope of this Question and is addressed in Question 7.2 (Murray-Prior et al., this SCS), this knowledge provides important context for policy and management when considering potential options for broader implementation of programs that support co-benefits from water quality management in the GBR catchment area. A brief description of the policy mechanisms and instruments that are relevant to the GBR is provided below. An overview of the findings from Question 7.2 is presented in Section 1.3 (Links to other questions).

There are different policy and legislative frameworks which provide price mechanisms to landholders to encourage adoption of co-benefits. Many of these are referred to as types of market-based instruments (MBIs), where some form of government design or regulation is required in conjunction with market forces to establish the new mechanism. There are three broad types of MBIs: price-based, quantity-based and market friction approaches, with a range of potential instruments that can be applied in each group (Gómez-Baggethun & Muradian, 2015; Tennent & Lockie, 2013;).

Price-based and quantity-based approaches are the most well-known types of MBIs. A conservation auction is a type of positive price-based mechanism while a carbon tax is an example of a negative price-based mechanism. In these cases, it is the price (positive or negative) that drives the change. A cap-and-trade mechanism is an example of a quantity-based mechanism, where the amount available is capped, and then the price adjusted in the market to suit. Many permit-to-pollute schemes are examples of cap-and-trade mechanisms where the total level of pollutant allowed is set and then permits are traded in the market to reach the cap. The Reef Credits scheme is another version of a quantity-based MBI[6], where the water quality targets under the Reef 2050 WQIP (Australian & Queensland Government, 2018) is used to set the cap, and then unit improvements within that cap are traded in the open market.

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[6] https://www.qld.gov.au/environment/coasts-waterways/reef/reef-credit-scheme

Other important mechanisms are eco-labels, which fall into the market friction category. These are generally developed at an industry level, for instance a product receives an accreditation label (e.g., avocados or sugar with Reef Certified labelling) for making a specific improvement, and a premium is then placed on the product to cover the cost of implementing the framework (De Valck et al., 2022; Rolfe et al., 2023).

Currently in Queensland, there are a number of market-based instruments for environmental policies at the landholder scale that adopt a quantity-based approach to co-benefits (Table 1) that are operating in parallel to programs designed to manage GBR water quality. These include:

- Australian Carbon Credit Units (ACCUs) designed for the *Carbon Credits (Carbon Farming Initiative) Act 2011* established as part of the Emissions Reduction Fund in 2015.
- Reef Credits designed for the removal of nitrogen (N) specifically from sugarcane catchments or reduced sediment losses as a result of gully restoration.
- Land Restoration Fund (LRF) which adds increased incentives to landholders for participating in carbon credits and generating ACCUs and then providing co-benefits at socio-economic, environmental and Indigenous levels.
- National Stewardship Trading Platform.

Each of these existing market mechanisms has different characteristics for landholders seeking to participate in the market. For example, Reef Credits and the Carbon Credit Markets do not allow additionality of co-benefits, whereas the LRF and the National Stewardship Trading Platform do allow additionality, but these are not open access markets and there are set periods for calls for projects. Similarly, the time period varies for credit generation for each of the programs (Table 1).

The Clean Energy Regulator (Australian Government) prepared a Blue Carbon Method (2022) to activate market mechanisms for industry and investment schemes to fund restoration of coastal wetlands, including mangroves and tidal marshes for their capacty to sequester greenhouse gas (GHG) (Clean Energy Regulator, 2021). The method focuses on re-introduction of tidal inflow via removal or modification of tidal restriction mechanisms (such as realignment of earthen bund walls), which results in rewetting of completely or partially drained coastal wetland ecosystems and the conversion of freshwater wetlands to brackish or saline wetlands. The method enables ACCUs to be earned for the establishment of coastal wetland ecosystems that occur as a result of project activities[7].

*Table 1. Existing Market-Based Instrument programs and attributes relevant to co-benefits from management practices that improve water quality in the GBR.*

| MBI program | Allows participation in other MBI programs | Credit generation timeframe | Market access |
|---|---|---|---|
| Australian Carbon Credits | No | 25-year or 100-year | Open |
| Reef Credit Scheme | No | 10 years | Open |
| The Land Restoration Fund (LRF) | Yes - ACCU'S | 5–15 years | Call for applications during set periods. |
| National Stewardship Trading Platform<br>Carbon + Biodiversity Pilot | Yes - ACCU'S | 10 years | Pilot areas - calls for applications during set periods. |

Each of the MBI's have a series of methods to assess the environmental change, with the ACCUs having the most established market and methods for assessment. For carbon reduction methods, the

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[7] https://www.cleanenergyregulator.gov.au/ERF/Choosing-a-project-type/Opportunities-for-the-land-sector/Vegetation-methods/tidal-restoration-of-blue-carbon-ecosystems-method

generation of ACCUs includes methods for agriculture in cattle, irrigated cotton, soil carbon and savanna fire management. There are also established vegetation methods for different situations such as reforestation, plantation forestry and by avoiding the clearing of native plants. The LRF was established in 2017 and is Queensland's $500 million fund to invest in high quality carbon farming projects[8]. The LRF invests in land management projects that keep carbon in the ground and deliver positive impacts, or 'co-benefits', for the environment and communities. The LRF defines co-benefits that are relevant to water quality management in the GBR as:

- Environmental co-benefits: Improved biodiversity, habitat for threatened species and healthier soils, wetlands and water.
- Socio-economic co-benefits: Improving the resilience and prosperity of regional communities by supporting jobs and skills, and generating economic benefits for local communities.
- First Nations co-benefits: A broad range of co-benefits including customary, cultural, economic and business development benefits, such as providing new on Country and service delivery business opportunities and supporting cultural and customary connections.

ACCUs can be co-benefits linked to biodiversity, reduction of greenhouse gas emissions, soil health, and Indigenous values. Projects that generate co-benefits are able to attach ACCUs generated by projects under the LRF. Essentially, co-benefits under these programs can be stacked over the same area that water quality improvement management practices are undertaken. Both the LRF and the ACCUs apply the Accounting for Nature Framework which requires projects to monitor and report the nominated outcomes to ensure additionality is achieved (e.g., water quality as well as biodiversity outcomes).

The LRF directly states that GBR projects with environmental and/or social and/or First Nations co-benefits are eligible. To claim a GBR co-benefit, LRF projects must result in: a) a verified improvement to native vegetation in pre-clearing wetlands in a GBR catchment; and/or b) a verified improvement to both native vegetation condition and soil condition within a GBR catchment that has a sediment target in the Reef 2050 WQIP. In addition, soil health, wetlands, coastal ecosystems, threatened ecosystems, threatened wildlife and native vegetation are all considered to contribute to the environmental co-benefits.

This Question explores the existing water quality risk management practices in the main agricultural land uses in the GBR catchment area and reviews how these practices could provide additional environmental, socio-economic or First Nations co-benefits that are relevant to the LRF.

There is increasing interest from governments to maximise the opportunities for co-benefits as a way to encourage greater adoption of improved water quality management practices in the future. As described in further detail in Question 7.1, Coggan et al., this SCS), water quality policy and programs have largely supported the adoption of water quality risk management practices through either incentives or extension and the Queensland Government has regulated a minimum standard for agricultural management practices in the GBR catchment area. Market mechanisms such as reverse tenders and Reef Credits for DIN reductions in sugarcane have also been employed. With significant government investment in achieving water quality outcomes, it is critical for outcomes to link to other benefits that may exist across the landscape to increase the return on investment, particularly in the context of increasing environmental pressures. While socio-economic benefits associated with water quality management practices are relevant and consider impacts on local communities, local employment, and skill benefits, the socio-economic benefits considered in this Question exclude consideration of on-farm private benefits from the adoption of management practices within the Paddock to Reef Water Quality Risk Framework. These private benefits are captured in Question 7.2 (Murray-Prior et al., this SCS) and to a lesser extent, Question 7.1 (Coggan et al., this SCS). Evidence of the economic and production outcomes are reviewed in Question 3.5 (Bartley & Murray, this SCS), Question 3.6 (Brooks et al., this SCS), Question 4.6 (Thorburn et al., this SCS) and Question 5.3 (Davis et al., this SCS). Links to other questions are highlighted in Section 1.3 below.

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[8] https://www.qld.gov.au/environment/climate/climate-change/land-restoration-fund

Finally, as noted in the LRF, First Nations benefits can encompass a broad range of outcomes including "customary, cultural, economic and business development benefits". There are two First Nations co-benefit classes that can be claimed and verified under the current version of the LRF Co-benefits Standard: 1) First Nations benefits based on location; and 2) First Nations benefits based on participation. First Nations participation was considered in this review. Question 7.3 (Espinoza et al., this SCS) reviews the critical success factors for greater Indigenous involvement in water quality decision making in the GBR region, highlighting factors that are also relevant to the LRF such as supporting business opportunities and recognising cultural connections. These additional outcomes or co-benefits have the capacity to support water quality improvements and broader environmental or social outcomes through increased financial payments that are aimed at encouraging landholder adoption.

## Water Quality Risk Management Practices in the GBR

Management practices for grazing, sugarcane, bananas, horticulture, and grains have been defined as part of the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (P2R program) in terms of the potential risk of the practices to water quality, from low to high. These practices provide the basis for all Reef Report Card monitoring of practices towards achieving the Reef Water Quality Targets. The grazing management practices are summarised in Table 2 and are based on the pollutant pathways of hillslope, streambank, and gully management along with herd and weaner management. Management practices for sugarcane, horticulture, bananas and grains, are identified for the main pollutant pathways for soil, nutrient, pesticide or irrigation management in Table 3. Examples of management practices include matching nutrients to crop requirements, controlled traffic, and inter-block soil mapping.

*Table 2. Broad grouping of pollutant pathways and examples of grazing management practices with lower relative water quality risk in the P2R Water Quality Risk Framework.*
*Source: https://www.reefplan.qld.gov.au/tracking-progress/paddock-to-reef/management-practices*

| Erosion source | Examples of grazing management practices with lower relative water quality risk |
|---|---|
| Hillslope (pasture) | Assessment of stocking rates, pasture utilisation and long-term carrying capacity.<br>Maintenance of ground cover thresholds.<br>Annual land condition assessments of soil, pasture and woodland condition that are considered in grazing and livestock management.<br>Vegetation management for woody regrowth to minimise erosion.<br>Recovery of heavily degraded land.<br>Property mapping. |
| Streambank | Grazing pressure on frontage country and wetlands managed through off-stream watering points, fenced off riparian zones, weed and pest control. |
| Gully | Remediation of gullied areas, stock exclusion, installation of temporary structures such as stick traps, porous check dams, contour banks, engineered check dams and mechanical gully reshaping and earth works.<br>Roads, tracks and fences designed to limit erosion. |
| Herd and weaner management* | Nutrition and disease, breeder management, weaner management. |

* Although part of the framework, herd and weaner management is not within the scope of this question but both are important for water quality and productivity outcomes.

*Table 3. Broad grouping of pollutant pathways and examples of management practices with lower relative water quality risk for sugarcane, grains, bananas and horticulture under the P2R Water Quality Risk Framework.*

| | Sugarcane | Grains | Bananas | Horticulture |
|---|---|---|---|---|
| Nutrient | Matching N, phosphorus (P) and mill mud supply to crop requirements. | Matching placement of nutrients to specific soils, soil moisture storage, timing of application. | Ground cover during fallow, inter-row and headlands, tillage. | Soil and leaf testing, nutrient matching to plant, calculation of rates. |
| Soil | Trash blanketing, fallow management, tillage. | Tillage, crop selection, controlled traffic, placement of contours and diversion banks. | Controlling runoff, inter-rows managed for rutting, sediment traps. | Use of buffers, fallow management, inter-row ground cover, roadways and slope of plantings, sediment traps. |
| Pesticide | Targeted use of herbicide, timing and selection. | Targeting through band spraying, use of residuals, efficient application and selection of product. | Monitoring of foliar diseases, root disease monitored, soil borne disease managed. | Recording usage, reducing drift, integrated pest management. |
| Irrigation | Timing and calculation, use of sensors and monitoring and capture of tailwater. | | Drip or sprinkler is efficient, scheduled and monitored. | Scheduling, matching irrigation to interval and volume requirements, water reuse. |

Although landholder adoption of the P2R Water Quality Risk Framework practices has been central to policy mechanisms, adoption has still been relatively low with low private benefits, risk to profitability, and climate variability all being cited as reasons why landholders have been slow to adopt such practices (Barbi et al., 2015; Gregg & Rolfe, 2017; Star et al., 2015). This is discussed further in Question 7.2 (Murray-Prior et al., this SCS).

## 1.1 Question

| | |
|---|---|
| Primary question | **Q8.1** What are the co-benefits e.g., biodiversity, soil carbon, productivity, climate resilience, of land management to improve the water quality outcomes for the Great Barrier Reef? |

The **biophysical** and **economic/social co-benefits** associated with **land management activities within the P2R Water Quality Risk Framework** for **agricultural** sectors were assessed in this review. The P2R Water Quality Risk Framework provides the reporting framework for the management actions for achieving water quality outcomes under the Reef 2050 WQIP and therefore provides a policy-relevant basis to this review.

Considerations were given to the four agricultural sectors that cover the majority of the GBR catchment area, i.e., **grazing**, **sugarcane**, **grains** and **horticulture including bananas**. It was assumed that agricultural land management activities directly affect biophysical components of the system that then have additional biophysical, economic, and social co-benefits that result from those direct effects.

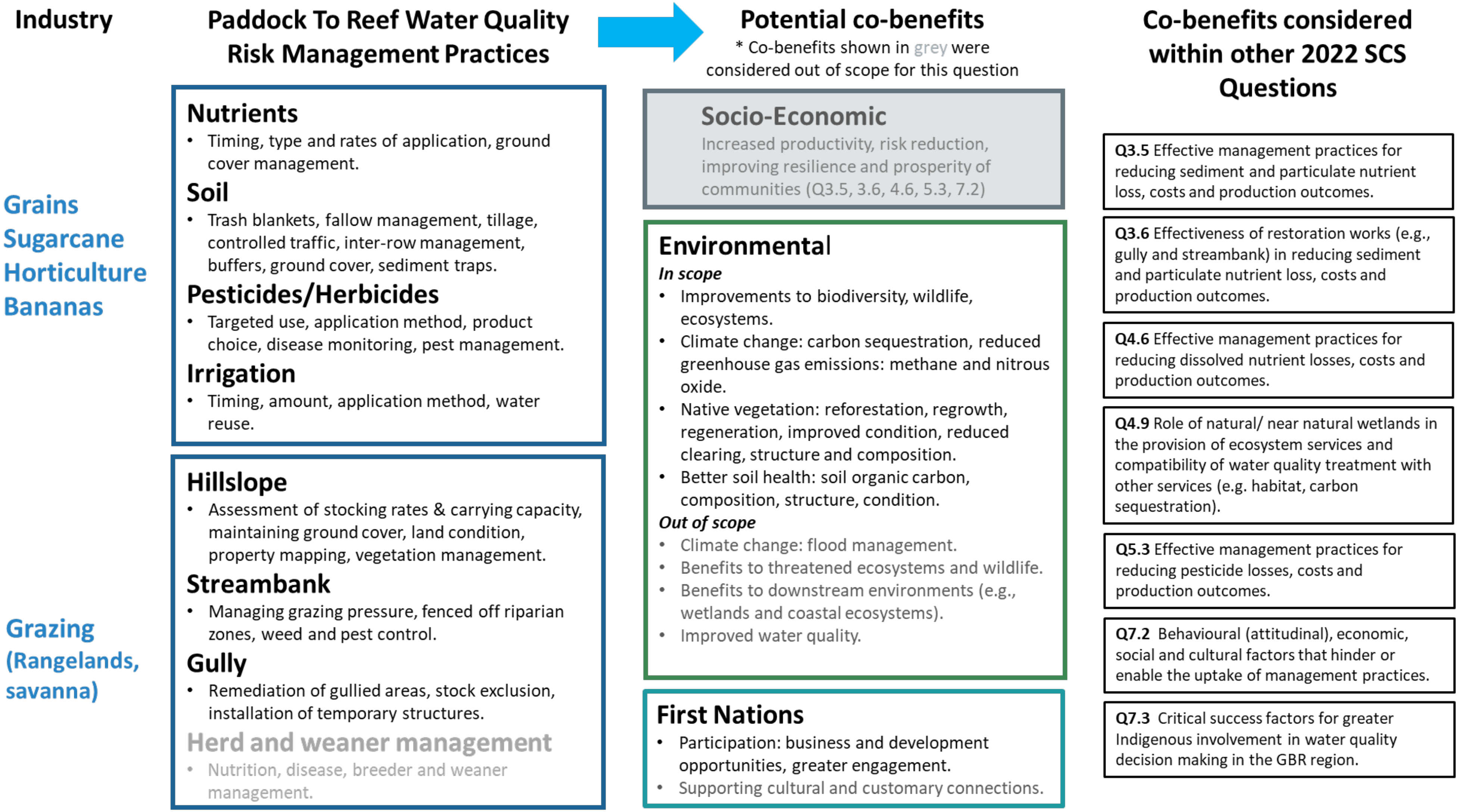
The review primarily focused on the on-site co-benefits and not on the effectiveness of management actions that lead to water quality improvement, the economic or production outcomes, or the potential downstream impacts of the co-benefits. These are covered elsewhere in the SCS for sediments and particulate nutrients, dissolved nutrients and pesticides (i.e., Questions 3.5 Bartley & Murray, 3.6 Brooks et al., 4.6 Thorburn et al., 4.7 Waltham et al., and 5.3 Davis et al., this SCS). For clarity, the focus here was on the co-benefits for biodiversity, soil carbon, greenhouse gas emission reduction and primary and secondary production from the ways in which agricultural land is managed to improve water quality. This is primarily achieved through changes in grazing regimes, and in other agricultural sectors the application of inputs such as fertilisers and pesticides.

The initial review incorporated international literature following preliminary testing and recognition that the initial search terms returned limited information from the catchments of the GBR. The second search was confined to literature from Australia.

The conceptual diagram in Figure 1 presents the scope of the review.

## 1.2 Conceptual diagram

The conceptual diagram presents the main types of management practices by industry in the P2R Water Quality Risk Framework including grazing, sugarcane, horticulture and grains as the basis for which additional co-benefits are derived. The co-benefits are restricted to those classified under the ACCUs and the LRF as socio-economic, environmental and First Nations. It is acknowledged that there are a number of other Questions in the SCS that contribute and link to understanding different aspects of the co-benefits, particularly Question 4.9 (Waltham et al., this SCS) regarding ecosystem services of wetlands, linking to co-benefits (or disbenefits) of wetland treatment systems.



**Industry**

**Grains**
**Sugarcane**
**Horticulture**
**Bananas**

**Grazing (Rangelands, savanna)**

**Paddock To Reef Water Quality Risk Management Practices**

**Nutrients**
- Timing, type and rates of application, ground cover management.

**Soil**
- Trash blankets, fallow management, tillage, controlled traffic, inter-row management, buffers, ground cover, sediment traps.

**Pesticides/Herbicides**
- Targeted use, application method, product choice, disease monitoring, pest management.

**Irrigation**
- Timing, amount, application method, water reuse.

**Hillslope**
- Assessment of stocking rates & carrying capacity, maintaining ground cover, land condition, property mapping, vegetation management.

**Streambank**
- Managing grazing pressure, fenced off riparian zones, weed and pest control.

**Gully**
- Remediation of gullied areas, stock exclusion, installation of temporary structures.

**Herd and weaner management**
- Nutrition, disease, breeder and weaner management.

**Potential co-benefits**

* Co-benefits shown in grey were considered out of scope for this question

**Socio-Economic**

Increased productivity, risk reduction, improving resilience and prosperity of communities (Q3.5, 3.6, 4.6, 5.3, 7.2)

**Environmental**

***In scope***
- Improvements to biodiversity, wildlife, ecosystems.
- Climate change: carbon sequestration, reduced greenhouse gas emissions: methane and nitrous oxide.
- Native vegetation: reforestation, regrowth, regeneration, improved condition, reduced clearing, structure and composition.
- Better soil health: soil organic carbon, composition, structure, condition.

***Out of scope***
- Climate change: flood management.
- Benefits to threatened ecosystems and wildlife.
- Benefits to downstream environments (e.g., wetlands and coastal ecosystems).
- Improved water quality.

**First Nations**
- Participation: business and development opportunities, greater engagement.
- Supporting cultural and customary connections.

**Co-benefits considered within other 2022 SCS Questions**

**Q3.5** Effective management practices for reducing sediment and particulate nutrient loss, costs and production outcomes.

**Q3.6** Effectiveness of restoration works (e.g., gully and streambank) in reducing sediment and particulate nutrient loss, costs and production outcomes.

**Q4.6** Effective management practices for reducing dissolved nutrient losses, costs and production outcomes.

**Q4.9** Role of natural/ near natural wetlands in the provision of ecosystem services and compatibility of water quality treatment with other services (e.g. habitat, carbon sequestration).

**Q5.3** Effective management practices for reducing pesticide losses, costs and production outcomes.

**Q7.2** Behavioural (attitudinal), economic, social and cultural factors that hinder or enable the uptake of management practices.

**Q7.3** Critical success factors for greater Indigenous involvement in water quality decision making in the GBR region.

*Figure 1. Conceptual diagram of co-benefits of agricultural land management practices to improve water quality.*

## 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 | **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?<br>**Q3.6** What is the effectiveness of restoration works (e.g. gully and streambank) in reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, does this vary spatially or in different climatic conditions? What are the costs and cost-effectiveness of these works, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices?<br>**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?<br>**Q4.7** What is the efficacy of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in GBR catchments in improving water quality (nutrients, fine sediments and pesticides)?<br>**Q4.9** What role do Natural/ Near Natural wetlands play in the provision of ecosystem services and how is the service of water quality treatment compatible or at odds with other services (e.g. habitat, carbon sequestration)?<br>**Q5.3** What are the most effective management practices for reducing pesticide risk (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?<br>**Q7.1** What is the mix of programs and instruments (collectively and individually) used in the Great Barrier Reef catchments to drive improved land management actions for Great Barrier Reef water quality benefits and how effective are they?<br>**Q7.2** What are the behavioural (attitudinal), economic, social and cultural factors that hinder or enable the uptake of management practices that aim to improve water quality outcomes for the Great Barrier Reef?<br>**Q7.3** What are the critical success factors for greater Indigenous involvement in water quality decision making in the Great Barrier Reef region? |

As noted above, the foundation for knowledge of co-benefits is linked to the effectiveness of management actions intended to improve water quality for the GBR. This information is synthesised in other SCS Questions and is briefly summarised here for context. **Note that the material below is directly extracted from the Evidence Statements of these questions.** As the SCS questions were completed in parallel, the authors also engaged expert knowledge and referred to the management actions in the P2R

Water Quality Risk Framework to guide the scope of this review. Readers should refer to the full syntheses for further detail of these conclusions.

***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?***

The costs, cost-effectiveness and productivity outcomes of management practices focused on sediment and particulate nutrient reduction are captured in Question 3.5 (Bartley & Murray, this SCS). Relevant conclusions include:

- The most effective management practices for reducing sediment and particulate nutrient loss from the GBR catchment area vary between land uses, but common practices across land uses include maintaining or reintroducing vegetation into landscapes (including pasture management and vegetation buffers), reducing the hydrological connectivity of flow pathways (via management of roads, drains, gullies etc.), and other practices that minimise soil runoff (such as green cane trash blanketing, zero/minimum tillage and controlled traffic farming).
- There is a lack of data on the cost and production implications of those interventions, and there is not always a “win-win” scenario between improving water quality and increasing profit. For most land uses very few studies have evaluated changes at the whole-of-business level including productivity. The quantity, diversity, and spatial relevance of studies was considerably lower in the evidence for bananas/horticulture, urban and roads compared to grazing, sugarcane and cropping.
- The results demonstrate the implications of land type, grazing pressure, tree basal area and enterprise operation on optimal grazing pressure for profit and for sediment reduction. The type of enterprise operation and initial start condition have a large impact on the profit made and sediment exported. It was concluded that land initially in poor condition with a reduced grazing pressure provides the cheapest reduction in sediment export if incentive payments are the chosen policy method. However, graziers who are using pasture past the optimal rate will require extension activities through education to reduce grazing pressure and sediment runoff.
- Considerable water quality improvements can be obtained at a benefit to the sugarcane farmers. Maximum benefits are expected to be obtained through a reduction in TSS and DIN water pollution of ∼20% and 25%, respectively, and are facilitated through the adoption of win–win management practices (reduced tillage and zero tillage; economic optimum rates of fertiliser application, nitrogen replacement and split nitrogen application). Reductions in water pollution beyond these levels come at a cost to the sugarcane industry.
- Water quality benefits of land use diversification were found to be mixed and dependent on the economic viability and erosion characteristics of the catchment. Tillage experiments in grains have shown that management strategies involving retention of crop residues (stubble), reduced tillage and crop rotation can reduce erosion and improve yield. Results from experimentation are highly variable, both in magnitude and direction of responses to tillage treatments. Much of this variation is due to variation in seasonal (climate) conditions, and because the western margin of the grain growing region in eastern Australia is characterised by high variability and extremes in rainfall and temperature.

***Q3.6 What is the effectiveness of restoration works (e.g., gully and streambank) in reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, does this vary spatially or in different climatic conditions? What are the costs and cost-effectiveness of these works, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices?***

The costs and cost-effectiveness of gully remediation and streambank rehabilitation works are captured in Question 3.6 (Brooks et al., this SCS). Relevant conclusions include:

- The large-scale remediation of alluvial[9] gullies has been demonstrated to be a highly effective strategy for significantly reducing tens of thousands of tonnes of fine sediment that is being delivered to the GBR each year. Gully remediation treatments can include major earth works and reshaping, soil treatment, installation of rock chute structures, earth bunds and water points, fencing and revegetation. A combination of these treatments can achieve over 90% fine sediment reduction within one to two years. In contrast, direct hillslope gully treatments appear less effective in reducing fine sediment losses (7 to 17% effectiveness). Destocking catchments may also reduce hillslope gully sediment yields by up to 60%, after ~25 years, however there is limited information on the practicality and costs of this approach.
- Although robust methods exist to calculate the cost-effectiveness of gully remediation projects, there is no consistency between projects and investment programs, and agreement on a standardised peer-reviewed method should be a priority. This is critical to assess and compare project viability, capture baseline data and monitor the effectiveness of gully remediation treatments ultimately leading to improved assessments of the cost-effectiveness of remediation design and implementation life.
- Streambank rehabilitation treatments include interventions to increase riparian vegetation, either directly through planting, or indirectly through the removal of disturbance pressures such as grazing to encourage natural colonisation, and in some cases bank reprofiling and stabilisation, which enables subsequent revegetation via planting and/or natural colonisation. Rehabilitation works cannot currently be evaluated due to limited measurement of treatment effectiveness, but studies have shown that bank erosion generally occurs at lower rates on vegetated streambanks than non-vegetated streambanks. There is a need to refocus efforts from site-scale management to whole-of-system approaches that seek to maximise recovery of riparian vegetation at the river reach to network scale, rather than focus on individual erosion sites.
- While streambank rehabilitation will assist in reducing sediment export in the Great Barrier Reef catchment area, estimates of return on investment are poorly understood.
- Obtaining quantitative monitoring data at a range of scales (site, subcatchment and catchment) is essential to evaluate the effectiveness, costs and production outcomes of gully and streambank projects and to maximise the benefits of remediation projects.

### *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?*

The costs, cost-effectiveness and productivity outcomes of management practices focused on dissolved nutrient reduction are captured in Question 4.6 (Thorburn et al., this SCS). Relevant conclusions include:

- 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 GBR 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.

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[9] There are two major gully types; alluvial (or river associated) and colluvial (or hillslope gullies). This distinction is based on the material the gullies are eroding into: alluvium - sediments deposited overbank from rivers and streams; and colluvium -sediments derived from *in situ* weathering on slopes and/or downslope processes on hillslopes.

However, the results are highly variable across sites and years and consistent benefits are often only seen when averaged across sites and seasons.

- The effect of improved irrigation practices on dissolved nutrient losses or on farm productivity in the GBR catchment area is uncertain, with most information derived from mechanistic modelling studies in sugarcane. The available results indicate that high irrigation efficiency, from low 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 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.

### ***Q4.9 What role do Natural/ Near Natural wetlands play in the provision of ecosystem services and how is the service of water quality treatment compatible or at odds with other services (e.g., habitat, carbon sequestration)?***

The role of natural and near-natural wetlands in the provision of ecosystem services is captured in Question 4.9 (Waltham et al., this SCS). Relevant conclusions include:

- Natural and near-natural wetlands in the GBR catchment include lacustrine (e.g., lakes), palustrine (e.g., vegetated swamps, billabongs), estuarine, and riverine wetlands. These wetlands support many ecosystem services including regulating services such as improved water quality and carbon sequestration, supporting services such as nutrient cycling and habitat provision, cultural services such as aesthetics and recreation, and provisioning services including food, water and other resources. However, these services are under threat in response to expansion of coastal agriculture development, as well as urban and industrial expansion.
- In tropical/subtropical wetlands, stressors that compromise wetland water quality can impact the ecosystem services that wetlands provide. For instance, connectivity and hydrology have an important role in protecting water quality and other wetland ecosystem services; disruption to connectivity or hydrology can change water chemistry with flow on effects to aquatic organisms (e.g., fish kills).
- In GBR coastal and floodplain areas where historical wetland losses are high, the capacity of the remaining wetlands to process the volume of pollutants they receive is likely to be reduced. Therefore, restoration efforts and engineering interventions may be required to increase the water quality improvement efficiency, and the associated delivery of associated ecosystem services, for the wetlands remaining within the Great Barrier Reef catchment area. While wetlands can be restored to enhance water quality conditions, the maintenance following restoration works or intervention activities is critical. Without a long-term maintenance plan and a mechanism to fund these works, restoration sites have a high chance of returning to a degraded state.

### ***Q5.3 What are the most effective management practices for reducing pesticide risk (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 costs, cost-effectiveness and productivity outcomes of management practices focused on pesticide reduction are captured in Question 5.3 (Davis et al., this SCS). Relevant conclusions include:

- The most effective management practices for reducing pesticide risk from the Great Barrier Reef catchment area vary between land uses. Practices that demonstrably reduce pesticide risk from agricultural land uses include reductions in the total amount of pesticide applied through lower application rates (within label recommendations), improved application methods, timing of application in relation to weather risk periods, use of pesticide products with lower environmental risk, reducing soil erosion through retaining cover, controlled traffic and improved irrigation management for pesticides with greater soil sorption. These findings have remained relatively consistent through time. The effectiveness of these practices also remains relatively consistent across climatic regimes and farming systems of the GBR catchments.
- In the assessment of cost-effectiveness of pesticide management in agricultural industries, economic returns remain critically dependent on region-specific variables including biophysical characteristics and enterprise structure, especially in relation to farm size and location. However, for sugarcane, progressing from traditional to industry standard herbicide management was reported to be generally profitable and provide return on investment across all farm sizes and sugarcane districts.
- Few studies have examined how pesticide practice change can influence crop production (crop yield), and available results tended to focus on broader implications of pesticide impacts. Assessment of pest management in conjunction with nutrient management would also provide further insights for changes in yields and productivity outcomes.

### *Q7.1 What is the mix of programs and instruments (collectively and individually) used in the Great Barrier Reef catchments to drive improved land management actions for Great Barrier Reef water quality benefits and how effective are they?*

- The Australian and Queensland Governments have sought to improve GBR water quality through investment in a range of initiatives focused on the management of private land under the Reef Trust Program, Reef Trust Partnership (Australian Government) and the Reef Water Quality Program (Queensland Government, agricultural and urban land). This investment is estimated at AUD$1.1 billion over the last 20 years, with approximately AUD$390 million of this for on-ground projects from 2017–2022. Investment has focused specifically on the instruments of extension (51%), followed by financial instruments with extension (36%). Less investment has been allocated directly to physical works such as on-ground gully remediation (5%), regulation and compliance (4%) and financial instruments in the absence of extension (3%).
- In the agricultural industries, land management actions for water quality benefits have primarily been generated through facilitative instruments (extension), incentive-based instruments (primarily financial incentives) and regulation/coercion. For urban land, actions have been motivated mostly through facilitative instruments and regulation.

### *Q7.2 What are the behavioural (attitudinal), economic, social and cultural factors that hinder or enable the uptake of management practices that aim to improve water quality outcomes for the Great Barrier Reef? [7.2.1] What factors influence disadoption of management practices in agricultural industries and are there examples from elsewhere on how to address it?*

- The factors that influence the uptake of management practices to improve water quality operate at various systems levels. These levels can be described as macro (governance, culture, media, economics, policy and legislation), meso (industry, research and development agencies and community), micro (individuals and relationships to people) and practice or behaviour characteristics. The macro context, including the enabling environment and governance systems, directs and moulds what occurs at each of these levels and hence influences efficiency and effectiveness.
- There has been extensive investigation of factors hindering and enabling the uptake of management practices at the practice, landholder and micro-level. Perceptions of these factors vary between researchers and farmers and within farming communities, creating a diversity of evidence about drivers of management practices. Options to address these factors need to be incorporated within the innovation processes (research, development and extension).

- Landholder distrust and suspicion of certain groups including government and scientists involved in GBR research, program delivery organisations, program managers and delivery staff is a key factor hindering uptake of management practices. To overcome this distrust, management practices and programs for agricultural and urban land managers would be more efficacious if they were developed, tested, scaled, monitored and evaluated using collaborative processes that actively involve key actors in the relevant communities, value chains and innovation systems.
- Context and the processes used to engage with the land managers are critical to consider but factors identified that may be associated with improved uptake include levels of human and social capital, economies of size, presence of trusted advisors and bottom-up development of practices.
- While real and perceived economic factors are important to landholder decision making, even profitable practices can take time to be adopted because of the interactions within and between economic factors and landholders, research, extension, industry and community attitudes and systems. Less profitable practices are likely to take even longer and will require further development of approaches, supporting policies and instruments. Additionally, for all land uses, demonstrating links between practice change and improved water quality outcomes was identified as an important factor that could enable and hinder practice adoption. Other factors for major land uses include:
  - For sugarcane, social norms, costs of adoption, compatibility with farming systems, economies of size effects, and the interaction of technology characteristics and context were identified as factors that hinder and enable uptake.
  - For grazing, the interaction of weather and climate with property and decision-maker context, financial and other support over time, transaction costs and skills required.
  - For urban, social resilience, and innovative and adaptive capacity may be important but there were few studies to support this.
- Mixes of instruments (e.g., regulation, incentives) could be collaboratively designed, implemented and evaluated alongside or in coordination with extension approaches to improve their efficiency and effectiveness.

### *Q7.3 What are the critical success factors for greater Indigenous involvement in water quality decision making in the Great Barrier Reef region?*

- The outcomes from Indigenous-led decision-making including a description of successful engagements or successful outcomes are rarely published in the scientific literature. To fully address this question requires Indigenous knowledge and input.
- Critical factors and key learnings from national and international studies include increased understanding and knowledge of Indigenous culture and connection to Country, helping to establish trust and respect between all partners through relationship building, support for increased capacity to engage and become involved in programs, support for improved capability to collaborate and deliver across all aspects of planning and delivery, and adoption of an adaptive management approach to program delivery.
- Learnings from the synthesis should be accompanied by the development of meaningful relationships, policies and frameworks led by Traditional Owners to ensure delivery of sustainable and holistic outcomes for the GBR and its associated catchments.

# 2. Method

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[10]. 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 Summary method was used.

While this Question follows the formal 2022 SCS Method for the Synthesis of Evidence, it was delivered in two phases, with the second phase completed following preliminary peer review. This is reflected in the methods below, showing the characteristics for each phase. The initial scope of the analysis primarily focused on the biophysical co-benefits and their associated social/economic co-benefits of water quality improvement across the grazing, sugarcane, and horticulture agriculture sectors in the GBR. The second phase included the grains sector with greater consideration of the economic and social co-benefits for all land uses.

## 2.1 Primary question elements and description

The primary question is: ***What are the co-benefits e.g., biodiversity, soil carbon, productivity, climate resilience, of land management to improve the water quality outcomes for the Great Barrier Reef?***

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[11] 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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[10] 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

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

*Table 4. Description of question elements for Question 8.1.*

| Question S/PICO elements | Question term | Description |
|---|---|---|
| Subject/ Population | Grazing, sugarcane, grains, horticulture & bananas | Grazing, sugarcane, grains and horticulture land use in the GBR catchment area where co-benefits can be generated on-farm. |
| Intervention, exposure & qualifiers | Management to improve water quality outcomes | Management practices identified in the P2R Water Quality Risk Framework for water quality improvement in the GBR catchment are in the grazing, sugarcane, grains and horticulture industries.<br>Sediments, nutrients, pesticides, herbicides. |
| Comparator | | (Not relevant) |
| Outcome & outcome qualifiers | Measure environmental, socio-economic and First Nations benefits<br>Future | Environmental co-benefits: reduced carbon/methane emissions, improved biodiversity, habitat for threatened species and healthier soils, wetlands and water[12].<br>Socio-economic co-benefits: improving landholder productivity, improving the resilience and prosperity of regional communities by supporting jobs and skills, and generating economic benefits for local communities.<br>First Nations co-benefits: customary, cultural, economic and business development benefits, such as providing new on-country and service delivery business opportunities and supporting cultural and customary connections (Qld Government, 2023). |

*Table 5. Definitions for terms used in Question 8.1.*

| Definitions | |
|---|---|
| **P2R Water Quality Risk Framework** | Management practices within the P2R Water Quality Risk Frameworks have been used to establish a baseline of management practices for the sugarcane, grazing, grains and horticulture sectors under the Paddock to Reef Integrated Monitoring, Modelling and Reporting program. The frameworks represent a continuum of management practices from unacceptable practices (High Risk to water quality, or formerly 'D' or poor practices) to cutting-edge (Low Risk, or formerly 'A' or Innovative practices). The benefit of improving water quality through practices that reduce erosion, nutrient and pesticide runoff was not considered within this question as a co-benefit because it is covered in other questions of the 2022 SCS. |
| **Climate resilience** | Capacity for co-benefits to be generated as climate change impacts occur across industries. |
| **Co-benefit** | An additional benefit from implementing a management action. |
| **Biodiversity** | Diversity of life. |
| **Grains** | The practice of agricultural production of plant grains from broadacre farming. |
| **Grazing** | The practice of agricultural production of domestic livestock on open pastures (native and sown). |

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[12] Note that while on-farm benefits are reviewed in this Question, it is accepted that these are likely to lead to downstream benefits.

| Definitions | |
|---|---|
| **Greenhouse Gas Emissions** | Methane ($CH_4$) and nitrous oxide ($N_2O$). |
| **Fertiliser** | A chemical or natural substance added to soil or land to increase its fertility (generally N, P and potassium). |
| **Horticulture** | The practice of agricultural production of plants and fruits, including bananas. |
| **Irrigation** | The supply of water to land or crops to help growth. |
| **Land management** | The process of managing the use and development of land resources. |
| **Pesticide** | Chemicals added in agriculture to reduce the effects of weeds and pests, including herbicides, insecticides and fungicides. |
| **Productivity** | Primary productivity equals vegetation (including crops) growth and reproduction. Secondary productivity equals domestic agricultural animal growth and reproduction. |
| **Restoration** | The repair of ecosystem structure and function through human intervention. |
| **Savanna** | A grassy plain in tropical and subtropical regions, with few trees. |
| **Soil organic carbon** | Measurable organic matter content of the soil. |
| **Soil health** | The capacity of soil to function, within managed or natural ecosystem boundaries, to sustain plant or animal productivity, maintain or enhance water and air quality, and support human health and habitation (Accounting for Nature, 2023). |
| **Sugarcane** | A perennial tropical grass (*Saccharum officinarum*) with tall stout jointed stems from which sugar is extracted. |
| **Water quality** | The physical, chemical and biological characteristics of water and the measure of its condition relative to the requirements for one or more biotic species and/or to any human need or purpose. |

## 2.2 Search and eligibility

The Method includes a systematic literature search with well-defined inclusion and exclusion criteria.

Identifying eligible literature for use in the synthesis was a two-step process:

1. Results from the literature searches were screened against strict inclusion and exclusion criteria at the title and abstract review stage (initial screening). Literature that passed this initial screening step were then read in full to determine their eligibility for use in the synthesis of evidence.
2. Information was extracted from each of the eligible papers using a data extraction spreadsheet template. This included information that would enable the relevance (including spatial and temporal), consistency, quantity, and diversity of the studies to be assessed.

### a) Search locations

Searches were performed on:

- Scopus
- Google Scholar

### b) Search terms

Table 6 shows a list of the search terms used to conduct the online searches.

*Table 6. Search terms for S/PICO elements of Question 8.1 used in the searches.*

| Question element | Search terms |
|---|---|
| Subject/Population | Rangelands, savanna, beef, grazing, sugarcane, horticulture, agriculture, grains, crop, cropping, broadacre, Australia, GBR |
| Exposure or Intervention | Sediments, nutrients, pesticides, herbicides, land management |
| Comparator | N/A |
| Outcome | Co-benefit, water quality, biodiversity, wildlife, carbon, soil carbon, Indigenous participation, productivity*, future |

### c) Search strings

Table 7 shows a list of the search strings used to conduct the online searches in the initial review (September 2022) and the additional searches conducted as part of the revisions to address preliminary peer review comments (July 2023). Note that the searches included GBR, national and international (non-specific) literature. After initial review it was deemed that ‘productivity’ was out of scope as productivity outcomes of agricultural management practices for sediment, nutrient and pesticide reductions are covered in other SCS Questions (refer to Section 1.3).

*Table 7. Search strings used for electronic searches in the initial searches for Question 8.1 (September 2022) and additional searches (July 2023). *Productivity was determined to be out of scope following preliminary peer review.*

| Search strings |
|---|
| *Initial search strings (September 2022)* |
| rangeland AND “land management” AND “water quality” AND biodiversity |
| rangeland AND “land management” AND biodiversity AND Australia |
| rangeland AND “land management” AND “water quality” AND “soil carbon” |
| rangeland AND “land management” AND “water quality” AND productivity* |
| “sugar cane” AND “water quality” AND productivity AND Australia |
| sugar cane AND “water quality” AND nutrients AND productivity* |
| sugar cane AND “water quality” AND herbicides AND productivity* |
| sugar cane AND “water quality” AND pesticides AND productivity * |
| sugar cane AND productivity AND Australia* |
| horticulture AND “water quality” AND biodiversity |
| horticulture AND “water quality” AND “soil carbon” |
| horticulture AND “water quality” AND productivity* |
| horticulture AND productivity AND Australia |
| horticulture AND “soil carbon” AND Australia |
| horticulture AND biodiversity AND Australia |
| savanna AND “land management” AND “water quality” AND biodiversity |
| savanna AND “land management” AND “water quality” AND “soil carbon” |
| savanna AND “land management” AND “water quality” AND productivity* |
| savanna AND “land management” AND biodiversity AND Australia |
| Rangeland AND Australia AND Future |
| Sugar AND Australia AND Future |
| Crop AND Australia AND Future AND “Land management” |
| Google Scholar: co-benefit AND “Great Barrier Reef” AND “water quality” AND agriculture |
| *Additional Search Strings (July 2023)* |

| Search strings |
|---|
| Grazing AND Indigenous AND participation AND Savanna AND Queensland |
| sugarcane AND cropping AND co-benefits AND Australia |
| biodiversity AND horticulture AND Australia |
| horticulture AND Australia |
| wildlife AND cropping AND Australia |
| biodiversity AND cropping AND Australia |
| carbon AND grains AND cropping AND Australia |
| carbon AND broadacre AND cropping AND Australia |

### d) Inclusion and exclusion criteria

Table 8 shows a list of the inclusion and exclusion criteria used for accepting or rejecting evidence items in the initial review stage.

*Table 8. Inclusion and exclusion criteria used for accepting or rejecting evidence items from the initial review stage (September 2022).*

| Question element | Inclusion | Exclusion |
|---|---|---|
| Subject/ Population | Grazing/rangeland, beef, cattle, horticulture, sugarcane, grains, bananas<br>Note that the search terms were across the Great Barrier Reef, national and international literature. | Dryland agriculture, irrigated cropping, cotton, conservation, urban, wetland. |
| Exposure or Intervention | Water quality risk management practices including land restoration, reduced grazing pressure, fertiliser management, herbicides, pesticides and irrigation. | Water sources that are not considered agricultural runoff from grazing, horticulture and crops. |
| Outcome | Improvements in biodiversity, soil carbon, productivity, climate resilience. | Efficacy in improving water quality and downstream ecological benefits. |
| Publication | Peer reviewed and published technical reports. | Non-peer reviewed studies. |
| Language | English. | Non-English written. |
| Timeline | Publications dated from 1990. | Excluded prior to 1990. |
| Study type | Field studies, surveys, interviews, monitoring, and modelling | Monitoring method development, frameworks. |

Table 9 shows a list of the inclusion and exclusion criteria used for accepting or rejecting evidence items in the additional search.

*Table 9. Inclusion and exclusion criteria applied to the search returns from the additional search (July 2023).*

| Question element | Inclusion | Exclusion |
|---|---|---|
| Subject/ Population | Rangelands beef grazing, sugarcane Australia, horticulture Australia, grains Australia, broadacre cropping Australia. | Sheep grazing, nursery and cut flower industries.<br>Native food, temperate or urban horticulture.<br>Policy instruments and adoption reviews<br>Not a water quality risk management practice.<br>Hay and silage, mining, national parks, forestry, permaculture, national parks, |

| Question element | Inclusion | Exclusion |
|---|---|---|
| | | canola, cotton specifically Genetically Modified Grains. |
| Exposure or Intervention | **Grazing:** Stocking rate, ground cover, land regeneration, riparian management. | **Not water quality risk management practices including:**<br>**Grazing**: Invasive species management, such as rat's tail grass and wild dogs. Increased watering points for greater utilisation, arid region studies, kangaroo industry, development of methods for monitoring and modelling. |
| | **Sugarcane:** Matching N, P and mill mud supply to crop requirements.<br>Trash blanket, fallow management, tillage.<br>Targeted use of herbicide, timing and selection.<br>Timing and calculation, use of sensor and monitoring and capture of tailwater. | **Sugarcane:** Application of alternative fertilisers such as seaweed extract.<br>Ground water management and extraction rates.<br>Irrigation management of allocations.<br>Biofuels.<br>Native vegetation. |
| | **Grains:** Matching placement of nutrients to specific soils, soil moisture storage, timing of application.<br>Tillage, crop selection, controlled traffic, placement of contours and diversion banks.<br>Targeting through band spraying, use of residuals, efficient application and selection of product. | **Grains:** Genetically modified impacts on management, southern cropping zone, Victorian, South Australian or Southern WA cropping, irrigated cropping.<br>Irrigation management. |
| | **Horticulture:** Soil and leaf testing, nutrient matching to plant, calculation of rates.<br>Use of buffers, fallow management, inter-row ground cover, roadways and slope of plantings, sediment traps.<br>Recording usage, reducing drift, integrated pest management.<br>Scheduling, matching irrigation to interval and volume requirements, water reuse. | **Horticulture and Bananas:** Pest and disease management e.g., Fruit fly, silverleaf whitefly, thrips.<br>Biosecurity measures and methods.<br>Studies in non-commercial or urban interactions i.e., recycled water for community gardens or smallholdings in close proximity to towns. |
| | **Bananas:** Ground cover during fallow, inter-row and headlands, tillage.<br>Controlling runoff, inter-rows managed for rutting, sediment traps.<br>Drip or sprinkler is efficient, scheduled and monitored. | |
| Outcome | Biodiversity, wildlife, carbon, soil carbon, Indigenous. | Economic co-benefits, productivity/production outcomes (addressed in Q3.5, 3.6, 4.6, 5.3)<br>Private benefits (addressed in Q7.2)<br>Downstream ecosystem benefits. |
| Publication | Peer reviewed and published studies. | Non-peer reviewed studies. |
| Language | English. | Non-English . |
| Timeline | Publications dated from 1990. | Excluded prior to 1990. |
| Study type | Field studies, surveys, interviews, monitoring, modelling. | Monitoring method development, frameworks. |

# 3. Search Results

## Initial search

A total of 354 studies were identified through the initial online searches. Sixteen studies were identified manually through expert contact and personal collections, which represented 4% of the total number of evidence items considered. Of these, 46 studies were eligible for inclusion in the synthesis of evidence (Table 10) (Figure 2). After initial peer review the scope was reconsidered and because the socio-economic components were noted to be covered in other SCS Questions, the search strings covering productivity were removed from the search results. These are noted (Table 10) with an asterisk.

*Table 10. Search results table for the initial search, separated by A) Academic databases, B) Search engines (Google Scholar) and C) Manual searches.*

| Date | Search strings | Sources |
|---|---|---|
| A) Academic databases | | Scopus |
| September 2022 | *Rangeland AND Land management AND Water quality AND Biodiversity* | *19* |
| September 2022 | *Rangeland AND land management AND biodiversity AND Australia* | *68* |
| September 2022 | *Rangeland AND Land management AND Water quality AND Soil carbon* | *24* |
| September 2022 | *Rangeland AND land management AND water quality AND productivity** | *12* |
| September 2022 | *Sugar cane AND Water quality AND Productivity AND Australia** | *7* |
| September 2022 | *Sugar cane AND Water quality AND Nutrients AND Productivity** | *15* |
| September 2022 | *Sugar cane AND Water quality AND Herbicides AND Productivity** | *1* |
| September 2022 | *Sugar cane AND Water quality AND Pesticides AND Productivity* | *5* |
| September 2022 | *Sugar cane AND Productivity AND Australia** | *51* |
| September 2022 | *Horticulture AND Water quality AND Biodiversity* | *17* |
| September 2022 | *Horticulture AND Water Quality AND Soil carbon* | *35* |
| September 2022 | *Horticulture AND Water quality AND Productivity** | *62* |
| September 2022 | *Horticulture AND Productivity AND Australia* | *26* |
| September 2022 | *Horticulture AND Soil Carbon AND Australia* | *11* |
| September 2022 | *Horticulture AND Biodiversity AND Australia* | *1* |
| September 2022 | *Savanna AND land management AND Water quality AND Biodiversity* | *12* |
| September 2022 | *Savanna AND Land management AND Water quality AND Soil carbon* | *9* |
| September 2022 | *Savanna AND Land management AND Water quality AND Productivity** | *4* |
| September 2022 | *Savanna AND Land management AND Biodiversity AND Australia NOT Fire* | *17* |
| September 2022 | *Rangeland AND Australia AND Future* | *19* |
| September 2022 | *Sugar AND Australia AND Future* | *5* |
| September 2022 | *Crop AND Australia AND Future AND Land management* | *3* |
| | *Total* | *296* |
| | *From PUB Carroll et al. 2012* | *22* |

| Date | Search strings | Sources |
|---|---|---|
| B) Search engine | | Google Scholar |
| *01/03/2023* | *Search string 1: co-benefit AND Great Barrier Reef AND water quality AND agriculture*<br>*Total return* | *56* |
| | ***Total unique items from online searches*** | ***338 (95%)*** |
| C) Manual search | | |
| Date | Source | Number of items added |
| *08/08/2022* | *Author's personal collection and expert network* | *16* |
| | ***Total items manual searches*** | ***16 (5%)*** |

### Additional searches

In the additional search, strings were added that focused on sugarcane, horticulture, and grains with the co-benefits of biodiversity, carbon and soil health (Table 11). These search strings returned 258 items, and a further 16 items were manually added. In total, 51 evidence items met the eligibility criteria and were included in the synthesis.

*Table 11. Search results table for the additional search (July 2023).*

| Date | Search strings | Sources: relevant returns |
|---|---|---|
| A) Academic databases | | Scopus (July 2023) |
| | *sugarcane AND cropping AND Australia* | *77* |
| | *(biodiversity AND horticulture AND Australia ) AND ( LIMIT-TO ( EXACTKEYWORD , "Australia" ) ) AND ( LIMIT-TO ( AFFILCOUNTRY , "Australia" ) )* | *18* |
| | *(horticulture AND Australia ) AND ( LIMIT-TO ( EXACTKEYWORD , "Queensland" ) )* | *38* |
| | *(wildlife AND cropping AND Australia )* | *4* |
| | *(biodiversity AND cropping AND Australia ) AND ( LIMIT-TO ( EXACTKEYWORD , "Australia" ) )* | *44* |
| | *(carbon AND grains AND cropping AND Australia ) AND ( LIMIT-TO ( AFFILCOUNTRY , "Australia" ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" )* | *73* |
| | *(carbon AND broadacre AND cropping AND Australia ) AND ( LIMIT-TO ( AFFILCOUNTRY , "Australia" ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) )* | *4* |
| | *Total* | *258* |
| C) Manual Search | | |
| Date | Source | Number of items added |
| | *Lead Author's personal collection* | *16* |
| | ***Total items manual searches*** | ***16*** |

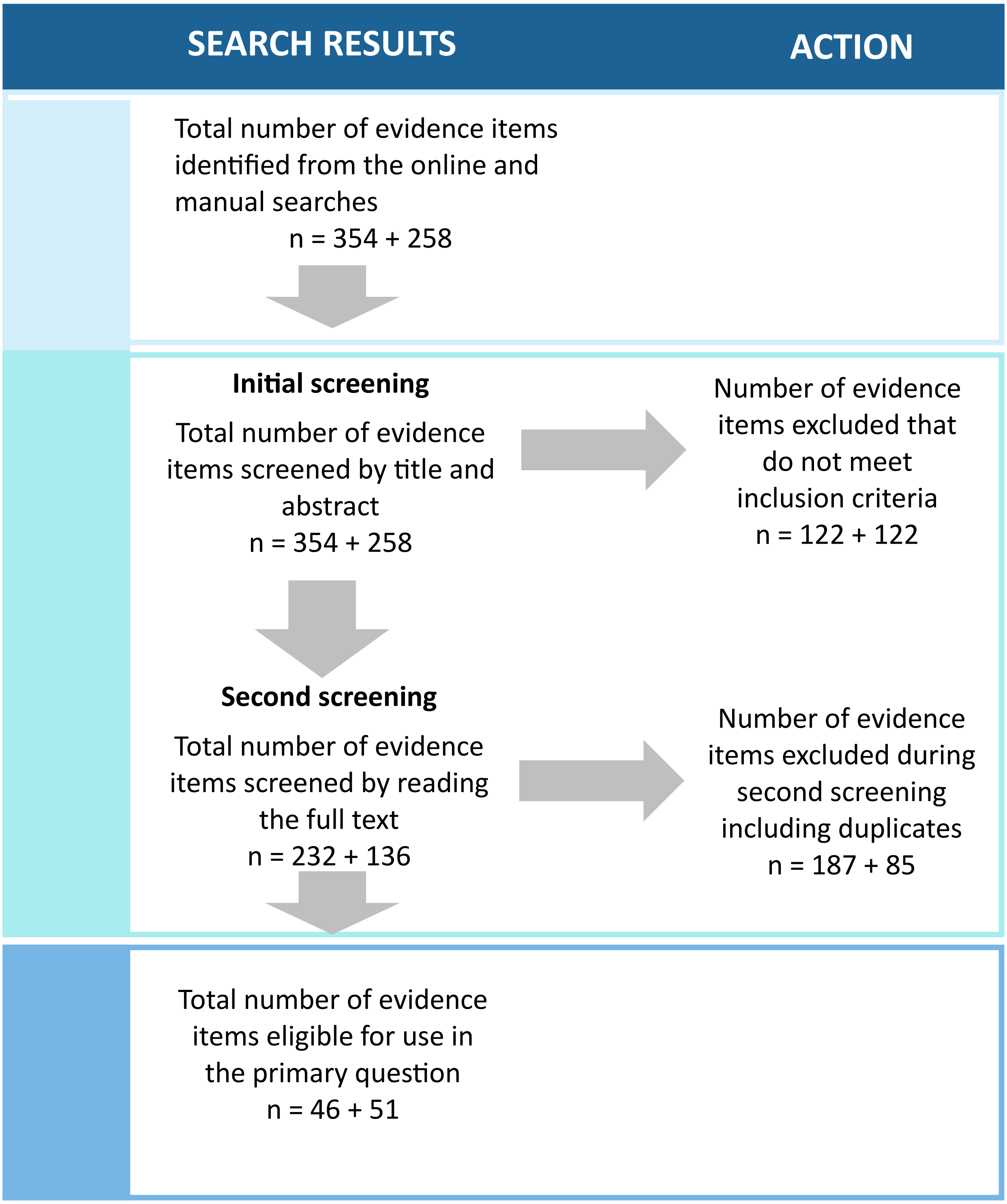

*Figure 2. Flow chart of results of initial and secondary screening stages from the initial and additional searches for Question 8.1.*

# 4. Key Findings

## 4.1 Narrative synthesis

### 4.1.0 Summary of study characteristics

Literature searches for this question were conducted in two phases, with the second phase completed following preliminary peer review. The initial scope of the analysis primarily focused on the biophysical co-benefits and their associated social/economic co-benefits of water quality improvement across the grazing, sugarcane, and horticulture agriculture sectors. The second phase focused on the Paddock to Reef Water Quality Risk Framework management practices generating water quality outcomes and co-benefits across sugarcane, horticulture and the grains sector. The eligible studies from both sets of searches are reported separately in Section 2 (Method) and Section 3 (Search Results) for transparency but were analysed together to inform the narrative synthesis.

In total, 97 studies were used to address this question, one of which was relevant to both grazing and grains. There were 57 studies related to grazing, 19 used for grains, 21 for sugarcane and a single study for horticulture including bananas.

#### Grazing

The initial search focused on grazing and the implications of co-benefits. The additional search did not create further search terms, however following peer reviewer feedback and drawing on the Lead Author's expertise, a further 16 studies were manually added. In total, 57 studies informed the grazing co-benefits section (Table 12).

*Table 12. Grazing studies included in the review.*

| Pollutant pathway | Specific Management Practice | Potential Co-benefit | Co-benefits Reported | Citations |
|---|---|---|---|---|
| Hillslope | Pasture utilisation and carrying capacity, ground cover, land condition, property mapping. | • Increased carbon sequestration<br>• Greenhouse gas emission reduction<br>• Improved soil health<br>• Maintain / protect / restore biodiversity<br>• Indigenous participation | • Carbon sequestration<br>• Improved soil health<br>• Maintain / protect / restore biodiversity<br>• Indigenous Participation | Allen et al., 2013; Arcoverde et al., 2017; Bartley et al., 2023; Barzan et al., 2021; Baumber et al., 2020; Bentley et al., 2008; Bradshaw et al., 2013; Bray et al., 2014; 2016; Bryan et al., 2016; Conrad et al., 2017; Cobon et al., 2009; Coggan et al., 2021; De Valck & Rolfe, 2018; Eldridge et al., 2016; Fernandez et al., 2020; Fensham & Guymer, 2009; Gebremedhn et al., 2022; Gowan & Bray, 2010; Gordon, 2007; Gordon & Nelson, 2007; Gurney et al., 2019; Hacker & McDonald 2021; Henry et al., 2002; Henry, 2023; Houston et al., 2015; Hunt, 2014; Jarvis et al., 2018; 2021; Jones et al., 2021; Kutt et al., 2012; Larson et al., 2020; 2023; Ludwig et al., 2004; McDonald et al., 2022; Neilly et al., 2018; O'Reagain et al., 2011; Parkhurst et al., 2022; Parsons et al., 2017; Robertson, 2003; Sakadavan & Nguyen, 2017; Schatz et al., 2020; Segoli et al., 2015; Shaw et al., 2013; Teague & Kreuter, 2020; Thornton & Elledge, 2022; van Oudenhoven et al., 2015; Wang et al., 2020; Waters et al., 2017; 2020; Williams et al.,2022; Witt et al., 2011 |

| Pollutant pathway | Specific Management Practice | Potential Co-benefit | Co-benefits Reported | Citations |
|---|---|---|---|---|
| Streambank | Grazing pressure on frontage country, off-stream watering points, fenced off riparian zones. | • Increased carbon sequestration<br>• Greenhouse gas emission reduction<br>• Improved soil health<br>• Maintain / protect / restore biodiversity<br>• Indigenous participation | • Maintain / protect / restore biodiversity | Agouridis et al., 2005; Cattarino et al., 2014; Collard et al., 2009; Martin et al., 2006; Pearson et al., 2019 |
| Gully | Revegetation of gullied area and stock exclusion, temporary structures such as stick traps, porous check dams, contour banks, engineered check dams and mechanical gully reshaping and earth works.<br>Roads, tracks and fences designed to limit erosion. | • Increased carbon sequestration<br>• Greenhouse gas emission reduction<br>• Improved soil health<br>• Maintain / protect / restore biodiversity<br>• Indigenous participation | | |

### Sugarcane

Many studies identified through the literature searches were excluded as they reported no water quality outcomes, adoption or productivity and were considered to have been addressed in other questions. In total, 21 studies met the eligibility criteria and were assessed in more detail. Although many studies covered multiple practices, often the studies were focused on one key management practice and outcome or co-benefit. The studies were dominated by nitrogen (N) and nitrous oxide or soil carbon (C) and soil management such as trash blanketing. The eligible studies included in the review are captured in Table 13. No Indigenous co-benefits were captured in the sugarcane search findings.

*Table 13. Sugarcane studies included in the review, classified by management practices in the P2R Water Quality Risk Framework groupings and the identified co-benefit.*

| Pollutant pathway | Specific Management Practice | Potential Co-benefit | Co-benefits Reported | Citations |
|---|---|---|---|---|
| Nutrient | Fertiliser application including rate and timing (primarily dissolved inorganic nitrogen) | • Increased carbon sequestration<br>• Greenhouse gas emission reduction<br>• Improved soil health | • Reduced nitrous oxide and greenhouse gas emissions<br>• Increased soil carbon | Agnew et al., 2011; Bell et al., 2019; Dalal et al., 2003; Park et al., 2010; Takeda et al., 2021; Thorburn et al., 2010; 2011; Wang et al., 2016; Warner et al., 2019; Webster et al., 2012 |
| Pesticides | Banded Spraying | • Greenhouse gas emission reduction<br>• Maintain / protect / restore biodiversity | • Reduced nitrous oxide and greenhouse gas emissions<br>• Improved soil carbon | Wang et al., 2016; Zhang et al., 2018 |
| Soil | Break crop, controlled traffic, trash blanketing | • Improved soil health<br>• Increased carbon sequestration<br>• Greenhouse gas emission reduction<br>• Maintain / protect / restore biodiversity | • Disease break<br>• Soil fertility<br>• Improved soil structure<br>• Reduced erosion | Bell et al., 2007; Blair et al., 1998; Braunack et al., 2006; Friedl et al., 2023; Jupiter & Marion, 2008; Liu et al., 2018; Manwaring et al., 2018; Nachimuthu et al., 2016; Pankhurst et al., 2003 |
| Irrigation | Timing | • Increased carbon sequestration<br>• Greenhouse gas emission reduction<br>• Improved soil health | • Salinity reduction | Hurst et al., 2004 |

## Horticulture

The majority of studies identified in the literature searches were linked to biosecurity issues such as pest management of thrips or fruit flies, or agronomic studies such as the application of different management methods and were therefore excluded. There was only one study that was included in the review (Table 14). No Indigenous co-benefits were found in the horticulture search findings.

*Table 14. Horticulture studies classified by management practices in the P2R Water Quality Risk Framework and the identified co-benefit.*

| Pollutant pathway | Specific Management Practice | Potential Co-benefit | Co-benefits Reported | Citations |
|---|---|---|---|---|
| Nutrient | Fertiliser application including rate and timing | • Increased carbon sequestration<br>• Greenhouse gas emission reduction<br>• Improved soil health | • Greenhouse gas emission reduction | Huang et al., 2012 |

| Pollutant pathway | Specific Management Practice | Potential Co-benefit | Co-benefits Reported | Citations |
|---|---|---|---|---|
| Soil | Maintaining ground cover, interrow and headland management | • Climate change/flood management<br>• Improved soil health<br>• Maintain / protect / restore biodiversity<br>• Increased carbon sequestration | | |

### Grains

Studies that were outside the Brigalow Bioregion of Queensland or northern New South Wales, and those which included sheep in rotations, policy instruments and adoption, method developments and frameworks were excluded. Studies from previous research stations such as Brigalow and Narayen Research Station in the Fitzroy and Burnett Mary regions respectively, provided a large amount of evidence, particularly those written in the early 1990's when the cropping industry was relatively new to these areas. Many studies explored multiple management practices, but for the review each was assigned to the dominant management practice it considered. There were 19 studies included in the review, listed in Table 15. No Indigenous co-benefits were captured in the grains search findings.

*Table 15. Grains studies classified by the management practices in the P2R Water Quality Risk Framework and the identified co-benefit.*

| Pollutant pathway | Specific Management Practice | Potential Co-benefit | Co-benefits Reported | Citations |
|---|---|---|---|---|
| Nutrient | Fertiliser application including rate and timing | • Greenhouse gas emission reduction<br>• Increased carbon sequestration<br>• Improved soil health. | • Greenhouse gas emission reduction<br>• Increased carbon sequestration | Bell et al., 1995; Bradshaw et al., 2013; Dalal et al., 1995; Palmer et al., 2017; Robertson et al., 1993; 1994 |
| Pesticides | Banded spraying | • Greenhouse gas emission reduction | • Greenhouse gas emission reduction<br>• Increased soil carbon | Rendon et al., 2015 |
| Soil | Crop rotations, controlled traffic, minimum tillage | • Improved soil health<br>• Greenhouse gas emission reduction<br>• Increased carbon sequestration<br>• Maintain / protect / restore biodiversity | • Disease break<br>• Soil fertility and structure<br>• Reduced erosion | Bell et al., 1995; Bradshaw et al., 2013; Graham et al., 2012; Hulugalle et al., 2002; 2020; Lebbink et al., 2022; Maraseni & Cockfield, 2011; Michael et al., 2021; Nevard et al., 2019; Radford & Thornton, 2011; Russell & Jones, 1996; Standley et al., 1990; Thomas et al., 1990; 2007 |

## 4.1.1 Summary of evidence to 2022

It is clear from the summary tables in Section 4.1.0 that there is significant variability in the scope and number of studies relevant to different land uses, management practices and co-benefits. As a result, the level of detail presented in the following section varies considerably. Where specific details were available, these were included to demonstrate the level of information that would be required to fully assess the co-benefits of management practices implemented for water quality improvement in the GBR catchment area.

#### 4.1.1.1 Grazing

Management of soil erosion in grazing lands is grouped by the main erosion types (hillslope, streambank and gully erosion). The studies identified in this review that had water quality outcomes and co-benefits were primarily focused on hillslope erosion management. This is largely because there are few studies in the GBR catchments that quantify the water quality outcomes of streambank and gully management practices (discussed further in Question 3.6, Brooks et al., this SCS). The relevant studies for streambank erosion are largely captured in the discussion of biodiversity outcomes which discuss landscape clearing and fragmentation more broadly, as well as in riparian areas. There were no specific studies discussing additional environmental or biodiversity co-benefits from the management of gully erosion (also noted as a knowledge gap in Question 3.6, Brooks et al., this SCS). Therefore, the environmental co-benefits are focused on management practices adopted for hillslope erosion.

##### *Environmental co-benefits*

##### Stocking rate (hillslope erosion management)

Grazing management strategies that reduce grazing pressure and sediment runoff are key practices in the P2R Water Quality Risk Framework (Table 2). Increasing vegetation cover (particularly in the dry season) by reducing grazing pressure (Gordon, 2007; Pulido et al., 2018; van Oudenhoven et al., 2015) or allowing tree regeneration, improves the infiltration of water into the soil and the soil organic matter by trapping the overland flow of vegetation- and animal-derived nutrient rich material (Gebremedhn et al., 2022). A key co-benefit is the positive impact on soil health and increased Soil Organic Carbon (SOC) under different grazing management strategies, a topic which has been studied in a long-term grazing trial at Wambiana in Charters Towers (O'Reagain et al., 2011). Several co-benefit studies have been completed at this field site:

- Segoli et al. (2015) explored the impacts of grazing intensity and rainfall on the dynamics of soil nutrients. Soil organic matter and mineral nitrogen were measured in surface soils (0–10 cm depth) 11, 12 and 16 years after trial establishment on experimental plots representing moderate stocking (stocked at the long-term carrying capacity for the region) and heavy stocking (stocked at twice the long-term carrying capacity). The study found that higher soil organic matter was found under heavy stocking, although grazing treatment had little effect on mineral and total soil nitrogen. Interannual variability had a large effect on soil mineral nitrogen, but not on soil organic matter, suggesting that soil nitrogen levels observed in this soil complex may be affected by other indirect pathways, such as climate.
- Soil health was also explored in the soil found between green tussocks (Williams et al., 2022). Two soil types two stocking rates (high, moderate), and resting land from grazing during wet seasons (rotational spelling) were examined. Rotational spelling had the highest biocrust (living soil cover). Biocrusts were dominated by cyanobacteria that bind soil particles, reduce erosion, sequester carbon, fix nitrogen, and improve soil fertility. Rotational spelling with a moderate stocking rate emerged as best practice at these sites.
- A study by Bray et al. (2014) explored carbon stocks and greenhouse gas emissions (reported as t $CO_2$-e) associated with livestock, pasture, woody vegetation, soil and fire under alternative grazing management strategies (moderate and heavy stocking rate) over a 16-year period at Wambiana. The results indicated that tree biomass and woody vegetation dynamics dominate the carbon stocks and fluxes in grazed savanna woodlands; this was also found by Gowen and Bray (2016). During the trial, both moderate and heavy stocking rate treatments had a positive net carbon balance, with the moderate treatment having a better 'net carbon position' (19 t $CO_2$-e $ha^{-1}$) than the heavy stocking rate (9 t $CO_2$-e $ha^{-1}$), primarily due to less livestock emissions and greater pasture biomass and soil carbon (Bray et al., 2014).

For comparison, work in the Douglas Daly catchment in the Northern Territory explored sequestration of SOC when cattle grazed buffel grass (*Cenchrus ciliaris* L.), a commonly found pasture in the GBR catchment area, under continuous grazing or intensive rotational grazing. SOC was measured in the topsoil (0–30 cm) twice each year for five years (2009–14) and changes in carbon stocks over time were compared between treatments (Schatz et al., 2020). The study found that intensive rotational grazing did not result in any increase in SOC over time.

A review of data from northern Australian studies found that stored SOC (to a depth of 30 cm) appeared to be influenced by various combinations of grazing intensity, land condition and land/soil type, and that it was difficult to establish evidence for a strong link between livestock management and SOC content (Henry, 2023).

Allen et al. (2013) sampled SOC stocks at 98 sites from 18 grazing properties across Queensland. These samples covered four nominal grazing management classes (Continuous, Rotational, Cell, and Exclosure), eight broad soil types, and a strong tropical to subtropical climatic gradient. Temperature and vapour-pressure deficit explained >80% of the variability of SOC stocks at 0–10 cm and 0–30 cm. Once detrended of climatic effects, SOC stocks were strongly influenced by total standing dry matter, soil type, and the dominant grass species. At 30 cm, there was a weak negative association between stocking rate and climate-detrended SOC stocks, and Cell grazing was associated with smaller SOC stocks than Continuous grazing and Exclosure management.

Waters et al. (2017) found that in plots from western New South Wales the benefit of increasing vegetation cover appeared to vary with soil type, for example, there was little effect of grazing management on Vertisols, but a significant effect on SOC for red soils (Lixisols). The ways in which climate warming and land management interact will affect co-benefits. For example, grazing practices that increase tree cover, ground vegetation cover and soil carbon are likely to trap more water on the property reducing the impacts of droughts (Fensham & Guymer, 2009; O'Reagain et al., 2011). Grazing management strategies appear to have limited impact on the SOC over the long and short term in studies that have been completed to date.

### Land condition (hillslope erosion management)

Land condition determines the capacity of grazing land to produce useful forage and is assessed on soil condition (including bare ground and soil erosion) and pasture condition (density of perennial grasses, maintaining 50% ground cover and minimising weeds). It is therefore directly related to carrying capacity, livestock production and profitability of a grazing enterprise. Land condition is classified in four categories (A to D)[13].In the ABCD land condition framework, 'A' or Good condition is characterised by at least 50% and often above 70% ground cover at the end of the dry season, good coverage of perennial grasses, little bare ground, few weeds, with no erosion and good soil surface condition, and 100% long-term carrying capacity. 'D' or Degraded condition typically has less than 20% ground cover, lack of perennial grasses, severe erosion or scalding and no long-term ability to carry stock. The characteristics of 'B' and 'C' land condition vary between these categories.

Understanding the links between land condition characteristics and carbon sequestration as a co-benefit is critical, as is the implementation of agricultural techniques and technologies that are specifically aimed at sequestering atmospheric carbon into the soil, and in crop roots, wood and leaves (Baumber et al., 2020). Management of native vegetation for timber harvesting and the proliferation of woody vegetation (vegetation thickening) in the grazed woodlands also represent large carbon fluxes (Henry et al., 2002). Bray et al. (2016) sought to identify the land condition indicators for analysis and tested relationships between land condition indicators and SOC stock using data from a paired-site sampling experiment (10 sites). Following this a further 329 sites were explored. The land condition indicators most closely correlated with SOC stocks across datasets and analysis scales were: tree basal area, tree canopy cover, ground cover, pasture biomass and the density of perennial grass tussocks. In

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[13] Reef Protection Regulations, Farming in the Reef Catchments. Grazing Guide (2020) https://www.qld.gov.au/__data/assets/pdf_file/0013/115141/grazing-guide.pdf; refer to Figure 3 p12 for the ABCD land condition framework.

combination with soil type, these indicators accounted for up to 42% of the residual variation after climate effects were removed. However, responses often interacted with soil type, adding complexity and increasing the uncertainty associated with predicting SOC stock change at any particular location (Bray et al., 2016). There was no significant difference ($P > 0.10$) in the average SOC stocks between 'Good' and 'Poor' land condition sites in either the 0–0.1-m soil layer (9.9 and 9.1 t C $ha^{-1}$, respectively), or the 0–0.3-m layer (23.3 and 21.9 t C $ha^{-1}$, respectively), but there was cogent evidence ($P < 0.01$) that the effect varied among land types, with Red Basalt having more SOC at the 0-0.1 m layer even in Poor condition than Alluvial, Granite, Black Basalt and Gold Fields (Bray et al., 2016).

A review of data from northern Australian studies found that stored SOC (to a depth of 30 cm) appeared to be influenced by various combinations of grazing intensity, land condition and land/soil type, and that it was difficult to establish evidence for a strong link between livestock management and SOC content (Henry, 2023). However, using a meta-analysis approach, the McDonald et al. (2022) review found that there was good evidence that grazing strategy did influence SOC.

Bartley et al. (2023) assessed long-term trial sites in the Burdekin catchment to assess regenerative grazing, which has been noted as a carbon farming management technique due to its potential impact on land condition. Regenerative grazing involves the subdivision of properties into numerous small paddocks, and alternating the use of high stocking densities for some part of the management cycle. It also incorporates longer periods of strategic rest. Bartley et al. (2023) found that strategically managed rests from grazing pressure will likely yield better vegetation and soil condition outcomes than the practice does at sites that do not use periods of strategic rest as part of their grazing management. Sites that maintained (remotely sensed) percentage ground cover at or above the minimally disturbed reference benchmark levels for more than 10 years, as well as having measurably higher biomass, basal area and litter, had significant increases in total nitrogen and SOC relative to the local control site. The study concluded that it is likely to take between 3 and 15 years for the key vegetation metrics to respond to changed grazing management, and in the order of 5–20 years to be able to detect changes in soil condition confidently.

Hunt (2014) proposed that judicious use of fire is a key component of sound grazing management in northern Australia, and future comparisons of land condition should be made with sites that have had suitable fire frequency. The field study on an open eucalypt savanna woodland and a savanna grassland-open shrubland suggested that fire regime had either no effect, or an inconsistent effect, on above ground carbon stocks. The opportunities to increase carbon stocks will depend on the frequency of fire and vegetation type, especially its woodiness or potential woodiness. Reducing fire frequency in woody rangelands will increase carbon stocks but may have adverse effects on pasture and livestock production. Reducing grazing pressure or destocking might also increase carbon stocks but may be relevant only when a property is overstocked or where relatively unproductive land could be taken out of livestock production. Any carbon gains from altering fire and grazing management are likely to be modest (Hunt, 2014).

A critical management approach to improve land condition has been the use of leucaena-grass pastures. Conrad et al. (2017) explored the carbon and nitrogen dynamics beneath leucaena-grass pastures, at 1 m soil depth. SOC stocks were also affected by the age of the leucaena stand. In the 0–0.3 m zone, SOC increased by 17–30% over 40 years, equating to a sequestration rate of 280 kg $ha^{-1}$ $yr^{-1}$. Although not tested in the context of the catchments of the GBR, elsewhere in Europe, USA and South America, integration of crops or legumes into livestock production provides opportunities for increasing resource use efficiencies, reducing environmental pollution, making systems resilient to impacts of climate change, and reducing GHG emissions from the system (de Albuquerque Nunes, et al., 2021).

In southwestern Queensland, the exclusion of grazing (for 40 years) in Mulga woodlands has shown a potential benefit of 0.92 and 1.1 t $CO_2$-$eha^{-1}$ $yr^{-1}$ (soil carbon sequestration is approximately 0.18 t $CO_2$-$eha^{-1}$ $yr^{-1}$, with above ground biomass contributing an additional 0.73-0.91 t $CO_2$-$eha^{-1}$ $yr^{-1}$) (Witt et al., 2011). The magnitude of the carbon sink in Queensland's 27 million ha grazed eucalypt woodlands is estimated to be 66 Mt $CO_2$-$eyear^{-1}$ (Henry et al., 2002).

Wang et al. (2020) reviewed how modelling can be used to draw together disparate lines of evidence to make predictions about the long-term impact of land management practices on soil carbon and greenhouse gas emissions in grazing systems. The study also identifies current knowledge gaps and recommends research priorities.

### *Biodiversity co-benefits*

Biodiversity in rangelands depends on resource availability (composition, abundance and structure), be that soil micro- or macro-biota, vegetation, or fauna (Hacker & McDonald, 2021). Heavy grazing pressure on rangelands can reduce vegetation composition, abundance, and structure (Eldridge et al., 2016; Waters et al., 2020). This can reduce the supply of organic matter to the soil, reducing soil carbon and nutrient contents (Teague & Kreuter, 2020), although this is not always the case with some studies showing negative effects, and some no effect (reviewed in Waters et al., 2020). These differences in results are very likely due to site variation in plant species composition, the carry-over effects from previous management, inherent variability in soil organic carbon and the length of the growing season. In addition to water quality influences, a meta-analysis by Barzan et al. (2021) shows that livestock grazing has a negative effect on bird abundance and species richness. Generally, cattle grazing is more detrimental to bird richness and abundance than is sheep grazing or a mixture of domestic livestock. This response will vary with space, time, and the taxonomic group in question; for example, reptile abundance and species richness did not significantly vary between grazing treatments in the Wambiana trial (see Neilly et al., 2018). Ant communities in rangelands also appear to be particularly resilient to livestock grazing and, whilst community composition may change, ant species richness does not appear to be affected by grazing pressure (Arcoverde et al., 2017).

In the P2R Water Quality Risk Framework, land condition is classified on a scale of A, B, C or D, from good to very poor respectively, although it is difficult to assess the relationships between land condition, habitat and biodiversity outcomes. This is because land condition classification is based on bare ground, woody weeds, and 3P (productive, perennial and palatable) grasses, but is not framed relative to climate or a comprehensive assessment of habitat attributes. Parsons et al. (2017) found that the land condition scale (A, B, C or D) partially explained species richness and abundance patterns only for mammals (especially rodents), which tended to be higher in better condition pasture; however, for other vertebrate groups, land condition was a very poor descriptor of richness and abundance.

The land condition scale was not useful to assess wildlife diversity primarily because ‘woody thickening’ (increases in woody vegetation on grazed land, including shrubs and trees) lowers the ‘grazing value’ of land while also generally promoting vertebrate diversity. In line with this, biodiversity decreased with increasing bare ground and erosion, together with, and in the absence of, vegetation cover (i.e., desertification), which is also consistent with land degradation.

Bradshaw et al. (2013) found that land management actions undertaken to reduce carbon emissions that could impact biodiversity outcomes were: 1) environmental plantings for carbon sequestration; 2) native regrowth; 3) fire management; 4) forestry; 5) agricultural practices (including cropping and grazing) and 6) feral animal control, and that these will only have real biodiversity value if they comprise appropriate native tree species and provide suitable habitats and resources for valued fauna. However, these plantings can also alter local hydrology and reduce water availability indicating that further investigations are required (Bradshaw et al., 2013; Bryan et al., 2016). Vegetation management and regrowth, fire management, and feral animal control are also relevant to water quality management; however, there is limited direct evidence of these interactions.

Management of regrowth after agricultural abandonment requires setting appropriate baselines and allowing for thinning in certain circumstances. Improvements to forestry rotation lengths are likely to increase carbon-retention capacity and biodiversity value. Prescribed burning is being used as a tool to reduce the frequency of high-intensity wildfires in northern Australia and increase carbon retention. Bradshaw et al. (2013) highlighted that the carbon price-based modifications to agriculture that would benefit biodiversity include reductions in tillage frequency and livestock densities, reductions in fertiliser use, and retention and regeneration of native shrubs; however, anticipated shifts to exotic perennial grass species such as buffel grass and Indian couch could have net negative implications for native biodiversity. Similarly, although reductions in greenhouse gas emissions are possible from feral animal control, the larger co-benefit will be achieved for biodiversity with the removal of feral animals (e.g., feral pigs) (Graham et al., 2012).

While the biodiversity of rangeland landscapes often benefits from reduced grazing pressure (Benckiser & Schnell, 2006), there is what is called the intermediate disturbance hypothesis (Fox, 1979) that suggests that optimal biodiversity outcomes rely upon some, but lower, grazing pressure (not no grazing pressure), creating heterogeneity in vegetation composition, structure, and distribution. There are no consistent relationships for grazing pressure and biodiversity responses, but improvements in vegetation cover are generally better for biodiversity outcomes. For example, reptile community resilience is greatest at moderate stocking levels with high stocking levels leading to a decline in reptile community diversity (Neilly et al., 2018), although arboreal reptiles were less affected by grazing regime than were ground-based reptile species (Neilly et al., 2018). Similarly, ground-foraging birds were most sensitive to different grazing regimes, but whether the responses were positive or negative depended on bird species' ecology (Kutt et al., 2012; Neilly & Schwarzkopf, 2019). For example, the red-backed fairy-wren decreased in abundance with increased grazing and was positively associated with grass and shrub (*Carissa ovata*) cover, whereas Australian magpies increased in abundance in the most heavily grazed paddocks (Neilly & Schwarzkopf, 2019).

Under the P2R Water Quality Risk Framework streambank management, fencing of riparian areas (frontage areas) and providing off-stream watering points for cattle is highlighted to limit streambank erosion. In the variegated landscapes of southeastern Queensland where riparian vegetation is surrounded by both extensive grazing and intensive cropping, Martin et al. (2006) found that 80% of bird species responded positively to changes in both riparian habitat condition and landscape context, while fewer than 50% of species were significantly influenced (either positively or negatively) by landscape context alone. The influence of landscape context on the bird assemblage increased as the surrounding land use became more intensive (e.g., woodland to native pasture to crop).

Although evidence is currently limited, Houston et al. (2015) found that woodland remnants along riparian corridors improved termite (Isoptera) diversity and functionality in those remnants, because of increased access to resources such as live and dead wood, thus having a positive impact on biodiversity.

The bioregions of Queensland have been assessed to understand the fragmentation and the specific drivers of different fragmentation patterns in grazing and cropping at fine and coarse scales (Cattarino et al., 2014). Fragmentation patterns occurred at approximately 100 ha (1 km$^2$), which is much smaller than the average property size in Queensland, i.e., 7,000 ha. Different drivers of clearing of native vegetation determine different fragmentation patterns between and within agricultural fields, in landscapes modified by different land uses. For example, it was found that cleared areas within agricultural properties were clustered around landscape features (e.g., riparian vegetation) and vegetation classes (e.g., dry eucalypt forests), which are indicators of high soil productivity. This may explain why, at coarse scales, cropping creates less fragmented patterns than grazing - the spatial clustering of vegetation clearing in areas of high soil fertility has a greater effect on the physical separation of agricultural land (e.g., crop fields) from remnant vegetation in cropped areas than in grazed ones (Cattarino et al., 2014).

Collard et al. (2009) found that in the Brigalow Bioregion the richness, abundance and diversity of birds were all significantly higher in Brigalow remnants than in the adjacent matrix of cropping and grassland. Within the matrix, species richness and diversity were higher in uncultivated grasslands than in current cultivation or previously cultivated grasslands. Forty-four percent of bird species were recorded only in Brigalow remnants and 78% of species were recorded in Brigalow and at least one other land management category. Despite high levels of landscape fragmentation and modification, small patches of remnant Brigalow vegetation provide important habitat for a unique and diverse assemblage of native birds. Catterino et al. (2014) and Pearson et al. (2019) highlighted the importance of scale and, therefore, land use when selecting relevant policy mechanisms for preserving native vegetation.

The impact of riparian management on bird species in southeast Queensland was explored by Martin et al. (2006) who assessed the individual species relative mean abundance, total species relative abundance, and total species richness. Monitoring over multiple years was undertaken in three designs:

- The influence of landscape context (three levels: grazed woodland, native pasture, crop) on uncleared grazed riparian habitats.
- The influence of landscape context (two levels: native pasture, crop) on cleared, grazed riparian habitats.
- The influence of both landscape context (two levels: native pasture, crop) and riparian habitat condition (two levels: uncleared, cleared).

Irrespective of landscape context, the clearing of trees and livestock grazing was the primary determinant of the bird species assemblage. Allowing trees to regenerate naturally or planting trees along cleared riparian habitat will result in a dramatic increase in bird species richness, relative abundance and change in community composition (Martin et al., 2006). Cleared riparian habitats surrounded by crops were characterised by generalist ground foraging species; crested pigeon, Pacific black duck, and the exotic common myna, whereas those surrounded by native pasture, a less intensive surrounding land use, were characterised by 'grassland species' (e.g., Richard's pipit, golden-headed cisticola). In both uncleared and cleared riparian sites the resource availability of the context appeared to influence the species composition of the riparian habitats. The context of a riparian habitat will provide birds with resources that are either additional to, complementary to, or absent from those found within the riparian habitat. On the other hand, many ground foraging bird species which prefer cleared habitat require trees to nest and roost, making uncleared riparian sites surrounded by native pasture or crops desirable habitat (e.g., grey-crowned babbler, apostlebird). The increased relative mean abundance of noisy miners at riparian sites surrounded by crops is likely to influence the presence and relative abundance of other woodland birds, through its aggressive behaviour, particularly to birds with a smaller body size (<65 g) than the noisy miner. The change in bird fauna recorded in riparian habitat surrounded by crops, therefore, cannot be attributed directly to changes in context but indirectly, by providing desirable habitat for the noisy miner (Martin et al., 2006).

### *Indigenous benefits*

Australia's First Nations People are often engaged in fire management through Indigenous land and sea management programs (ILSMPs) to mitigate large savanna fires that emit large amounts of carbon. Larson et al. (2023) highlighted the key messages of the inter-connectedness of the system, and the need for resource managers to monitor not only the extent and condition of natural systems but also the extent and condition of an inextricably connected human system, in addition to human interactions. Indigenous business development, a co-benefit associated with investment in ILSMPs in northern Australia, has resulted in more than 65% of ILSMPs undertaking commercial activities that generate revenue and create jobs (Jarvis et al., 2021). In addition to generating environmental benefits, ILSMPs also generate economic benefits (co-benefits) that support Indigenous aspirations and help to deliver multiple government objectives.

In an assessment of eight years of data relating to Indigenous businesses that are registered with the Office of the Registrar of Indigenous Corporations, Jarvis et al. (2018) found that ILSMPs have characteristics that indicate an ability to initiate self-sustaining growth cycles. This supports the proposition that expenditure on ILSMPs generates positive spillovers for Indigenous businesses (even those not engaged in land management), albeit with a 3-year lag. ILSMPs have been shown to be an appropriate mechanism for achieving a wide range of short-term benefits and may also work as catalysts for Indigenous business development, fostering sustainable economic independence.

Larson et al. (2020) explored the outcomes of ILSMP's including consideration of 26 wellbeing factors, identifying that 'Health centres', 'Language', 'Schools', and 'Safe community' emerged as having the highest importance to the largest percentage of the respondents. When grouped, using principal components analysis the 'Community and society' domain emerged as the most important, accounting for 52% of the variation, and hence of the overall importance of all wellbeing factors. The second most important domain was the 'Country and culture', contributing 31%. Lastly, 'Economic aspects' contributed only 17%. Respondents believed that ILSMPs have played a considerable causal role in improving wellbeing, by positively changing factors most important to them. Specifically, 73% of perceived causal links were related to improvements in the 'Country and Culture' and 23% to

‘Community and Society’ domain. Larson et al. (2020) concluded that land management for Indigenous people is much more than ecological or environmental management with ILSMPs; it is perceived to provide a wide range of cultural and social benefits (Larson et al., 2020).

In summary, evidence to date suggests that reductions in grazing pressure and maintenance of woodlands, which are beneficial for water quality improvement, will generally create improvements in the co-benefits of soil carbon, biodiversity and potentially cultural wellbeing in Queensland’s rangeland systems. Whilst the research on grazing land management to improve water quality is growing year on year (Bartley et al., 2023; Thorburn et al., 2013) there is still much to learn. For example, no clear evidence is available for the role that adaptive, multi-paddock management, a technique commonly used in rangelands in the US (Teague & Kreuter, 2020), could have on co-benefits and water quality in the catchments of the GBR.

#### 4.1.1.2 Sugarcane

##### *Environmental co-benefits*

##### Nitrogen management

Sugarcane production requires high rates of nitrogen (N) fertiliser (Thorburn et al., 2010) with nitrogen application rates a key management practice in the P2R Water Quality Risk Framework. While nitrogen is added for plant growth, it is also a component of nitrous oxide ($N_2O$), a major greenhouse gas contributing to global warming. A reduction in nitrogen fertiliser rate (or better timing or use of slow-release nitrogen fertiliser) can reduce $N_2O$ emissions, and affect the extent of $N_2O$ emission reductions. The principal processes causing $N_2O$ emissions in the soil are nitrification, nitrifier denitrification, and denitrification. Nitrification is the microbial oxidation of ammonium ($NH_4^+$) to nitrate ($NO_3^-$), with $N_2O$ emitted as a by-product. Nitrifier denitrification is the reduction of nitrite ($NO_2^-$) to nitrogen monoxide (NO), then to $N_2O$, and finally to dinitrogen ($N_2$). Denitrification is a two-step process whereby $NO_3^-$ is converted to $N_2O$ and then into inert $N_2$ under anaerobic conditions. In the denitrification pathway, $NO_2^-$, NO and $N_2O$ are obligate intermediates. Soil moisture, rainfall and temperature all impact the rate at which nitrogen transformation to $N_2O$ occurs.

Weier (1998) reported a total estimated $N_2O$ production in Australia between 2.1 and 2.4 Gg $N_2O$-N yr$^{-1}$ from sugarcane. In sugarcane production, $N_2O$ is primarily produced in soil by the activities of microorganisms during nitrification and denitrification processes. The ratio of $N_2O$ to $N_2$ production is described as depending on oxygen supply or water-filled pore space, decomposable organic carbon, nitrogen substrate supply, temperature, pH and salinity (Dalal et al., 2003). $N_2O$ production from soil is sporadic both in time and space, and therefore, it is a challenge to scale up the measurements of $N_2O$ emissions from a given location and time to regional and national levels (Dalal et al., 2003).

Estimates of $N_2O$ emissions from various agricultural systems vary widely. For example, Dalal et al. (2003) showed that in irrigated sugarcane crops, 15.4% of fertiliser was lost over a 4-day period whereas in arable cereal cropping, $N_2O$ emissions range from <0.01% to 9.9% of N fertiliser applications, and in flooded rice in the Riverina Plains, $N_2O$ emissions ranged from 0.02% to 1.4% of N fertiliser applied. This highlights the regional variability and impact of soil microbes, oxygen, pH, salinity and temperature (Dalal et al., 2003). Nitrogen use, together with the warm, wet environment in which sugarcane grows, produces a high potential for nitrous oxide ($N_2O$) emissions from soils (Thorburn et al., 2010). Through Agricultural Production Systems sIMulator (APSIM) modelling Thorburn et al. (2010) found emissions between 3-5% of applied nitrogen but noted that this varied between regions and soils, and were higher in clay soil, where substantial irrigation was applied, and where crop residues were retained (trash blanketing).

While most of the reactive nitrogen is ultimately removed by denitrification, estimates of denitrification are highly uncertain due to methodological constraints. For example, Warner et al. (2019) applied a mobile isotope ratio mass spectrometer system (Field-IRMS) for *in situ* quantification of $N_2$ and $N_2O$ fluxes from fertilised cropping systems. Annual $N_2O$ rates were 13.2 kg N ha$^{-1}$ for manual chambers and 18.2 kg N ha$^{-1}$ with automatic chambers. High rainfall was identified as a factor for large daily $N_2O$ emissions along with warm and wet conditions, poor drainage, moderately low pH and high availability of soil mineral nitrogen (Warner et al., 2019). Steep increases in $N_2O$ intensity demonstrates environmental inefficiency at high fertiliser N rates (up to 200 kg N $ha^{-1}$), emphasising the importance of avoiding excessive N fertiliser application in tropical sugarcane systems from both agronomic and environmental perspectives (Takeda et al., 2021).

Controlled release fertilisers have been explored to reduce runoff for water quality purposes with a year-long field experiment conducted in Ingham to assess the efficacy of polymer-coated urea (PCU) and nitrification inhibitor (3,4-dimethylpyrazole phosphate (DMPP))-coated urea (NICU) (Wang et al., 2016). Emissions of $N_2O$ were measured using manual and automatic gas sampling chambers in combination, and showed that:

- The nitrogen release from PCU continued for >5–6 months, and lower soil $NO_3$- contents were recorded for ≥3 months in the NICU treatments compared with the conventional urea treatments.
- The annual cumulative $N_2O$ emissions were high, amounting to 11.4–18.2 kg $N_2O$-N $ha^{-1}$.
- Decreasing the fertiliser application rate from the recommended 140 kg N $ha^{-1}$ to 100 kg N $ha^{-1}$ led to a decrease in sugar yield by 1.3 t $ha^{-1}$ and 2.2 t $ha^{-1}$ for the conventional urea and PCU treatments, respectively, but no yield loss occurred for the NICU treatment. Crop nitrogen uptake also declined at the reduced N application rate with conventional urea, but not with the PCU and NICU.

These results demonstrated that substituting NICU for conventional urea may substantially decrease fertiliser N application from the normal recommended rates whilst causing no yield loss or N deficiency to the crop (Wang et al., 2016).

Friedl et al. (2023) used a $^{15}N$ gas flux method, which uses a stable 15N-$NO_3$- tracer injected or applied on the surface of soil under a closed static chamber, for the measurement of both $N_2O$ and $N_2$ denitrification fluxes. This method was applied to understand the effect of sugarcane trash removal and the use of the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP) on $N_2$ and $N_2O$ emissions on a commercial sugarcane farm in Bundaberg. High gaseous nitrogen losses were observed under the standard grower practice where sugarcane trash retention and N fertiliser application (145 kg N $ha^{-1}$ as urea) resulted in $N_2$ and $N_2O$ emissions (36.1 kg N $ha^{-1}$) from the subsurface N fertiliser band, with more than 50% of these losses emitted as $N_2O$. Sugarcane trash removal reduced $N_2$ emission by 34% and $N_2O$ emission by 51%, but had no effect on the $N_2O/(N_2 + N_2O)$ ratio. The use of DMPP lowered $N_2$ and $N_2O$ emission by 35% and 98%, respectively, reducing the percentage of these losses ($N_2 + N_2O$) emitted as $N_2O$ to only 4%. The overall findings were that the use of DMPP is an effective strategy to reduce nitrogen losses and minimise $N_2O$ emissions, while maintaining the benefits of sugarcane trash retention in sugarcane cropping systems (Friedl et al., 2023).

### Pesticide management

There is limited evidence on the interaction of pesticide management and $N_2O$ emissions. However Zhang et al. (2018) explored the impacts of herbicides (atrazine and glyphosate) and nitrification inhibitors (3,4-dimethylpyrozole phosphate, DMPP) on gross nitrification, nitrite and nitrate consumption, $N_2O$ emission, and abundances of microbial functional genes related to nitrogen cycling. The study found that DMPP, atrazine, and glyphosate could decrease soil gross nitrification and denitrification rates perhaps by inhibiting microbial functional gene abundances and that application of DMPP could effectively reduce $N_2O$ emissions in the sugarcane cropping soil (Zhang et al., 2018).

### Fallow management, controlled traffic and trash blanketing

Fallow management, including the use of a green manure crop, is identified as a management approach to reduce N fertiliser inputs for crop growth. It is also a critical factor for breaking the monoculture and has been identified as a critical management practice for fungal disease such as the fungal root pathogen (*Pachymetra chaunorhiza*) and the lesion nematode (*Pratylenchus* zeae). Pankhurst et al. (2003) evaluated different rotation breaks (sown pasture, alternate crops, bare fallow) for their impact on soil health. All breaks reduced populations of known detrimental soil biota and significantly increased the yield of the following sugarcane crop. A single legume-based break crop appeared to be sufficient to capture the majority of these benefits. Other possible management options included the use of organic amendments and minimum tillage techniques (Pankhurst et al., 2003). Modelled outcomes from a Bundaberg farm found that nitrogen was still available to the crop after planting and first ratoon after a soybean legume fallow (Park et al., 2010).

Links between organic matter status and soil biological health, particularly in the variability of farming systems, have proven difficult to quantify. This has been partly due to a lack of tools or criteria for monitoring relevant soil properties and the limited understanding of the interactions between soil health and other system components. However recent studies suggest that the amount and quality of organic matter returned as roots and residues, and the placement of that residue relative to areas of future crop root activity, may be significant factors for management practices in the future (Bell et al., 2007).

Soil Organic Carbon (SOC) is a component of soil health and has been found to vary in sugarcane in the Burnett Mary region based on physical and chemical benefits of practices such as residue retention, reduced tillage and controlled traffic, which improved SOC (Nachimuthu et al., 2016). SOC has generally been recognised as an important component of soil fertility, but more for the role it plays in physical soil structure and chemical fertility. In the Burnett catchment, Nachimuthu et al. (2016) assessed the interactions with SOC and the following water quality management practices:

- Full tillage after an intensive vegetable rotation with traditional residual herbicides (Conventional).
- Only the beds were tilled after the vegetable phase (zonally tilled with the interspace left undisturbed) and residual herbicide use was reduced (Improved practices).
- Minimum tillage system (one pass of a single tine ripper in the bed zone prior to the vegetable and sugarcane phases), where vegetative trash mulch was maintained during sugarcane planting, no residual herbicides were used, and a legume intercrop was established after sugarcane establishment (Aspirational).
- Minimum tillage system with grain legume rotation crops, retention of a surface trash mulch, and a combination of residual and knockdown herbicide (New farming system).

Soil management practices had a significant influence on dissolved organic carbon (DOC) and total organic carbon (TOC) losses. The Conventional practices resulted in the highest offsite runoff losses of TOC and DOC, followed by the New Farming System, while the lowest losses occurred from the Improved practices. Treatments that employed minimum tillage produced less offsite DOC losses than conventionally tilled systems. The lower carbon losses under minimum tillage are consistent with observations of greater microaggregate formation and subsequent carbon stabilisation inside microaggregates under minimum tillage practices. Critically, SOC sequestration can be impeded by losses through deep drainage, with the TOC losses in runoff in sugarcane systems ranging from 12 to 44 kg ha$^{-1}$ yr$^{-1}$ (Nachimuthu et al., 2016).

In a study by Blair et al. (1998) total carbon and labile carbon concentrations were lower in the surface layer (0–1 cm) of the cropped soil compared to a nearby uncropped reference soil. Burning resulted in a greater loss in total carbon and labile carbon at a depth of 0–1 cm than green cane trash management. At one of the sites, sugarcane cropping resulted in a decline in total carbon relative to the reference in the green trash management treatment but an increase in labile carbon (Blair et al., 1998). Bell et al. (2007) highlighted the need to improve understanding of the impact of the increasing stratification of organic matter, nutrients and microbial activity in the top 5–10 cm of the soil profile across sugarcane and grains to influence soil carbon concentrations.

Trash blanketing in sugarcane typically has some to no effect (e.g., 20% increase in soil carbon; Robertson & Thorburn, 2007) on total SOC concentrations and the effect is highly site specific (Thorburn et al., 2013). However, there are trends for the movement of carbon down the soil profile and an increase in the proportion of total profile carbon present as charcoal — presumably because of the historical burning of sugarcane residues (Skjemstad et al., 1999). Importantly, green cane trash blanketing had little effect on the mineralisation of nitrogen in the soil and did not compromise the availability of nitrogen for the crop in the short term (up to 6 years; Robertson & Thorburn, 2007), and nitrogen mineralisation increased with longer term green cane trash blanketing, improving availability of nitrogen for crop production (up to 24 years; Meier & Thorburn, 2016). In contrast, there is some evidence showing that land management changes can positively impact soil organic matter levels, including soil carbon (Robertson & Thorburn, 2007). For example, the subsoil application of compost may increase the supply of organic carbon and nitrogen for microbial communities which in turn could enhance nutrient cycling processes, improve soil environmental conditions and soil health for sugarcane growth, and thus increased sugarcane productivity (Liu et al., 2018). Soil pH was the main factor governing soil enzyme activities, with an overall decrease in all enzyme activities in response to liming. Overall, liming and trash blanket practices improved sugarcane soil fertility (Liu et al., 2018).

Braunack et al. (2006) assessed the impact of harvesting equipment on compaction and subsequent crop yield at sites in the Wet Tropics. At Tully, sugarcane varieties responded differently to the effect of harvesting traffic with the yield response; variety Q138 had significantly greater yield than Q117. A similar result was observed at Ingham, where Q124 tended to yield higher than Q115. Yields were greater at the Tully site overall compared to the Ingham site, reflecting the differences in harvesting equipment used as well as soil type and climatic conditions. Low ground pressure machinery was also used at Tully compared to high ground pressure machinery at Ingham, imparting different stresses through the soil profile. The effect of traffic appeared to be cumulative, as the degree of soil compactness and bulk density increased, with treatment differences becoming significant with each additional year of traffic. Traffic over the row resulted in a yield loss compared to traffic near-the-row and down the inter-row, highlighting the co-benefits of implementing controlled traffic systems on GPS.

##### *Biodiversity co-benefits*

There were limited studies regarding on-farm biodiversity benefits in sugarcane systems. Of greatest significance is the finding that there is some evidence of downstream benefits to biodiversity from maintaining streambank vegetation in sugarcane areas (Arthington et al., 2015). Manwaring et al. (2018) also found that trash blanketing, i.e., leaving trash on the soil surface, can increase the biodiversity of micro-arthropods, specifically predatory mites (*Mesostigmata*) in sugarcane areas.

#### 4.1.1.3 Horticulture and bananas

##### *Environmental co-benefits*

There were limited studies in horticulture and bananas that directly linked fertilisation rates with $N_2O$ emissions in the GBR catchments. However, one study in Nambour was identified that analysed annual emissions for mango, pineapple and custard apples over a 12-month period. The results highlighted the highly variable nature of $N_2O$ emissions over time and in different crops within the same landscape, with the change in soil water content the key variable for describing $N_2O$ emissions at the weekly scale and soil temperature at the monthly scale (Huang et al., 2012). Given the close proximity of the horticultural regions of the Burnett Mary region, these results could also be reflected in Bundaberg horticultural crops with similar climate conditions.

##### *Biodiversity co-benefits*

There were only two studies identified on biodiversity impacts from horticulture with each of these in different regions and with a different focus. Both studies were not considered, as one was at a landscape level which was deemed out of scope and the other described how a benchmark could be created to assess impacts of agriculture on waterways.

#### 4.1.1.4 Grains

##### *Environmental co-benefits*

###### Nutrient management

There are few specific examples of the environmental co-benefits of water quality management practices in grains, with the focus largely on reducing fertiliser inputs.

The cropping sector in Australia contributes 2.5% of national greenhouse gas emissions, not accounting for the historical loss of soil carbon (Rochecouste et al., 2015). Greenhouse gas abatement in the agricultural cropping industry can be achieved by employing management practices that sequester soil carbon or minimise $N_2O$ emissions from soils. However, carbon sequestration stimulates $N_2O$ emissions, making the net greenhouse gas abatement potential of management practices difficult to predict (Palmer et al., 2017). Cereal (e.g., wheat, rye, oats, barley, millet, and maize) production in Australia dominates ammonia ($NH_3$) which is the primary source of gaseous nitrogen emissions, which is a greenhouse gas, from land fertilisation (62%). Urea is the most widely used N fertiliser in Australia, accounting for 78% of the $NH_3$ emission from N fertilisation (Zhang et al., 2022). Roberston et al. (1993) highlighted that the variance of soil types with nitrogen in the clay soils of the Brigalow region of Queensland (Fitzroy and Burnett Mary) declined rapidly under sown pasture, but under continuous cultivation and cropping, it remained high enough to supply the needs of cereal crops for at least 20 years. Other than reduced fertiliser rate it is difficult to identify farm management practices that consistently provide greenhouse gas abatement at different locations because the effectiveness of practices is greatly influenced by climate and soils (Meier et al., 2023).

Reduced emissions from SOC sequestration can offset increased $N_2O$ emissions over time, highlighting the opportunity for water quality management practices associated with pulse crops in crop rotation and nutrient management. Fine root (<2 mm diameter) turnover (production and mortality) drives soil processes such as nutrient fluxes, carbon cycling and sequestration, activity of soil biota and structural stabilisation. Research on fine root dynamics has been focused primarily on rain-fed perennial and annual ecosystems in coarse and medium-textured soils (Hulugalle et al., 2020). Using a modelling approach Meier et al. (2023) increased cropping intensity, achieved by including cover crops, additional grains crops, or crops with larger biomass in the rotation. This factor, cropping intensity, was the leading predictor of the change in greenhouse gas emissions balance across the scenarios and sites. Abatement from increased cropping intensity averaged 774 $CO_2$-e $ha^{-1}$ $yr^{-1}$ (25 years) and 444 kg $CO_2$-e $ha^{-1}$ $yr^{-1}$ (100 years) compared to the baseline.

### Crop selection and fallow management

The P2R Water Quality Risk Framework identifies that maintaining 30% or more stubble cover is a high priority when choosing crops for minimising soil erosion, with avoiding successive low-stubble crops and no occurrence of back-to-back pulses (lentil, faba bean, field pea, chickpea and lupin) crops.

Management practices involving legume leys, grain legumes, no-tillage and stubble retention, along with N fertiliser application for wheat cropping, were examined for their effectiveness in increasing soil organic matter (0–10 cm depth) from 1986 to 1993 in a field experiment on a Vertisol soil at Warra on the Darling Downs in Queensland (Dalal et al., 1995). The treatments were:

- Grass + legume leys (purple pigeon grass, *Setaria incrassata*; Rhodes grass, *Chloris gayana*; lucerne, *Medicago sativa*; annual medics, *M. scutellata and M. truncatula*) of four years duration followed by continuous wheat.
- 2-year rotation of annual medics and wheat (*Triticum aestivum* cv. *Hartog*).
- 2-year rotation of lucerne and wheat.
- 2-year rotation of chickpea (*Cicer arietinum* cv. *Barwon*) and wheat.
- No-tillage (NT) wheat.
- Conventional tillage (CT) wheat. Fertiliser N as urea was applied to both NT wheat and CT wheat at 0, 25, and 75 kg N $ha^{-1}$ $yr^{-1}$.

The CT wheat also received nitrogen at 12.5 and 25 kg N $ha^{-1}$ $yr^{-1}$. After 4 years, soil organic carbon (C) concentration under grass + legume leys increased by 20% (650 kg C $ha^{-1}$ $yr^{-1}$) relative to that under continuous CT wheat. Soil total nitrogen increased by 11%, 18%, and 22% after 2, 3, and 4 years, respectively, under grass + legume leys relative to continuous CT wheat. These increases in soil organic matter were mostly confined to the 0–2.5 cm layer. These data show that restoration of soil organic matter in Vertisol requires both grass and legume leys, primarily due to increased root biomass, although soil total nitrogen can be enhanced by including only legume leys for longer duration in cropping systems in semi-arid and subtropical environments (Dalal et al., 1995).

Crop selection and rotation, and fallow management are important for managing productivity, soil health and potential erosion over time. For example, three cropping systems using five crop species were compared over a 10-year period on a cracking clay soil (Vertisol) in Mundubbera (Russell & Jones, 1996). The three cropping systems were continuous (the same crop every year), alternate (the same crop every second year) and double (a winter and summer crop in the one year). There were two cereal crops (sorghum and wheat) and three grain legumes (chickpea, green gram and black gram). The effect of cropping system was measured in terms of grain and protein yields and changes in SOC (surface 0–10 cm) and nitrogen concentrations. Summer and winter rainfall was below average in 8 and 5 years out of 10, respectively. Grain yield of cereal monocultures was about twice that of legume monocultures. The potential for double cropping, despite the generally below-average rainfall, was clearly shown with the highest grain and protein yields coming from the combination of green gram (summer) and wheat (winter). Soil nitrogen and carbon levels, with initial values of 0.22 and 2.96%, were reduced at the end of 10 years by 16 and 27% respectively. Their rate of decline did not differ between cropping systems (Russell & Jones, 1996). This study highlights the complexity and importance of crop selection in conjunction with monitoring soil health over time with fallow periods and rainfall potentially important.

The co-benefits of crop selection and fallow periods to soil health over time was assessed by Bell et al., (1995). The productivity of Ferrosols used for rainfed agricultural production in the south and central Burnett regions of southeast Queensland were examined in relation to the duration under continuous cultivation. A range of crops grown in on-farm situations during 1986–1990 were examined using paired sites to assess the extent of yield decline over time under cropping. The changes in soil chemical characteristics that occurred during the cropping period were also assessed. All locations showed evidence of a significant reduction in crop growth (50–100%) where continuously cropped sites were compared to sites which had either never been cropped or which had been under grazed grass pasture for 20 years or more. In the absence of severe late season water deficits, this reduced growth rate was always reflected in lower (21–72%) crop yields at maturity. However, crop dry matter could interact with crop water use under conditions of late-season water deficit to negate, or even reverse, early growth advantages on previously untilled soil. The decline in soil nitrogen status occurred despite a high frequency (>50%) of grain legumes in the crop rotations practised on all farms monitored and illustrates the small nitrogen return from these crops under rainfed conditions. The reduction in SOC due to cropping assessed with continuously cropped areas having organic carbon levels of only 0.9 to 1.5% in the 0–10 cm layer-values which were 25–40% of levels in untilled soil. Grazed grass leys were only partly successful in the restoration of SOC status.

In addition to fallow and crop selection, the co-benefits of soil health were explored by Robertson et al. (1993) in the Brigalow bioregion in southeast Queensland. The dynamics of carbon and nitrogen were compared under in these soils under permanent green panic (*Panicum maximum* var. *trichoglume* cv. Petrie) pasture and continuous cropping with grain sorghum (*Sorghum bicolor*). Although the sorghum system was more productive, it contained 18% less nitrogen and 29% less carbon. Annual flows of carbon and nitrogen through the soil microbial biomass were, respectively, 4,500 and 240 kg ha$^{-1}$ under sorghum, and 4,050 and 60 kg ha$^{-1}$ under pasture. Over 80% of carbon and nitrogen inputs to the sorghum system occurred after harvest. Under pasture, the continuous supply of residues of high C/N ratio (50–75) enabled the development of a large and active microbial biomass, which competed with the pasture plant for nitrogen, resulting in slow net mineralisation of nitrogen and low levels of inorganic soil nitrogen. The productivity of these soils under the two management systems was controlled by the amount, quality and timing of organic matter inputs. These in turn controlled the size of the soil microbial biomass and its carbon and nitrogen supply, and hence the balance between immobilisation and mineralisation of nitrogen.

### Tillage

The P2R Water Quality Risk Framework specifies that for the lowest water quality risk (soil management) tillage is only used when required to deal with severe compaction, nutrient stratification, or as part of a strategy to manage certain difficult weeds, and that fertiliser is applied using zero-till machinery.

All cultivated soils are prone to rapid reconsolidation when wet, particularly structurally unstable soils. This predisposes them to waterlogging, slow and limited infiltration, rapid drying, and poor establishment, growth, and production of crops. Minimum tillage and controlled traffic systems also contribute to co-benefits in soil structure and health. Field-scale research was undertaken to develop soil management and/or engineering practices that will maintain a stable, loose tilth with aeration, drainage and infiltration properties that prevent waterlogging, enhance infiltration, and increase crop production (Hamilton et al., 2019). The effects of deep ripping plus gypsum, permanent raised beds (PRB), deep blade loosening at 250 mm depth (DBL) and no-tillage crop establishment (NT) were studied in controlled traffic regimes on rainfed and irrigated crops with a self-mulching crop in Queensland self-mulching clays. Hamilton et al. (2019) found that deep blade loosening increased root growth, organic carbon and lateral infiltration along with productivity.

No-till (NT) systems for grain cropping are increasingly being practiced. A trial site in Goondiwindi (Thomas et al., 2007) assessed the effects on soil organic matter of tillage, stubble and fertiliser management on the distribution of organic matter and nutrients in the topsoil (0–30 cm) of a Luvisol soil. Measurements were made at the end of nine years of NT, reduced till (RT) and conventional till (CT) practices, in combination with stubble retention and fertiliser N (as urea) application strategies for wheat (*Triticum aestivum* L.) cropping. Under NT, there was a concentration gradient in organic carbon, total nitrogen, and microbial biomass nitrogen, with concentrations decreasing from 0–2.5 to 5–10 cm depths. Therefore, NT and RT practices resulted in significant changes in soil organic carbon and nitrogen and exchangeable cations in the topsoil of a Luvisol, when compared with CT. NT is beneficial long term for soil chemistry and physical status along with production due to the increased organic matter accumulation close the soil surface (Thomas et al., 2007). This study highlights the co-benefits for soil health of the no-tillage system in cropping over time.

The effects of fallow surface management treatments on subsequent growth and yield of grain sorghum were studied during seven cropping periods on a grey Vertisol near Biloela in central Queensland, Australia (Thomas et al., 1990). Treatments were disc (D), blade (B) and zero (Z) tillage, each with stubble or residue from previous crops either retained (+) or removed (-) at the start of the fallow period. Yields from Z+ were significantly higher in three crops than those from D+ and B+ and lower in three other crops. Stubble retention consistently resulted in significantly higher yields than stubble removal in the Z treatment. Crop water use was consistently lower in Z- than in all other treatments. Over seven years, SOC at 0–0.1 m with stubble retained was higher than with stubble removed although both were still decreasing (Thomas et al., 1990).

In the same field experiment in Biloela, six treatments using disc (D), blade (B) or zero (Z) tillage, each with stubble (crop residue) retained (+) or removed (-), were imposed during fallow periods between annual grain sorghum crop. Standley et al. (1990) created plots that were neither irrigated nor fertilised. Soil profiles for chemical analysis were sampled post-harvest and pre-plant after fallow. For surface soil (0–0.1 m and sometimes also 0.1–0.2 m) during the seven years, net decreases were measured for organic and total C. General means at 0–0.1 m decreased annually from June 1978 by 3.9% for organic carbon. Decreases in organic carbon and total nitrogen had similar trends for each tillage treatment, being greater with stubble removed than with stubble retained (Standley et al., 1990).

Radford and Thornton (2011) carried out a long-term study over 20 years with four tillage treatments: traditional tillage (TT), stubble mulch tillage (SM), reduced tillage (RT) and no till (NT), each with and without applied fertiliser (N+Zn). After 20 years of treatment application, all treatments were managed using no till and appropriate fertiliser (N+Zn) application for a further 7 years. During the 20 years when tillage treatments were being applied, the reduced tillage treatments (NT, RT and SM) outyielded TT in 10 of 22 crops grown. Mean yields without fertiliser were 2.0 t $ha^{-1}$ (TT) and 2.6 t $ha^{-1}$ (NT) while mean yields with fertiliser were 1.9 t $ha^{-1}$ (TT) and 2.9 t $ha^{-1}$ (NT). During the next five years of across-the-site no till with fertiliser, the former reduced tillage treatments outyielded the former TT in each of the five crops grown. For example, the long-term NT gave an average yield of 3.3 t $ha^{-1}$ while the short-term NT, formerly TT for 20 years, produced only 2.1 t $ha^{-1}$ - a 57% yield increase for the long-term no-till. This increase was due to both increased soil water storage and higher water use efficiency. Both were attributed to the development of improved soil structure, higher population densities of soil macrofauna and slightly higher SOC content. High water use efficiency in no till was also attributed to a beneficial effect resulting from slow early growth under no till. Results indicate it takes at least 20 years to attain the full soil benefits (physical, chemical, and biological) of a no till system. The large yield responses from the three reduced tillage treatments, during and after treatment application, were realised in part because cropping frequency exceeded the appropriate level for traditional tillage (Radford & Thornton, 2011).

The soil co-benefits of minimum tillage and crop selection in Emerald were highlighted in a study by Hulugalle et al. (2002), which compared 1 m and 2 m beds on cotton and wheat rotations. The study found that the 2 m beds with minimum tillage resulted in lower runoff and soil erosion, lower exchangeable sodium, exchangeable sodium percentage and higher EC1:5/exchangeable sodium, a higher rate of decrease in soil organic matter and better soil structure in the surface soils (0-–0.15 m depth) than the 1 m beds. Soil physical and chemical properties were best, and runoff and erosion lowest, with 2 m beds and cropping systems producing a high level of ground cover (Hulugalle et al., 2002).

Studies of soil carbon sequestration and $N_2O$ emissions under the different cropping systems were reviewed on the Darling Downs based on a crop rotation that includes barley, chickpea, wheat, and durum wheat (hereafter durum). The value chain analysis revealed that the net effect on greenhouse gas emissions by switching to zero tillage is positive but relatively small. In addition, the review of the sequestration studies suggests that there might be soil-based emissions that result from zero tillage that are being underestimated. Therefore, zero tillage may not necessarily reduce overall greenhouse gas emissions. This could have major implications on current carbon credits offered from volunteer carbon markets for converting conventional tillage to a reduced tillage system (Maraseni & Cockfield, 2011).

### *Biodiversity co-benefits*

#### Crop selection

Carr-Cornish and Hall (2016) assessed cropping and biodiversity outcomes in Australia’s high rainfall zone which includes the Fitzroy and the Burnett Mary regions. The high rainfall zone has 46% coverage of native vegetation, hosts 11 out of 15 of Australia’s most species-rich regions, and contains aquatic and wetland environments of national importance. The loss of biodiversity resources in the high rainfall zone was greater than the rest of the continent with the changes observed between 1992 and 2005, including decreases in grazed native grassland and increases in both cropping and developed pastures. These changes suggest the emergence of biodiversity-threatening processes and impacts of crop selection (i.e., grassed fallows) such as the loss of connectivity due to fragmented landscapes that impact native species and can harbour invasive predators (Graham et al., 2012), and the degradation of understorey and grassland vegetation (Lebbink et al., 2022).

Land clearing for cropping, particularly in Central Queensland, has led to the remaining fragments of remnant vegetation and the native ecosystem being impacted by two invasive perennial grass species, namely Indian couch (*Bothriochloa pertusa*) and buffel grass (*Cenchrus ciliaris*). These invasive species increased significantly during 1997–2018 as the area underwent development for cropping, while native pasture species declined. There was also a moderate increase in the cover and presence of the annual herb Parthenium weed (*Parthenium hysterophorus*) (Lebbink et al., 2022).

Cropping and the removal of rocks for soil amelioration has been identified as impacting habitat for rock and burrow-dwelling reptile species. Using the *Environmental Protection and Biodiversity Conservation Act 1999*, Michael et al. (2021) found overlap between endangered species and the Brigalow Bioregion in Queensland, with the Brigalow Belt being a bioregion with over 60 species within the impact zone.

The Australian sarus crane (*Antigone antigone gillae*) breeds primarily on remote pastoral areas in north Queensland and along with the brolga, migrates 500 km to spend the dry, non-breeding season on the Atherton Tablelands. Nevard et al. (2019) found that crop selection in arable cereal crops (especially maize) and peanuts are important to dry-season crane flocks on the Atherton Tablelands. Abundances of the bird species are positively correlated with each other over both time and space. Sarus cranes were nevertheless markedly more abundant on the fertile volcanic soils of the central Tablelands, whilst brolgas were more abundant on a variety of soils in outlying cropping areas close to roost sites, especially in the southwest of the region. Both species used a wide variety of crops and pastures but occurred at highest densities on ploughed land and areas from which crops (especially maize) had been harvested. In addition, brolgas were also strongly associated with early-stage winter cereals with volunteer peanuts from the previous crop (Nevard et al., 2019).

Wolf spiders are a species that has benefited from reduced tillage and rotations in cropping areas. The species burrows in the ground and they increased both in diversity of species type and in the number of spiders in areas which had implemented reduced tillage and rotations between crop types. The spider also consumes pest *Helicoverpa* spp. so could be considered as a conservation and biological control element when implementing agronomic and pest management strategies (Rendon et al., 2015).

#### 4.1.1.5 Trends, patterns and inconsistencies in study findings

Across all the land uses there is considerable spatial variability in ecosystem, soil, and climate effects. This highlights the biophysical heterogeneity across the catchments and landscapes. There are also some key consistencies and trends across these studies.

##### *Grazing*

As a consequence of the limited literature to cover a broad area of subject matter for this question more generally, there is little evidence available to determine the spatial and temporal hereogeneity of co-benefit outcomes from water quality management in rangelands. The Wambiana trial, referred to above (O'Reagain et al., 2011), is an exception. This study applies a long-term set of grazing management treatments (stocking rates, fixed versus variable rates), allowing the assessment of temporal effects, as driven by seasonal/yearly rainfall, for example. This in turn demonstrates that, in contrast to common practice, heavy stocking rates are likely to be uneconomic in the medium to long term, with profitability eroded by high costs and reduced price of animals in most years. Moderate stocking at long-term carrying capacity is likely to be more profitable because of lower costs, increased product value and, probably, improved management flexibility. More such trials are required across all agricultural sectors in order to be able to assess the long-term economic/social outcomes of different land management practices, particularly in the face of climate change.

The results are often ambiguous when considering variation in space, for example. Whilst removal of agricultural activity generally improves soil condition, the impacts on invertebrates are much more varied (Parkhurst et al., 2022).

##### *Sugarcane*

There is a small sample of studies (6) that assess the co-benefits of implementing the P2R Water Quality Risk Framework practices in sugarcane with the co-benefit of $N_2O$ emissions. However, those that do all find that there is high variability based on the soil type and location. There are also a few papers (3) that have explored interactions between multiple management practices and co-benefits. For example (Zhang et al., 2018) explored the relationships between N, herbicide impacts and nitrous oxides, higlighting the complexity of biophysical interactions. It was consistently found that there were losses of nitrogen application through nitrous oxide, runoff and deep water drainage, however the rates varied. Relative to the cropping industry, field trials in sugarcane are short, limiting the abiility to assess long-term impacts and provide more reliable insights.

##### *Horticulture and bananas*

Only one study on these topics was directly linked to the P2R Water Quality Risk Framework. The variation in $N_2O$ emssions between two different perennial crops in the same site highlighted the complexity of $N_2O$ emissions and the overall measurement techniques and understanding (Huang et al., 2012).

##### *Grains*

There are extensive long-term trials from research stations in the Brigalow Bioregion of Queensland and northern New South Wales, which provide critical insights into the importance of ongoing research and monitoring of biodiversity and soil health co-benefits. A key aspect to note was that the majority of significant differences were noted in the top 0–2.5 cm (Dalal et al., 1995) and 0–10 cm of the soil profile for increased SOC (Standley et al., 1990; Thomas et al., 1990; 2007), whereas the current Carbon Credits Methodology Determination[14] requires changes to be assessed at 30 cm deep, where less variation was found. Key differences were found, however, in yields over the long-term highlighting the private benefits of implementing no-till systems and crop rotation (primarily grains).

### 4.1.2 Recent findings 2016–2022 (since the 2017 SCS)

While there are few studies that directly measure the co-benefits of land management practices to improve water quality, there is increasing determination by policymakers, government and landholders to recognise, and to deliver additional benefits. These benefits are increasingly being recognised in Australian environmental markets. For example, green markets are a relatively new mechanism in Australia with Australian Carbon Credit Units designed for the *Carbon Credits (Carbon Farming Initiative) Act 2011* established in the Emissions Reduction Fund in 2015.

Currently, only the Land Restoration Fund in Queensland permits the 'stacking' of benefits (e.g., carbon and biodiversity). As a consequence, the monitoring and the science behind co-benefits is relatively new and continues to be explored. Careful program design, including consideration of additionality and timescales to achieve different co-benefits, is required to ensure that different co-benefits can and do occur. This was underscored in a review of the management practices for carbon outcomes and the opportunities for biodiversity benefits (Bradshaw et al., 2013). Identification of the specific co-benefits being sought, along with the monitoring of such co-benefits, is also critical (Cattarino et al., 2014; Parsons et al., 2017). It should also be noted that the time to achieve different co-benefits will vary, as highlighted by the long-term cropping studies (Dalal et al., 1995; Standley et al., 1990; Thomas et al., 2007). Further to this, specified guidelines for measurement of changes will be critical with large differences found in soil carbon changes up to the first 10 cm compared to samples from 30 cm; however the current measurement guideline for ACCU is at 30 cm. Again, careful program design is required to ensure that different co-benefits can occur. Although several studies have been completed exploring one co-benefit, there is less research on the interactions between them, and the trial design which current programs require is variable, thus affecting their comparability. The practices in the P2R Water Quality Risk Framework are designed to focus on water quality outcomes, and the realised co-benefits from these practices vary across the landscape. Some co-benefits may be mutually exclusive; therefore, monitoring is essential to understand these relationships.

### 4.1.3 Key conclusions

- While limited, the available literature clearly indicates there may be significant environmental and social co-benefits from land management practices designed to improve water quality in the GBR.
- Co-benefits occur where a specific land management practice implemented to improve water quality for the GBR has additional positive secondary impacts, such as improving economic and production outcomes, reducing carbon emissions, increasing biodiversity or improving soil health.
- There is growing interest by policymakers, government and landholders in recognising and delivering additional benefits.
- There are existing policy mechanisms such as the Land Restoration Fund and Australian Carbon Credit Unit scheme that are relevant to supporting co-benefits (environmental, socio-economic and First Nations) flowing from GBR water quality management practices. While these existing mechanisms could offer opportunities for water quality benefits to be stacked with other co-benefits over the same area, differences in the guidelines, timelines, measurement and specific practices of the programs currently impede this.

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[14] Supplement to the Carbon Credits (Carbon Farming Initiative- Estimation of Soil Organic Carbon Sequestration using Measurement and Model) Methodology Determination 2021. https://www.cleanenergyregulator.gov.au/DocumentAssets/Documents/Supplement%20to%20the%202021%20Soil%20Carbon%20Method.pdf

- The Paddock to Reef Water Quality Risk Framework defines management practices within four categories related to the risk posed to water quality, ranging from low- to high-risk practices. The land uses in the framework include grazing, sugarcane, bananas, horticulture and grains. While many of these practices have the potential to generate co-benefits, further work is required to align these practices with related policies and programs.
- Co-benefits associated with management practices to improve water quality can be complex, and therefore are not guaranteed, and they require careful planning and design. Contextual and site factors, the specific design and implementation of the management action, and program design, can all influence the extent, magnitude and duration of any co-benefit.
- Key considerations for successful policy and program design for encouragement and greater adoption of practices yielding co-benefits include the specific co-benefit being sought, the capacity to stack multiple benefits, the framework that is applied to measure it and to achieve additional co-benefits, the time expected to achieve co-benefits and the monitoring and maintenance required to demonstrate their achievement.
- The ways in which land management practices and climate warming interact will affect co-benefits. As an example, grazing practices that increase tree cover, ground vegetation cover and soil carbon are likely to trap more water on the property and thus improve vegetation productivity, reducing the impacts of droughts.
- Further work is needed to understand the potential co-benefits associated with water quality improvement actions in the GBR catchment area, and to devise appropriate mechanisms to encourage adoption of practices with multiple benefits.
- Economic and production co-benefits and the ‘downstream’ effects of these co-benefits on GBR ecosystems, as well as non-agricultural land uses (such as urban), conservation areas and wetlands were outside of the scope of this review, with economic and production co-benefits being addressed elsewhere in the SCS.

### Grazing

- There are opportunities for achieving carbon and biodiversity outcomes in grazing, but not all of these align. For example, woody weeds are associated with poor land condition in some circumstances but are regarded as important for some forms of biodiversity in others.
- The relationship between grazing management strategies and soil organic carbon over the short and long term is complex. Stored soil organic carbon (to a depth of 30 cm) appears to be influenced by various combinations of grazing intensity, land condition, rainfall and land/soil type, and it is difficult to establish evidence for a strong link between livestock management and soil organic carbon content. Studies to date indicate that the benefits of maintaining ground cover and/or reducing stocking rates for soil health can take many years.
- Improved riparian and vegetation management in grazing (and cropping) lands has been shown to result in positive changes for a range of bird, insect and other invertebrate species, with evidence of increases in species richness, relative abundance and change in composition.

### Sugarcane

- In sugarcane, a critical Paddock to Reef Water Quality Risk Framework management practice to reduce the risk of nutrient runoff is to reduce the amount of fertiliser applied to match industry recommended rates. Reducing the amount of fertiliser applied can also reduce emissions of the greenhouse gas nitrous oxide; however there are still losses through other pathways including deep drainage and runoff. Nitrous oxide losses vary with soil type, temperature, and soil water which also vary across sugarcane growing regions.
- Maintaining sugarcane trash on paddocks after harvesting, or green cane trash blanketing can both minimise soil erosion and runoff, and improve soil health. The use of soybean break-crops to inhibit monoculture fungus and pests has also shown benefits for soil health. There is limited evidence that trash blanketing is beneficial for soil carbon.

- The methods for measuring outcomes of co-benefits in sugarcane vary between studies, with additional variability in temporal and spatial characteristics, making it difficult to compare benefits between studies.

#### Horticulture and bananas

- There was only one study specific to horticulture, but many of the principles, practices and outcomes are similar to those of other cropping systems. As with sugarcane, reducing the amount of fertiliser applied in horticulture and bananas reduces the risk of nutrient runoff and potentially, nitrous oxide emissions. Nitrous oxide emissions linked to the amount of fertiliser applied have been compared among horticulture crops, with emissions varying across the plots. Increased monitoring will help to understand these potential co-benefits.

#### Grains

- There are potential improvements to soil health from crop rotation and fallow management, which reduce sediment erosion, break monoculture and reduce disease pressure.
- Grain cropping systems have the most long-term comprehensive datasets to assess the various co-benefits flowing from water quality improvement practices, and to understand the impacts of different climate cycles and climate change. These data however do not necessarily align across different environmental benefits. For example, a number of soil carbon recordings are made at different depths from those required for credit by the Australian Carbon Credits Unit.

### 4.1.4 Significance of findings for policy, management and practice

Co-benefits are complex in nature and in some instances are mutually exclusive, making it difficult for policy and program design. For example, land condition is used for assessing grazing productivity, but the assessment framework does not clearly define biodiversity or habitat (Parsons et al., 2017). Furthermore, there are no approved methods for measuring all identified co-benefits (socio-economic, specific biodiversity outcomes and greenhouse gas emissions) and, therefore participation in some programs and enviromental markets is limited. The review found that there is limited and varied measured data for the co-benefits of the practices in the P2R Water Quality Risk Framework for grazing, sugarcane, horticulture, or grains. There are also large variations in findings suggesting that the establishment of projects to generate multiple benefits would require specific planning and monitoring to assess their achievement. An example of this is the different time periods for carbon ACCU contracts and the measurements required (30 cm depth) for soil carbon, as opposed to 10 cm which has been used in a large number of trials.

In sugarcane the spatial variability of outcomes generally represents the differences between soil types and measurement approaches. Integration of co-benefits into policy or programs would require establishing a baseline before inception with ongoing monitoring to follow. This can be costly and may not achieve the expected outcomes.

The misalignment of existing market timeframes and methods adds complexity to participation for landholders and the recent increases in commodity prices are reflected in land values which may be significantly higher then the value of stacked co-benefit markets.

Long-term field trials in cropping provided key findings and considerations regarding tillage and soil health in below and above average rainfall conditions. This range of studies allows more robust consideration of different management practices and the likelihood of achieving specifc co-benefits.

There is limited direct evidence on the question of specific land management practices for water quality improvement to support co-benefits in the GBR catchment area. The studies investigating the potential co-benefits of land management in grazing, horticulture, sugarcane and grains rarely mentioned water quality improvement. The broader literature does, however, point to the fact that there are certain land management practices that can lead to other potential benefits from water quality improvement actions. There can be synergistic benefits that have a flow-on effect from the initial co-benefit, however these were deemed out of scope and highlight the need for clear policy regarding the co-benefits being sought.

An integrated synthesis of this evidence in addition to economic and production co-benefits of practices through biophysical improvements is also recommended. An example of this integrated knowledge would be that grazing land management improves vegetation cover, particularly in the dry season (e.g., moderate stocking, wet season spelling), which can increase vegetation productivity, soil carbon and biodiversity, with potential knock-on effects for economic returns/resilience. Specifically, carbon farming opportunities could lead to a significant improvement in the environmental impact of the grazing industry and address several other Government priorities including GBR water quality, drought preparedness, sustainable landscapes, carbon storage and leasehold land condition. In addition, practices that reduce the rate of fertiliser application in sugarcane (and other crops including horticulture) such as managing quantity and strategic timing to meet the plants' needs, can improve soil health and carbon content of the soil. This could potentially reduce fertiliser costs and improve economic returns/resilience if a coherent carbon trading scheme is put in place.

Climate warming and its effects on the spatial and temporal patterns of rainfall (including flooding and multi-year droughts), and periods of excessive temperatures will impact on the productivity of agricultural systems in the GBR catchment area. This will be especially felt in the broad-scale rangeland-based grazing systems as water input into sugarcane, and horticultural systems will alleviate some of these stressors. The ways in which climate warming and land management interact will affect co-benefits. For example, grazing practices that increase tree cover, ground vegetation cover and soil carbon are likely to trap more water on the property and thus improve vegetation productivity, reducing the impacts of droughts (Fensham & Guymer, 2009; Gordon, 2007; O'Reagain et al., 2011). Landholders will have to build their capacity, and that of the land they are responsible for, to adapt to climate warming and the resilience of the system (Cobon et al., 2009).

The policy and program design is critical to achieving measured co-benefits. Key considerations for policy include the specific co-benefit being sought and the capacity to stack multiple benefits, the framework that is applied to measure and achieve additional co-benefits, the time expected to achieve co-benefits and the monitoring and maintenance required to demonstrate their achievement. Further work is required to understand how to increase the adoption of appropriate practices and enhance delivery of co-benefits in each of the main agricultural land uses, and /or increase the potential extent, magnitude and duration of all or some of the co-benefits.

### 4.1.5 Uncertainties and/or limitations of the evidence

- The review has identified specific co-benefits of the management practices in the P2R Water Quality Risk Frameworks for the dominant land uses in the GBR catchment area, but there are few studies that quantitatively assess the co-benefits of these management practices. In addition, the available studies were typically relatively short-term.
- Much of the data used in this review were from experimental studies, but these were often context specific which makes extrapolation difficult.
- The initial review included GBR, national and international literature, but the search terms and exclusions for the second search were confned to Australia, providing a focused output directly relevant to the GBR catchment area.
- The focus on the management practices in the P2R Water Quality Risk Frameworks might have excluded studies where the land management practice was conducted for primary reasons other than to improve water quality, but may have had associated benefits of relevance.
- Managing invasive species in conjunction with achieving co-benefits has not been explored, which represents a limitation of the review. Invasive species have the capacity to diminish public and private benefits further and a landscape level strategic outlook is required. For example, although Indian couch provides ground cover, it provides very little other benefits to biodiversity or private benefits.
- Biodiversity in a large pool of species and in specific groups such as mammals or reptiles was not specifically searched for, potentially limiting the findings.

## 4.2 Contextual variables influencing outcomes

Several examples of the contextual variables that have the potential to influence the outcomes of Question 8.1 are presented in Table 16. These have been collated from the authors review of the selected studies.

*Table 16. Summary of the contextual variables for Question 8.1.*

| Contextual variables | Influence on question outcome or relationships |
|---|---|
| Tropical systems | The temperatures and increase rainfall of tropical sugarcane systems increased the variance in nitrous oxide that was released from soils. The variability between sites and over time was highlighted in sugarcane and horticulture (Friedl et al., 2023; Huang et al., 2012; Park et al., 2010; Thorburn et al., 2010; Wang et al., 2016; Zhang et al., 2018). |
| Brigalow Bioregion | The Brigalow Bioregion has high biodiversity and rich soils and has been developed for cropping in Queensland since the 1980s. These landscapes are relatively young and have not been exposed to long term cropping and agriculture which was in part why the trials were so long and monitored closely. Conversely, being cleared is also why the species monitored are vulnerable to fragmentation (Graham et al., 2012; Lebbink et al., 2022). Other studies in newly developed areas or locations with less diversity may not have the same outcomes. |
| Improved ground cover | Ground cover reduces the energy of overland water flow which increases the infiltration of water and nutrients into the soil and reduces sediment loss. This has flow on effects for ground cover itself, increasing vegetation/crop productivity and through that secondary animal production, drought, and economic and social resilience. Biodiversity also benefits from the increased vegetation cover, structure and composition through habitat effects (Agouridis et al., 2005; Parkhurst et al., 2022; van Oudenhoven et al., 2015). |
| Improved soil health | The definition of improved soil health for different elements and micro/macro-organisms impacted the variability of results along with the methods used to assess these changes. |

## 4.3 Evidence appraisal

The appraisal was completed for both the initial search and the revised search to obtain the overall scores, but the evidence was independently assessed by two separate authors. A summary table (Table 17) is below followed by discussion of each of the land uses.

### Relevance

#### Grazing

The relevance of the overall body of evidence was High, with High ratings for the relevance of the study approach and spatial relevance, and a Moderate rating for temporal generalisability. This is because, with a few notable exceptions (e.g., O'Reagain et al., 2011), the research tends to be of a short timeframe (one season to two years). While it is early days for the field of research on the co-benefits of agricultural land management for water quality improvement, it is evident that co-benefits can be achieved with some agricultural management practices e.g., fertiliser application (Thorburn et al., 2011) and grazing management (O'Reagain et al., 2011).

#### Sugarcane

Relevance of the study approach to the question was based on the applicability of the evidence to the sugarcane industry in the GBR catchments in terms of number of field sites and the spatial extent. For example, Wang et al. (2016) explored seven treatments in Ingham and therefore the study was given a High relevance rating (3). The studies that were scored 2 were typically studies that used field results from one region and then applied a paddock scale model (such as APSIM) to another region (e.g., Park et al., 2010; Thorburn et al., 2010). Finally, papers that were spatially generalised such as "Queensland Sugar Industry" or did not specify the region, scored 1. These were typically review papers (e.g., Dalal et al., 2003; Takeda et al., 2021). The overall relevance score was Moderate at 2.3.

The spatial relevance was scored based on the location of the field sites with 1 being a review of the sugarcane industry and little specificity to actual sites in the GBR (e.g., Hurst et al., 2004), 2 being only one site in the GBR where there were a number of trial plots completed (e.g., Blair et al., 1998; Nachimuthu et al., 2016; Warner et al., 2019) and 3 being more than one site where replications within those sites was completed (e.g., Braunack et al., 2006). The spatial relevance score was Moderate at 2.1.

The temporal aspect considered the length of time assessed in the field trial with a full cane plant cycle or multiple year study scoring a 3 (e.g., Bell et al., 2007; Blair et al., 1998; Braunack et al., 2006; Jupiter & Marion, 2008; Zhang et al., 2018). Studies that were conducted over a 12-month period were scored a 2 (e.g., Nachimuthu et al., 2016) and studies that were short term such as nine days after harvest were scored a 1 (e.g., Thorburn et al., 2010; Warner et al., 2019). The temporal relevance score was Moderate at 2.0.

#### Horticulture and bananas

There was only a single study that met the eligibility criteria. It was classified as having a High (3) overall relevance of the study approach to the question, High (3) spatial relevance and High (3) temporal relevance.

#### Grains

Studies which were outside of the Brigalow Bioregion in NSW and all other States were excluded from the grains studies, leading to a High spatial relevance score of 2.5. A large proportion of studies came from the Darling Downs and the Central Highlands, and the relevance of the study approach to the question was rated as High (2.9). A large number of the grains field studies were on research stations and covered multiple years of data and therefore temporal relevance was also ranked as High (2.5), with those that were modelled or less than two years scored a 1.

### Consistency, Quantity and Diversity

The nature of different co-benefits being derived from different land uses and management practices resulted in a large diversity across studies. Grazing was given a Low score for Quantity, High for Diversity and Low for Consistency. Sugarcane was ranked Moderate for Quantity, High for Diversity and Moderate for Consistency. Grains were ranked High for Quantity, Moderate for Diversity and High for Consistency. Horticulture was ranked Low for Quantity as there was only one study, and as a result was not scored for Diversity or Consistency.

### Confidence

Based on the overall relevance to the question and consistency of studies, there was High Confidence for grains, Moderate Confidence for sugarcane, and Limited Confidence for grazing, and horticulture and bananas.

*Table 17. Summary of relevance by land use of evidence appraisal for Question 8.1.*

| Land use | Total citations | Relevance of the study approach/ results to the question | Spatial Relevance | Temporal Relevance | Overall Relevance | Quantity | Diversity | Consistency | Confidence |
|---|---|---|---|---|---|---|---|---|---|
| Grazing | 57 | 2.6<br>High | 2.5<br>High | 2.2<br>Moderate | 7.4<br>High | Low | High | Low | Limited |
| Sugarcane | 21 | 2.3<br>Moderate | 2.1<br>Moderate | 2.0<br>Moderate | 6.5<br>Moderate | Moderate | High | Moderate | Moderate |
| Horticulture & bananas | 1 | | | | | Low | | | Limited |
| Grains | 19 | 2.9<br>High | 2.5<br>High | 2.5<br>High | 7.9<br>High | High | Moderate | High | High |

## 4.4 Indigenous engagement/participation within the body of evidence

In the review of evidence items, a total of four studies in grazing assessed the co-benefits of Indigenous engagement. Items specifically identified Indigenous engagement and capacity to generate positive social co-benefits.

- Jarvis et al. (2021). The Learning Generated Through Indigenous Natural Resources Management Programs Increases Quality of Life for Indigenous People – Improving Numerous Contributors to Wellbeing. Ecological Economics, 180.
- Jarvis et al. (2018). Indigenous land and sea management programs: Can they promote regional development and help “close the (income) gap”? Australian Journal of Social Issues, 53(3), 283-303.
- Larson et al. (2023). Piecemeal stewardship activities miss numerous social and environmental benefits associated with culturally appropriate ways of caring for country. Journal of Environmental Management, 326.
- Larson et al. (2020). Indigenous land and sea management programs (ILSMPs) enhance the wellbeing of Indigenous Australians. International Journal of Environmental Research and Public Health, 17(1).

## 4.5 Knowledge gaps

*Table 18. Summary of knowledge gaps for Question 8.1.*

| Gap in knowledge (based on what is presented in Section 4.1) | Possible research or M&E question to be addressed | Potential outcome or Impact for management if addressed |
|---|---|---|
| Long term effects of agricultural sector land management to improve water quality on biophysical, economic, and social co-benefits. | Meta-analysis of published and grey literature and modelling of co-benefits to assess co-benefits of improvements to water quality.<br>Long-term experimental trials to assess co-benefits of improvements to water quality in investments allowing scope to modify frameworks to facilitate management action with co-benefits. | Land management options to improve co-benefits of water quality investments. |
| Prediction of climate warming on the co-benefits. | Modelling to assess the long-term consequences of climate warming on co-benefits of improvements to water quality. | Climate resilient land management options to improve co-benefits of water quality investments. |
| How o-benefits could be practically implemented on commercial properties. | What are the monitoring systems, timeframes and approaches that need to be implemented, how would these be completed and under what methodology? What aspects could be stacked? | Case study example of understanding how co-benefits could be implemented across a large number of participants. |
| Potential for market-based instruments to provide income from co-benefit outcomes from land management. | Formulation and trialing of market-based instruments to provide income from co-benefit outcomes from land management. | Viable and effective market-based instruments to provide income from co-benefit outcomes from land management. |
| Interaction between invasive species and biodiversity and or emissions. | What is the impact of invasive species such as Indian couch on biodiversity outcomes? | Potential increased native pasture restoration and increased cover in grazing systems. |
| The critical biodiversity-habitat locations or species and best management | What are the key biodiversity outcomes to be achieved? | Potential to better position management practices that achieve multiple outcomes. |

| Gap in knowledge (based on what is presented in Section 4.1) | Possible research or M&E question to be addressed | Potential outcome or Impact for management if addressed |
|---|---|---|
| practices to support these outcomes. | What are the main practices that support these outcomes and how are they best measured?<br>What are the timeframes for achieving these outcomes? | |
| Systems understanding of suites of practices and the overall biodiversity or carbon emissions outcomes. | What is the life cycle analysis for different industries and group of practices on emissions and biodiversity? | Improve program design. |
| Indigenous outcomes for participation in carbon or water quality programs. | What are the key links that could be achieved for water quality and carbon outcomes through Indigenous land and sea management programs? | Program design. |

## 5. Evidence Statement

The synthesis of the evidence for **Question 8.1** was based on 97 studies undertaken in the Great Barrier Reef, nationally and internationally, and published between 1990 and 2023. The synthesis includes a *Moderate* diversity of study types (63% observational or experimental, 26% reviews and 11% modelling), and has a *Moderate* confidence rating (based on *Moderate* consistency and *Moderate* overall relevance of studies).

**Summary of findings relevant to policy or management action**

Co-benefits occur where a specific land management practice implemented to improve water quality for the Great Barrier Reef has additional positive on-farm secondary impacts such as improving economic and production outcomes, reducing carbon emissions, increasing biodiversity or improving soil health. Economic and production co-benefits and the 'downstream' effects of these co-benefits on Great Barrier Reef ecosystems were outside of the scope of this Question and are addressed elsewhere in the Scientific Consensus Statement. The potential direct co-benefits of water quality improvement practices in grazing, sugarcane, bananas, horticulture and cropping (primarily grains) were included in this review; non-agricultural land uses (such as urban), conservation areas and wetlands were not in scope. Indirect or 'expected' co-benefits such as reduced gully erosion as a result of ground cover management in grazing lands, was not within scope. While limited, the available literature clearly indicates there may be significant environmental and social co-benefits from land management practices designed to improve water quality in the Great Barrier Reef. For example, reducing grazing pressure and changing the timing of grazing can lead to increased vegetation cover, particularly of perennial grasses. Increased vegetation cover can improve water infiltration and reduce runoff, which can lead to improved soil health, higher levels of soil carbon and greater biodiversity. In sugarcane and grain cropping systems, nitrogen management strategies (type, timing, and quantity applied) implemented to reduce the amount of nitrogen entering the Great Barrier Reef can also reduce nitrous oxide and greenhouse gas emissions. The use of break-crops, rotations, controlled traffic farming and trash blanketing, all of which are used to reduce runoff and erosion, also has demonstrated benefits for soil health. Co-benefits associated with management practices to improve water quality can be complex, and therefore are not guaranteed and require careful planning and design. Contextual and site factors, the specific design and implementation of the management action and program design can influence the extent, magnitude and duration of a co-benefit. Further work is needed to understand the potential co-benefits associated with water quality improvement actions in the Great Barrier Reef catchment area, and to devise appropriate mechanisms to encourage adoption of practices with multiple benefits.

**Supporting points**

- There are existing policy mechanisms such as the Land Restoration Fund and Australian Carbon Credit Unit scheme that are relevant to supporting co-benefits (environmental, socio-economic and First Nations) flowing from Great Barrier Reef water quality management practices. While these existing mechanisms could offer opportunities for water quality benefits to be included with other co-benefits over the same area, differences in the guidelines, timelines, measurements and specific practices of the programs currently impede this.

- Key considerations for successful policy and program design for encouragement and greater adoption of practices yielding co-benefits include the specific co-benefit being sought, the capacity to accrue multiple benefits, the framework that is applied to measure it and to achieve additional co-benefits, the time expected to achieve co-benefits and the monitoring and maintenance required to demonstrate their achievement.

- The ways in which land management practices and climate warming interact will affect co-benefits. As an example, grazing practices that increase tree cover, ground vegetation cover and soil carbon are likely to trap more water on the property and thus improve vegetation productivity, reducing the impacts of droughts.

*Grazing*

- The relationship between grazing management strategies and soil organic carbon over the short and long term is complex. Stored soil organic carbon (to a depth of 30 cm) appears to be influenced by various combinations of grazing intensity, land condition, rainfall and land/soil type, and it is difficult to establish evidence for a strong link between livestock management and soil organic carbon content. Studies to date indicate that the benefits of maintaining ground cover and/or reducing stocking rates for soil health can take many years.
- Improved riparian and vegetation management in grazing (and cropping) lands has been shown to result in positive changes for a range of bird, insect and other invertebrate species, with evidence of increases in species richness, relative abundance and change in composition.

*Sugarcane*

- In sugarcane, a critical Paddock to Reef Water Quality Risk Framework management practice to reduce the risk of nutrient runoff is to reduce the amount of fertiliser applied to match industry recommended rates. Reducing the amount of fertiliser applied can also reduce emissions of the greenhouse gas nitrous oxide, however, there are still losses through other pathways including deep drainage and runoff. Nitrous oxide emissions vary with soil type, temperature, and soil water which also vary across sugarcane growing regions.
- Maintaining sugarcane trash on paddocks after harvesting, or green cane trash blanketing can both minimise soil erosion and runoff, and improve soil health. The use of soybean break-crops for inhibiting monoculture fungus and pests has also shown benefits for soil health. However, there is limited evidence that trash blanketing is beneficial for soil carbon. There is some evidence of downstream benefits to biodiversity from maintaining streambank vegetation in sugarcane areas.
- The methods for measuring outcomes of co-benefits in sugarcane vary between studies, with additional variability in temporal and spatial characteristics, making it difficult to compare benefits between studies.

*Horticulture and Bananas*

- There was only one study specific to horticulture, but many of the principles, practices and outcomes are similar to those of other cropping systems. As with sugarcane, reducing the amount of fertiliser applied in horticulture and bananas reduces the risk of nutrient runoff and potentially, nitrous oxide emissions. Nitrous oxide emission rates linked to the amount of fertiliser applied have been compared among horticulture crops, with emissions varying across the plots. Increased monitoring will help to understand these potential co-benefits.

*Grains*

- There are potential improvements to soil health from crop rotations and fallow management, which reduce sediment erosion, break monoculture and reduce disease pressure.
- Grain cropping systems have the most long-term comprehensive datasets to assess the various co-benefits flowing from water quality improvement practices, and to understand the impacts of different climate cycles and climate change. However, these data do not necessarily align with different environmental benefits. For example, a number of soil carbon recordings are made at different depths from those required for credit by the Australian Carbon Credits Unit.

## 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.

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# Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 8.1

## Theme 8: Future directions and emerging science

**Question 8.1** What are the co-benefits e.g., biodiversity, soil carbon, productivity, climate resilience, of land management to improve water quality outcomes for the Great Barrier Reef?

## Author team

| Name | Organisation | Role in addressing the Question | Sections/Topics involved |
|---|---|---|---|
| 1. Megan Star | CQU & Star Economics Pty Ltd. | Lead author | Second phase searches and data extraction focused on the Paddock to Reef Water Quality Risk Framework management practices generating water quality outcomes and co-benefits across sugarcane, horticulture and the grains sector. Revision of all sections following second round of peer review. |
| 2. Iain Gordon | CQU | Initial Lead Author, Contributor | All Sections, initial searches and data extraction primarily focused on the biophysical co-benefits of water quality improvement across the grazing, sugarcane, and horticulture agriculture sectors. |
| 3. Anne Bibost | CQU | Contributor | Initial searches and data extraction prior to preliminary peer review. |