2022 Scientific Consensus Statement

Question 3.5 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?

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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

[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

[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 3.5 What are the most effective management practices for reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments? 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?

Considerations were given to the **spatial variability and climate conditions** under which the management practices were effective. Similarly, where appropriate, the **costs, cost-effectiveness and production outcomes** of these practices were collated.

Background

Assessing the impact of improved land management practices on the loads of suspended sediment and particulate nutrients in rivers can be extremely difficult and will likely take decades. This challenge is amplified in the Great Barrier Reef (GBR) catchment area due to the often-extreme natural flow variability, and large catchment areas. As a result, there are no studies that have demonstrated measured improvements on end of system loads in response to changes in land management in the GBR. Catchment models have predicted the likely sediment and particulate nutrient changes that may occur with improved management, however, due to time lags between management actions, landscape repair and water quality response, these modelling predictions are difficult to validate and require long-term measured datasets to detect actual change trends. There are, however, considerably more studies that have demonstrated this link at smaller hillslope or plot scales (<100 km^2). This review attempts to collate and synthesise information on the published and peer reviewed evidence for improvements in total suspended sediment (TSS), particulate nitrogen (PN) and particulate phosphorus (PP) from studies that have implemented improved land management practices. The focus was on studies from the GBR catchments, however, studies from other areas of Queensland and Australia were also included where relevant. This question focuses on management practices on 'hillslopes' or paddocks or agricultural land. Question 3.6 (Brooks et al., this Scientific Consensus Statement (SCS)) deals with effectiveness of practices for gullies and streambanks. The six land uses considered include grazing (representing ~72% of the catchment area of the GBR), sugarcane (~1%), cropping (~2.2%), bananas and horticulture (<0.1%), urban areas (0.6%) and roads.

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[5]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Review method was used.
- Search locations were Web of Science, Scopus, and Google Scholar.
- Main source of evidence: Primarily studies from the GBR catchment area, however, studies from other areas of Queensland and Australia were also included where relevant.
- A total of 530 papers were collated from the initial search, and after screening, 162 papers were found to be eligible and included in the synthesis.
- Given the enormous size of the catchment area draining to the GBR, and the variety of land uses, a broad range of techniques are presented in the collated studies. As part of this review, the studies were partitioned into broad categories according to whether the dominant approach

[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

relied on: i) on-ground measurements collected within the GBR catchments; ii) on-ground measurements collected for that land use in other parts of Australia; iii) studies based on modelling; or iv) synthesis, review or other methods.

Method limitations and caveats to using this Evidence Review

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

- Only studies written in English were included.
- Only two academic databases were searched.
- Only studies published post 1990 were included.
- Given the focus of the question was specifically on the effectiveness of management practices for reducing sediment and particulate nutrient loss, papers that discussed general land management practice changes and decisions associated with management practice but did not include reductions in sediment and particulate nutrient loss, were not included. The exception to this was for papers that included measured runoff or hydrological parameters without sediment and particulate nutrient data; they were included where appropriate, as collection of runoff data is rare and very informative of how a system is responding to land management.
- On-ground measurements, if collected using a robust sampling design, over a sufficiently long climate period, with documented error or uncertainty, are often considered as the point of truth in terms of representing the outcomes from changed land management. Monitoring is, however, expensive, and there will never be sufficient measured data to represent all management practices across all land uses. To fill this gap, modelling is used to estimate likely changes to water quality following different management actions. However, there are a broad range of models and modelling approaches, and many rely on data inputs or parameters that have not necessarily been developed for local conditions. Therefore, models are best used to estimate likely outcomes or scenarios but cannot be used as a point of truth (see Section 2.3 for more detail).
- Studies on topics such as climate adaptation, pasture or grazing management, weed control and fertiliser use were not included if they did not present data on runoff, sediment and particulate nutrient exports.
- Given that >500 papers were reviewed as part of this formal evidence appraisal process (via Web of Science, Scopus or Google Scholar), within a relatively short resource constrained timeframe, additional ancillary or applied studies that primarily used modelling to help make decisions regarding management effectiveness (e.g., Regional Water Quality Improvement Plans, Reef Water Quality Report Cards) or investment documents (Alluvium, 2016; 2019) were not included. In addition, many of these studies did not meet the requirements and terms of this Evidence Review as they were not discoverable via the key search methods (e.g., Web of Science, Scopus or Google Scholar). They are more 'applied' in nature and were not considered as part of this scientific review process. These approaches have been reviewed elsewhere (The State of Queensland, 2016).

Key Findings

Summary of evidence to 2022

As described below, six land uses are used to answer the question. These land uses were selected by policy for the SCS process.

Grazing

Based on the synthesis of 32 papers, the most effective management practices in grazing lands that are demonstrated to reduce fine sediment and particulate nutrient loss include the following factors.

- Moderate, sustainable stocking rates; noting that stocking rates will vary with land type, rainfall zone and seasonal climate variability. Stocking rates should be regularly adjusted to support minimum ground cover (and biomass) levels.
- Ground cover levels should be maintained above 40% and preferably ~70%.
- Regular periods of strategic rest from grazing, which is particularly relevant early in the wet season. Strategic rest should be included in all grazing management systems and be adaptive to climate and pasture conditions.
- Where there are large areas of bare ground, exclude cattle and consider using soil amelioration, and sowing perennial pastures to assist recovery.
- If using burning as a management tool, consider having unburnt vegetation buffers of at least 2 m.

These management practices are fairly generic, however, their effectiveness varies in different parts of the catchment and under different climatic conditions. The costs and cost-effectiveness of the practices are also highly variable and depend on the site location and type of production system. The outcome of grazing production is also highly variable, but in most cases (with exception of the wet tropics), there are long-term production benefits from these practices, although quantitative evidence for this is scarce.

Sugarcane

Based on the synthesis of 24 papers, the most effective management practices in sugarcane lands that are demonstrated to reduce fine sediment and particulate nutrient loss include the following factors:

- The gradual elimination of water furrows following laser-levelling will likely reduce sediment export by as much as 20% and repairing eroding drain banks is considered an effective measure for reducing sediment. However, this is more effective for coarse (>63 µm) rather than fine (<63 µm) sediment and is likely to be far more expensive than other options.
- Runoff, soil loss and particulate nutrient losses are reduced with green cane trash blanketing (GCTB), zero tillage and controlled traffic farming (CTF), however, infiltration capacities of soils may take several years to recover following changed management. Mound beds, which had no cultivation after planting, also have better runoff and water quality outcomes.
- Riparian zones in sugarcane lands play an important role in reducing nitrate and nitrite concentrations, however, they were less effective at reducing sediment and particulate nutrients as agricultural drains seem to dominate these sources.
- Economic modelling studies suggest that a 20% water quality improvement in sediment yields can be obtained at no additional cost to sugarcane farmers. Reductions in water pollution beyond these 20% (TSS) reductions will come at a cost to the sugarcane industry.
- Best management practices (BMPs) that are likely to be associated with net production benefits, and that are likely to have higher adoption levels, include GCTBs, variety selection, soil health analysis, and nitrogen management. BMPs likely to be associated with net production costs (where adoption may be more difficult to encourage) are sediment traps, precision farming, controlled traffic and riverbank and streambank stabilisation.
- There appears to be significant variation (heterogeneity) in cost estimates and farm gross margins between regions and (to a lesser extent) across farm sizes. This indicates that a single representative farm model is likely to misrepresent the actual financial-economic consequences of changing management. These models are best used to estimate the range of outcomes.
- Risk and uncertainty in financial returns may increase the private costs to producers. As such, it would be desirable to apply a range of cost and effectiveness estimates rather than single estimates.

Cropping

In general, on a per unit area basis, cropping lands pose a greater risk to downstream water quality (runoff, sediment, and particulate nutrients) than pasture, particularly when the cropping systems are located downstream of dams and closer to the coast. Based on the synthesis of 40 papers, the most effective management practices in cropping lands that are demonstrated to reduce fine sediment and particulate nutrient loss include the following factors:

- Slope steepness is by far the most important factor determining the inherent erodibility of a cropping area, and appropriate contour banks and conservation structures should be implemented on cropping lands >1% slope.
- Although results from experiments can be highly variable, primarily due to seasonal climate conditions, overwhelmingly, published research has shown that management strategies involving retention of crop residues (stubble), reduced tillage and crop rotation can reduce erosion and improve yield. Runoff and soil loss are reduced by an order of magnitude with ~50% ground cover, and retaining cover considerably reduces concentrations of particulate nitrogen and phosphorus.
- Traffic and tillage effects also appear to be cumulative. Therefore, using the combination of controlled traffic (i.e., dedicated wheel tracks) and zero tillage (i.e., low soil disturbance) using a high crop rotation (as opposed to continuous cropping) is considered cropping best practice and has benefits for water quality as well as improved crop yield (production) outcomes.
- The effectiveness of irrigation drain sediment traps are improved when combined with cropping best practice. Strategic tillage is often applied to support weed control in cropping systems. Although this may reduce pesticide use, it does increase runoff, erosion and particulate nutrient loss.
- Grass and tree buffers have been shown to reduce runoff, sediment and nutrient losses in cropping lands, with wider buffers trapping more sediment, and generally buffers of 4-6 m can reduce sediment loading by more than 50%.
- The benefits of cropping best practice such as controlled traffic and zero tillage have been demonstrated repeatedly, including improved economic viability, across different soils and mechanisation systems. However, adoption of new practices appears to have been related to practical and economic considerations and proved to be more profitable after the findings from focused research and development (R&D) were implemented.

Bananas and Horticulture

Based on the synthesis of 16 papers, the key messages to take away from the bananas and horticulture literature identified as part of this review include the following factors:

- Bananas and horticulture generally deliver high amounts of TSS, TN and TP concentrations and loads per unit area relative to other land uses.
- Several environmental BMP guidelines are available for these industries; however, they are not necessarily backed by specific runoff and water quality data. This is the case for BMP recommendations in most land uses, however, the lack of data demonstrating the effectiveness of management practice is more pronounced for bananas and horticulture. The key BMP recommendations seem to align with studies in cropping and sugarcane research.
- There is a need to demonstrate the profitability of environmental BMPs to encourage widespread industry adoption of environmentally sustainable practices.
- Several studies suggested that larger improvements in runoff water quality in horticulture and bananas are accompanied by crop yield reductions to the point that it may not be commercially viable to farm these products in some areas. This is, however, based on market prices at the time of the studies and does not consider more recent environmental markets and premium product pricing (e.g., low input organic products).
- Vegetation buffers are useful for trapping sediment and particulate nutrients from bananas and horticulture, although they are more effective for coarse, rather than fine sediment and particulate nutrients. Therefore, where possible, reductions should be focused on the source.

Urban areas

There were 35 papers from urban areas, although no papers were from the GBR region. Most remediation measures employed in urban areas for reducing runoff, sediment and nutrient concentrations are shown to be effective to some degree, however, there are some broad lessons and considerations for tropical systems adjacent to the GBR. These include the following factors:

- Loads of all variables, including sediment and particulate nutrients, were strongly correlated with imperviousness and hydrological connection of impervious surfaces.
- Due to the high variability in concentrations between sites and different types of urban areas (residential vs industrial etc.) the effectiveness of structural measures would not be universal.
- The need for extensive restoration of the upper catchment as well as stormwater treatment if sediment and nutrient loadings are to be kept to acceptable levels.
- Most urban treatment options were more effective for sediment than for nutrients.
- For treatments such as bioretention systems to be effective, they need to be the right size for the volume of water that will move through them. If stormwater bypasses the systems, they will not be effective. This is an important consideration for tropical systems that can have a very large range between base and event flows.
- It appeared that the effectiveness of wetlands was optimal in small events and decreased following medium to large rain events with trap efficiency falling for sediment and nutrients. See also Questions 4.6 (Thorburn et al., this SCS) and 4.7 (Waltham et al., this SCS).
- In general, combining treatments, into treatment trains (which are a set of hydrologically linked treatments), are more effective than single treatments.
- Cost-effectiveness indicates that wetland-based stormwater treatments are relatively inexpensive. However, they do encompass about 3-5% of the land they drain which is comparatively high in comparison to other stormwater management practices. This can make them untenable in areas where land values are high.

Roads

There were 14 papers reviewed that evaluated remediation of roads. The only papers included from the GBR region did not include any water quality data. There were some broad lessons and considerations for roads adjacent to the GBR. These include the following factors:

- Dirt and gravel roads are a major source of sediment and particulate nutrients, whereas sealed roads are a major source of runoff (and other contaminants such as heavy metals, hydrocarbons and other chemicals).
- There are numerous manuals and engineering ‘how to’ guides for road maintenance, however, these documents generally do not contain runoff or water quality information and are not published and peer reviewed. Therefore, they were not included in this review.
- Similarly, there is considerable research from the United States and elsewhere regarding the effectiveness of various forestry logging management approaches for reducing sediment yield (e.g., snig tracks, filter strips etc.), but less research on rural road networks as a source of sediment and particulate nutrients.
- The most efficient and economic soil erosion control strategy on roadsides is revegetation, however, fine sediment will be very difficult to remove using vegetated filter strips alone, and there is a need to reduce sediment generation, prevent flow concentration and discharge runoff as high as possible in the landscape.

Recent findings 2016-2022

The body of evidence presented here is represented by considerably more studies published prior to 2016 (with <30% of the evidence from papers published after 2016 for all land uses except Urban). This may be for several reasons including the R&D funding environment, the long-term, and therefore often sporadic and delayed nature of publications from such studies, a stronger focus on modelling in recent years, and a change in R&D priorities or focus. For example, gullies and streambanks have been identified as a major source of fine sediment and particulate nutrients to the GBR, and the evaluation of the effectiveness of remediation of these sources has increased in recent years (see Question 3.6, Brooks et al., this SCS). This more recent focus has resulted in a scaling back of studies evaluating surface or plot erosion. Outside of the long-term trial sites such as Brigalow, Wambiana and Virginia

Park that continue to publish new findings, there are few new studies that have explicitly measured a water quality change following the implementation of best management practices across any land use.

Significance for policy, practice, and research

The key recommendations that were consistent across all land uses suggest that:

- There is a general lack of measured runoff and water quality field data, combined with commensurate land management practice information, to demonstrate improvements for many practices.
- Vegetation is a key component to maintaining sustainable landscapes and implementing management practices that involve the addition or re-introduction of vegetation is generally correlated with improved water quality. In most cases, the more vegetation, the better.
- Hydrologically connected systems will produce more sediment and particulate nutrients (via roads, drains, gullies etc.), and therefore remediation measures should be focused on reducing the hydrological connectivity of flow pathways for all land uses.
- Outputs from models, particularly those that have not had sufficient local calibration using multiple lines of evidence, will have a limited temporal value and are best used to show relative and approximate changes in water quality response to land management.
- For studies that have demonstrated an improvement in sediment and particulate nutrient runoff, there is a general lack of data on the cost and production implications of those interventions. There is not always a "win-win" scenario between improving water quality and increasing profit, and very few studies have evaluated changes at the whole-of-business level for most land uses. Regional level analyses could also provide insights into changes at the community level.
- Information on the impact of BMPs on production and costs is of most interest to landholders. This information is considered important for increasing uptake of BMPs across all land uses.

As Australia (and the rest of the world) increasingly move towards carbon net zero and nature positive policies that will (potentially) be supported by Natural Capital Markets, information on the measured changes in biophysical assets will be critical. Strategic investment into additional long-term multi-dimensional measurement studies in the GBR catchment areas is needed. These investments may be augmented with shorter-term focused student projects. The Brigalow Catchment Study in the Fitzroy basin, which is Australia's longest running paired catchment study, is the only study of its kind in the GBR catchments. Studies such as Brigalow, that evaluate land use and land management change, alongside soil, runoff and water quality outcomes, while quantifying production and economic implications, are vital for demonstrating the 'actual' effectiveness (or otherwise) of land management adjustments. Modelling is useful for predicting likely or approximate outcomes, but it can have large uncertainties. Experimental and monitoring data to validate and reduce the uncertainties in modelled outputs is critical. Investing in long-term monitoring, including the equipment and people to support such studies, is expensive. However, long-term data generally becomes more useful with time, and therefore the benefits of this knowledge are likely to re-pay severalfold into the future. This review has highlighted that long-term on ground measurements of land management change with coincident environmental and economic data, are grossly lacking in the GBR catchments, and additional sites should be established to support future decision making.

Key uncertainties and/or limitations

There were no studies from the GBR catchments, that were applicable to all aspects of this question. That is, no studies: i) used measured data to evaluate a range of agricultural management practices on fine sediment and particulate nutrient export loss, ii) included data on the cost-effectiveness of the practices; and, iii) can be broadly extrapolated to other spatial areas under different climate conditions. This is primarily because no study captures all issues over an average rainfall period (~10 years) while comparing to appropriate control conditions across a range of soil, terrain and land use types. The only studies that combine these elements are based on modelling outputs, which have generally low confidence due to a lack of field validation, particularly for remediation approaches. The key long-term monitoring studies that have collected both land (grazing) management and water quality data over at least a 10-year climate period, are from the Brigalow Catchment Study (Fitzroy, Qld Dept of Resources), Wambiana Grazing Trial (Burdekin, QDAF) and Virginia Park Research site (Burdekin, CSIRO). These studies provide extremely valuable data and insights into land management practices and their effectiveness on water quality, however, the results need to be used carefully when extrapolating outside of their geomorphological, climatic and economic context. There are no equivalent monitoring sites in any of the other agricultural commodities.

Evidence appraisal

The quantity of papers varied for each land use, ranging from 14 for roads, to 40 for cropping. The overall relevance was Moderate, with scores ranging from 4.0 for roads and up to 6.8 for cropping (where 1 is low and 9 is high). Grazing, sugarcane cropping, and bananas/horticulture were given a diversity ranking of 2 (out of 3) as they were derived from a range of study types, however, urban and roads received a diversity value of 1 (Low), as there were no studies from within the GBR catchment area. Due to the broad range and location of studies, all studies were given a nominal consistency value of Moderate (value = 2 or Moderate). This reflects the general pattern that improved land management generally leads to improved water quality regardless of the location and method used, however, the timescales over which this occurs varies widely (hence only Moderate ranking applied). The overall confidence of the papers was Moderate for grazing, sugarcane and cropping and Moderate-Limited for bananas/horticulture, urban and roads due to fewer studies, and very few from tropical environments.

1. Background

Suspended sediment and nutrients play an important role in freshwater and marine biogeochemical processes and food webs (Krumins et al., 2013; Wood & Armitage, 1997). Sediment and particulate nutrient delivery is highly variable in time and space and is controlled by a combination of landscape (e.g., geology, soil type and terrain), climate (e.g., rainfall, drought, cyclones) and land use factors. There is considerable evidence demonstrating that this variability has been further enhanced by human activity (e.g., D'Olivo & McCulloch, 2022), and sediment and particulate nutrient delivery to the Great Barrier Reef (GBR) has increased since agricultural development (see Question 2.3, Lewis et al., Question 3.1, Lewis et al., and Question 3.4, Wilkinson et al., this Scientific Consensus Statement (SCS)). However, quantifying the effectiveness of improved land management activities on suspended sediment and particulate nutrient delivery, against the high variability of natural loads in tropical rivers, is very challenging.

Thorburn et al. (2013) highlights that there have been many more studies of land degradation than of improvement in agricultural land condition or water quality in the GBR catchments. This lack of data evaluating the effectiveness of improved land management is not a unique problem for the GBR region. There are very few rivers globally that have demonstrated a reduction in end of river sediment loads to coastal waters in response to improved land management, and even fewer (<10) that have demonstrated improvements in ecosystem health (Bartley et al., 2014a; Kroon et al., 2016). This is because measurable improvements in river and coastal marine water quality are likely to take decades to detect (Darnell et al., 2012) and require commensurate information about changes in the land management practices implemented, to support the evidence for changes in any water quality response measured. Where reductions in end of system sediment and nutrient loads have occurred, the financial investments into catchment restoration have been substantial, and both the land uses and associated conservation practices that dominated these studies have been more intensive (e.g., land use conversion, shelter belts, no-till farming, flood retarding structures etc.) (e.g., Garbrecht & Starks, 2009), as compared to the more common, but less intensive activities applied in many areas of the GBR (e.g., pasture management) (e.g., Bartley et al., 2022). Although quantifying the link between changes in land management and improvements in water quality is very challenging at the large catchment or GBR scale, there are considerably more studies that have demonstrated a link at smaller hillslope or farm scales (<100 km^2). In an international review of the effects of agricultural management changes on surface water quality by Melland et al. (2018), positive water quality effects were measured in 17 out of 25 studies. Improvements in water quality occurred from 1 to 10 years after the measures were implemented, however, it took from 4 to 20 years to confidently detect the effects for catchments ranging in size from between 1 and 100 km^2. The response time broadly increases with catchment size, and there were no sites from Australia included in that study.

This review collates and synthesises information on the published and peer reviewed evidence for improvements in total suspended sediment (TSS), particulate nitrogen (PN) and particulate phosphorus (PP) from studies that have implemented improved land management practices. The focus was on studies from the GBR catchments, however, studies from other areas of Queensland and Australia were included where relevant. As TSS, PN or PP export loss is strongly controlled by hydrology, studies that focused on changes in runoff were also included where appropriate. Details of the specific land management activities are important to document, and this has invariably focused the studies at the paddock and small catchment (<50 km^2) scale. Information on the costs, cost-effectiveness and production outcomes of the practices were also collated if they were presented alongside changes in TSS, PN or PP. These results were presented with due consideration of the spatial variability and climatic conditions at the time of the study.

1.1 Question

Primary questions	**Q3.5** What are the most effective management practices 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 primary question evaluated here is: **What are the most effective management practices for reducing sediment and particulate nutrient loss from the GBR catchments?** Considerations were given to the **spatial variability and climate conditions** under which the management practices were effective. Similarly, where appropriate, the **costs, cost-effectiveness and production outcomes** of these practices were collated. Considerable global literature is available on this topic, however, due to time constraints, this review focused on studies from Australia and Queensland only. For modelling studies, only studies published in scientific journal papers were included (very few reports or conference papers were considered). If modelling papers were not validated with field data, and/or papers were >20 years old, they were excluded. This is because many older papers would have been superseded and updated by more recent and advanced modelling studies and the results would no longer be relevant due to updated digital data sources (see Section 4.1.1). Several papers were excluded from the synthesis if they described land management in a vague generic sense and did not describe specific land management actions that were associated with fine sediment and particulate nutrient changes. The focus was on six land-uses (Table 1): grazing, sugarcane, cropping (irrigated and dryland), bananas and horticulture, urban areas, and roads.

Table 1. Summary of key land uses assessed and % representation in GBR catchment area (Australian & Queensland Government, 2021) and modelled sediment and particulate nutrient loads for key land uses derived from Bartley et al. (2017). SedNet modelling (McCloskey et al., 2021) has not reported contributions by land use by region so Bartley et al. (2017) remains the best peer reviewed estimates by land use, although there are concerns that these estimates need further evaluation. Note that streambank erosion is not associated with a land use and these contributions are by land use with the streambank contribution presented in Bartley et al. (2017) removed. Noting that nature conservation and forestry contribute disproportionally high sediment and particulate nutrient loads as they are generally on steeper and wetter areas of the landscape.

		Proportion of modelled total load to GBR from each land use (contribution of gully and hillslope erosion only)		
Land use	% of GBR catchment area	Fine sediment	Particulate Nitrogen (PN)	Particulate Phosphorus (PP)
Grazing	73%	60%	41%	49%
Sugarcane	1.2%	10%	13%	15%
Irrigated and dryland cropping	2.8%	4%	1%	2%
Bananas and horticulture	0.2%	1%	1%	<1%
Urban	0.7%	2%	1%	1%
Roads	Unknown	NA	NA	NA
Other (conservation and natural environments, water, forestry). It is also likely that 'roads and tracks' are captured under Other.	21.6%	23%	43%	33%

This question focuses only on management practices on 'hillslopes' or paddocks or agricultural land i.e., land surfaces. This question does not address the management of gullies or streambanks (which is addressed in Question 3.6, Brooks et al., this SCS). Similarly, we do not address sediment and particulate nutrient sources unless they included an aspect of management (as this is addressed in Question 3.3, Prosser & Wilkinson and Question 3.4, Wilkinson et al., this SCS) or changes associated with fertiliser use (see Question 4.6, Thorburn et al., this SCS). This question is focused on the key management practices that will 'improve' water quality.

1.2 Conceptual diagrams

The conceptual framework, that was developed specifically for this SCS process, is provided for each land use below (Figures 1-6). These frameworks demonstrate that the key hillslope or paddock biophysical attributes (e.g., ground cover) can vary with both natural (e.g., climate) and human (e.g., land use) factors. The key management factors affecting the biophysical attributes are documented for each land use separately. The hypothesis is that if the management actions are improved, then the biophysical attribute will also improve, and the combined outcome will be improvement in TSS, TN and TP loads. The additional considerations, including spatial and climate variability, cost-effectiveness and production outcomes are recorded if available, but the key considerations are the management actions on sediment and particulate nutrient reduction.

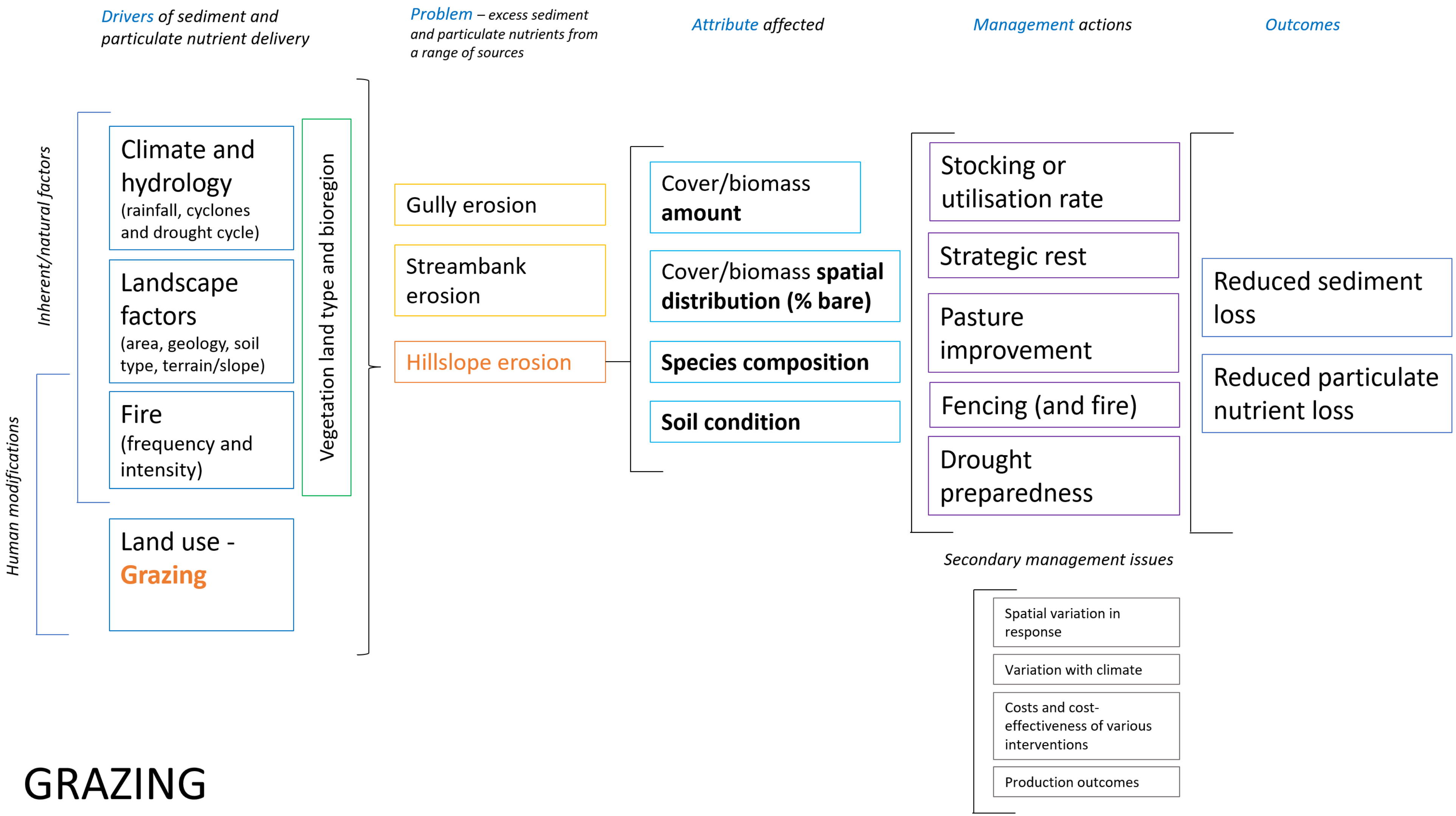

Figure 1. Conceptual model used to evaluate the most effective management practices for reducing sediment and particulate nutrient loss from grazing land.

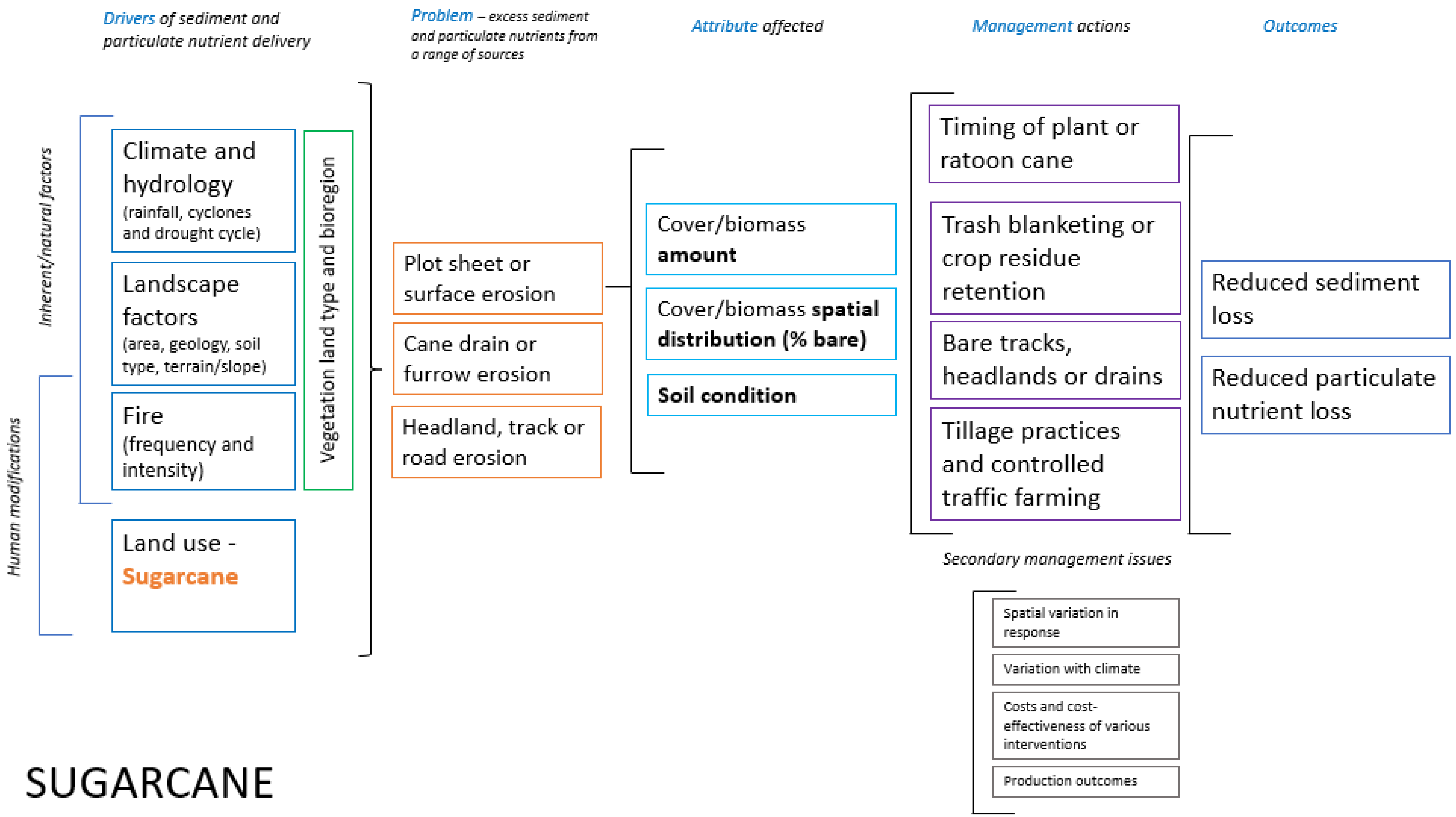

Figure 2. Conceptual model used to evaluate the most effective management practices for reducing sediment and particulate nutrient loss from land under sugarcane.

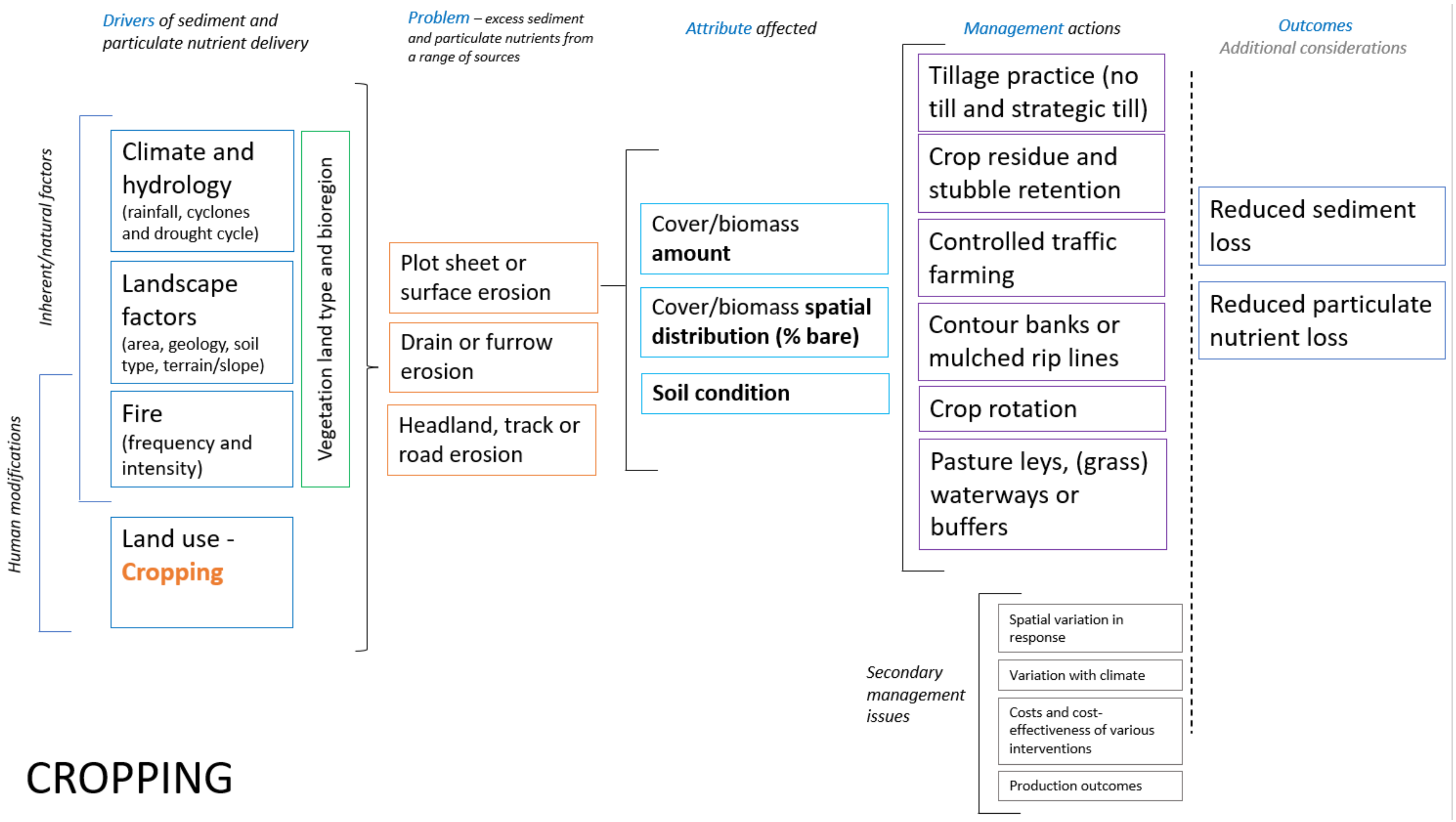

Figure 3. Conceptual model used to evaluate the most effective management practices for reducing sediment and particulate nutrient loss from cropping lands.

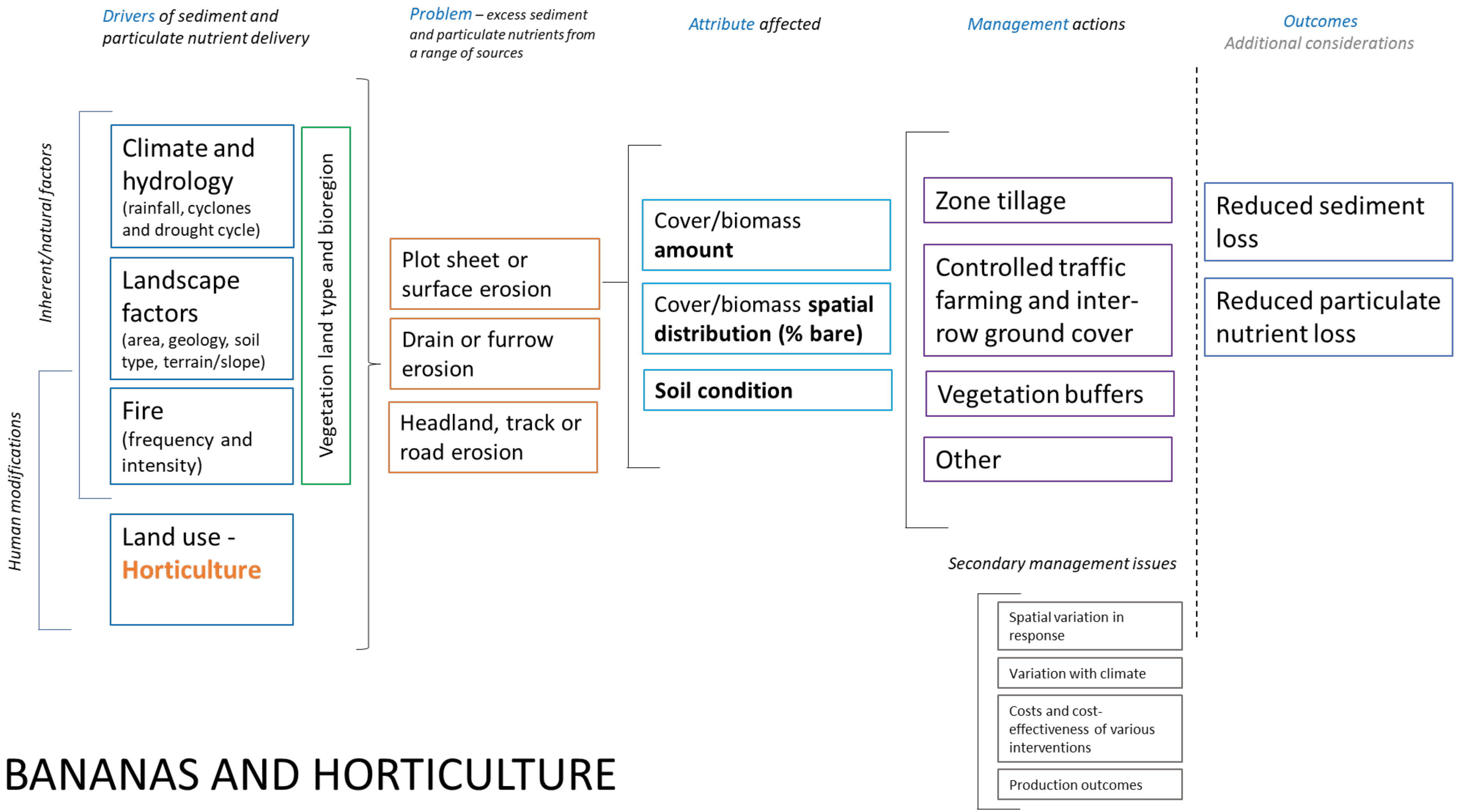

Figure 4 Conceptual model used to evaluate the most effective management practices for reducing sediment and particulate nutrient loss from bananas and horticultural lands.

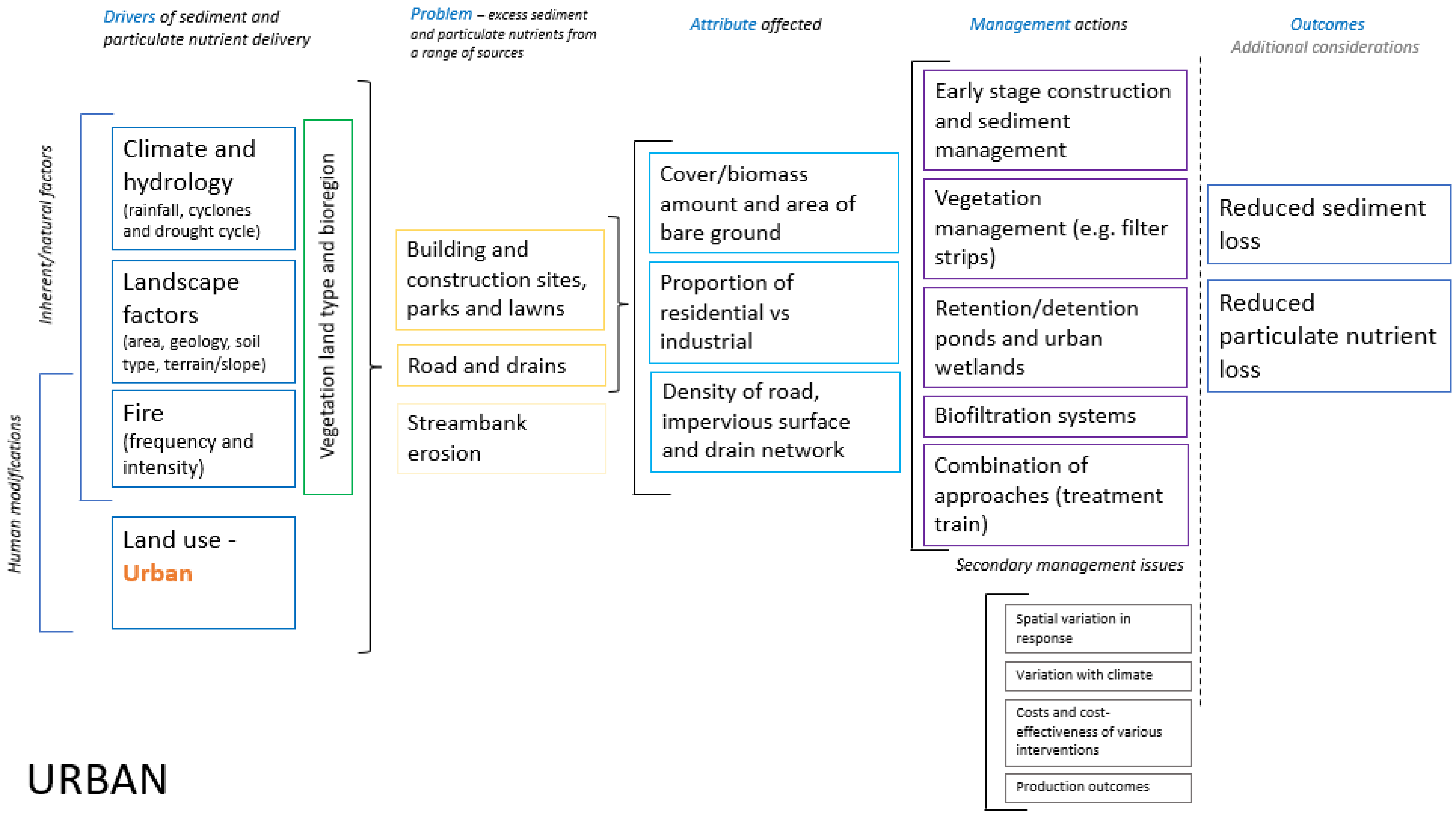

Figure 5. Conceptual model used to evaluate the most effective management practices for reducing sediment and particulate nutrient loss from urban areas.

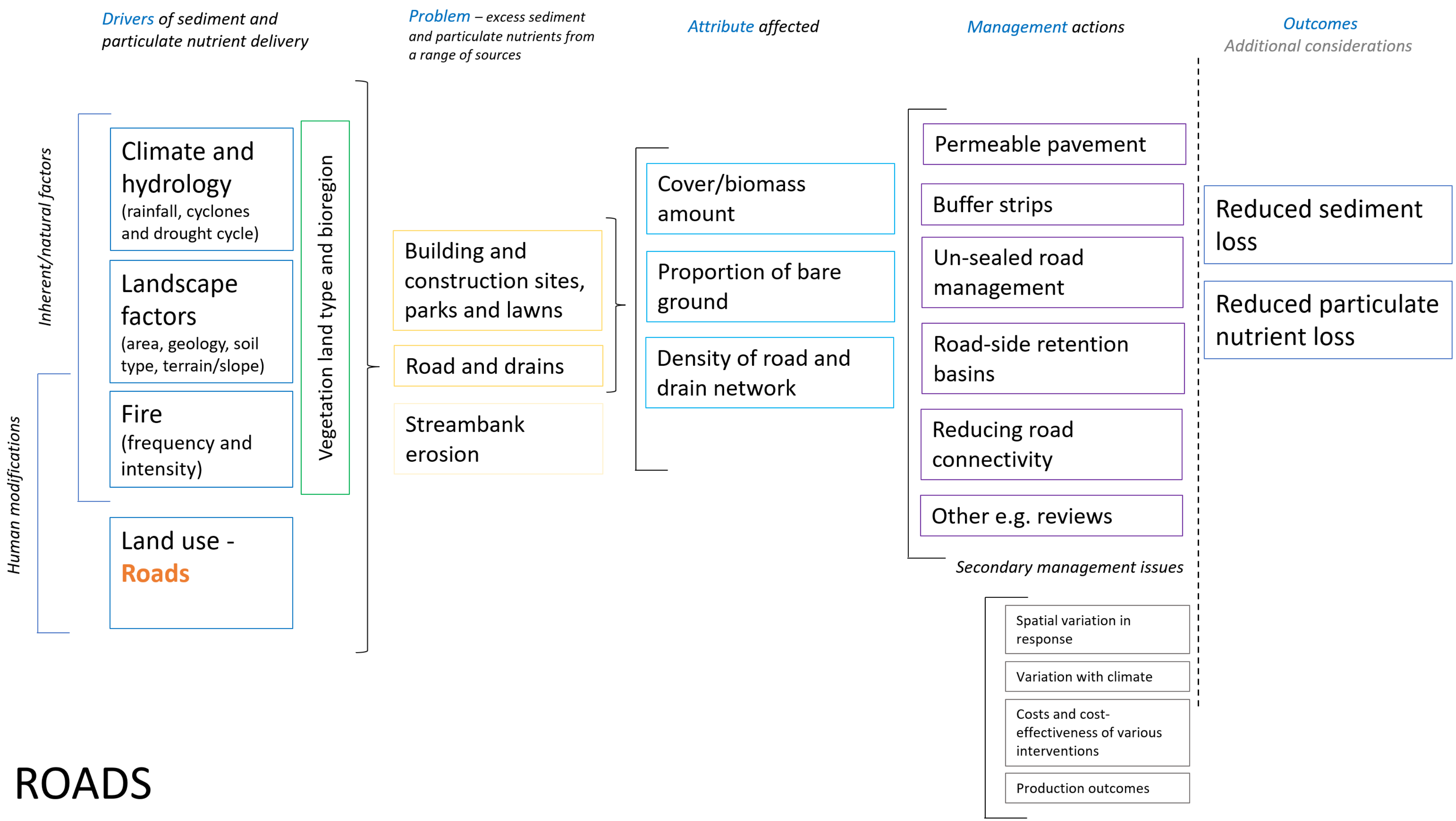

Figure 6. Conceptual model used to evaluate the most effective management practices for reducing sediment and particulate nutrient loss from roads.

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	**Q3.1** What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef? **Q3.2** What are the measured impacts of increased sediment and particulate nutrient loads on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef? **Q3.3** How much anthropogenic sediment and particulate nutrients are exported from Great Barrier Reef catchments (including the spatial and temporal variation in delivery), what are the most important characteristics of anthropogenic sediments and particulate nutrients, and what are the primary sources? **Q3.4** What are the primary biophysical drivers of anthropogenic sediment and particulate nutrient export to the Great Barrier Reef and how have these drivers changed over time? **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? **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?

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[6]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Review method was used.

2.1 Primary question elements and description

The primary question is: ***What are the most effective management practices (for specified land uses) for reducing sediment and particulate nutrient loss from the GBR 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?***

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[7] 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?

The key terms in the questions are defined in Table 2.

Table 2. Description of question elements for Question 3.5.

Question S/PICO elements	Question term	Description
Subject/Population	Sediment and particulate nutrient export	Fine sediment, TSS, particulate nutrients (nitrogen and phosphorus)
Intervention, exposure & qualifiers	Management practices influencing sediment and nutrient loss in grazing, sugarcane, etc.	See management practices described for each land use in conceptual models and Table 3.

[6] 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

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

Question S/PICO elements	Question term	Description
Comparator (if relevant)	Variation with spatial location and climate condition and cost-effectiveness	If there are differences in management across spatial locations – why, what is this in response to e.g., site variables, % cover, annual rainfall distribution etc. Also search for climate adaptation, drought preparedness, cost, cost-effectiveness, agricultural production.
Outcome & outcome qualifiers	Effectiveness for reducing sediment and particulate nutrient export loss	Field trials that measure runoff and fine suspended sediment and particulate nutrients. Studies may include elements of remote sensing, reviews of other studies, modelling.

Table 3. Definitions for any relevant terms used in Question 3.5.

Definitions	
Management practices	Definition will vary with land use. Only management practices that directly manage/influence the land i.e., not those setting management recommendations, policy, regulations etc.
Sediment	Fine sediment (generally <63 µm), suspended sediment.
Particulate nutrients	Particulate nitrogen, particulate phosphorus
Land use	see Table 1.
Climate conditions	Climate adaptation, drought. Where possible also fire and floods.
Cost-effectiveness	There is not necessarily a consistent term applied in all studies. Data on both the cost and effectiveness of management practice interventions are generally scarce.
Production outcomes	Definition will vary with land use

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:

- Web of Science
- Scopus
- Google Scholar

b) Search terms

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

Table 4. Search terms for S/PICO elements of Question 3.5.

Question element	Search terms
Subject/Population	Sediment, particulate nutrient, nitrogen, phosphorus, water quality
Intervention, exposure & qualifiers	Depends on land use – see Table 5
Comparator (if relevant)	Management
Outcome & outcome qualifiers	Reduction in runoff, sediment, particulate nutrient, nitrogen, phosphorus

c) Search strings

Table 5. Search strings used for electronic searches.

Search strings
Sediment and particulate nutrients for **GRAZING** **Web of Science and Scopus** (“grazing” OR “rangeland*” OR “cattle”) AND (“sediment” OR “suspended solids” OR “runoff” OR “particulate nutrient” OR “water quality”) AND (“management” OR “stocking rate” OR “utilisation rate” OR “rest” OR “pasture improvement” OR “fencing” OR “climate adaptation” OR “drought preparedness” OR “cost” OR “cost-effectiveness” OR “agricultural production”) AND (“effective” OR “reduction” OR “decline”) AND (“Queensland” OR “Australia”) **Google Scholar** “grazing” AND (“sediment” OR “runoff”) AND (“management” OR “stocking” OR “rest” OR “fencing” OR “adaptation” OR “cost” OR “agricultural production”) AND (“effective” OR “reduction”) AND “Australia”
Sediment and particulate nutrients for **SUGAR** **Web of Science and Scopus** (“sugar” OR “sugarcane”) AND (“sediment” OR “suspended solids” OR “runoff” OR “particulate nutrient” OR “water quality”) AND (“management” OR “ratoon cane” OR “trash blanketing” OR “crop residue” OR “bare ground” OR “drains” OR “climate adaptation” OR “drought preparedness” OR “cost” OR “cost-effectiveness” OR “agricultural production”) AND (“effective” OR “reduction” OR “decline” OR “important”) AND (“Queensland”)

Search strings
Google Scholar ("sugar" OR "sugarcane") AND ("sediment" OR "runoff") AND ("management" OR "ratoon cane" OR "trash blanketing" OR "drains" OR "adaptation" OR "cost") AND ("effective" OR "reduction") AND "Queensland"
Sediment and particulate nutrients for **CROPPING** **Web of Science and Scopus** ("cropping" OR "crop lands") AND ("sediment" OR "suspended solids" OR "runoff" OR "particulate nutrient" OR "water quality") AND ("management" OR "vegetation" OR "tillage" OR "cover crops" OR "stubble" OR "diversion banks" OR "contour banks" OR "mulching" OR "strip" OR "grass waterway" OR "bare" OR "climate adaptation" OR "drought preparedness" OR "cost" OR "cost-effectiveness" OR "agricultural production") AND ("effective" OR "reduction" OR "decline") AND ("Queensland") **Google Scholar** "crop*" AND ("sediment" OR "runoff") AND ("management" OR "tillage" OR "cover crops" OR "diversion banks" OR "contour banks" OR "mulching" OR "cost") AND ("effective" OR "reduction") AND "Queensland"
Sediment and particulate nutrients for **BANANAS and HORTICULTURE** **Web of Science and Scopus** ("banana*" OR "horticulture*") AND ("sediment" OR "suspended solids" OR "runoff" OR "particulate nutrient" OR "water quality") AND ("management" OR "ratoon" OR "trash blanketing" OR "crop residue" OR "bare" OR "drains" OR "climate adaptation" OR "drought preparedness" OR "cost" OR "cost-effectiveness" OR "agricultural production" OR "diversion banks" OR "contour banks" OR "cover crops" or "mulching") AND ("effective" OR "reduction" OR "decline") AND ("Queensland" OR "Australia") **Google Scholar** ("banana* OR horticulture*") AND ("sediment" OR "runoff") AND ("management" OR "ratoon" OR "trash blanketing" OR "drains" OR "adaptation" OR "cost") AND ("effective" OR "reduction") AND "Queensland"
Sediment and particulate nutrients for **URBAN** **Web of Science and Scopus** ("urban" OR "city") AND ("sediment" OR "suspended solids" OR "runoff" OR "particulate nutrient" OR "water quality") AND ("management") AND ("vegetation" OR "construction" OR "sediment barrier" OR "settling" OR "retention" OR "pond" OR "wetland" OR "roads" OR "grass waterway" OR "bare" OR "climate adaptation" OR "cost" OR "dust" OR "cost-effectiveness") AND ("effective" OR "reduction" OR "decline") AND ("Queensland" OR "Australia")

Search strings
Google Scholar “urban*” AND (“sediment” OR “runoff”) AND (“management” OR “construction” OR “sediment barrier” OR “settling pond” OR “wetland” OR “roads” OR “cost”) AND (“effective” OR “reduction”) AND “Queensland”
Sediment and particulate nutrients for **ROADS** **Web of Science and Scopus** (“road*”) AND (“sediment” OR “suspended solids” OR “runoff” OR “particulate nutrient”) AND (“management” OR “vegetation” OR “filter strip” OR “grassed swale” OR “check dam” OR “whoa-boy” OR “construction” OR “sediment barrier” OR “retention pond” OR “wetland” OR “roads” OR “grass waterway” OR “bare” OR “climate adaptation” OR “cost” OR “cost-effectiveness”) AND (“effective” OR “reduction” OR “decline”) AND (“Queensland” OR “Australia”) **Google Scholar** “road*” AND (“sediment” OR “runoff”) AND (“management” OR “whoa-boy” OR “sediment barrier” OR “retention pond” OR “wetland” OR “grass swale” OR “cost”) AND (“effective” OR “reduction”) AND “Queensland”

d) Inclusion and exclusion criteria

Table 6 shows a list of the inclusion and exclusion criteria used for accepting or rejecting evidence items.

As this question covered multiple land uses and had several components, there were slight variations in the way each land use was assessed. This was dependent on the following conditions:

- Papers that provided measured data, were preferenced over modelled data, for the reasons outlined below. There were, however, several exceptions. Modelling studies were included when they were published in peer reviewed journals, and/or had attempted to provide some form of data calibration, and/or included economic analysis of the management practice changes.
- Given the delivery of TSS, TN and TP are reliant on runoff, studies that measured a change in runoff following changes in land management practices, with or without TSS, TN and TP data, were often included. This was most relevant for the cropping land use where considerable research had been conducted on the changes to runoff with land management.
- In some cases, baseline studies, that provided a description of the key sources of TSS, TN and TP were included in the review, particularly where they documented sources within a land use (e.g., cane drains versus ratoon crops). Without this context, it is difficult to describe the influence of any subsequent management action on TSS, TN and TP.
- The papers had to provide sufficient detail about the actual management practice changes that occurred. Many papers were vague about the actual practice adoption approaches, and when there was insufficient detail, they were excluded.
- Information on the costs, cost-effectiveness and production outcomes of the practices were only collated if they were presented alongside changes in TSS, PN or PP.
- The results were presented with due consideration of the spatial variability and climatic conditions; but only for studies that had shown an improvement in TSS, PN or PP following land management change.
- There is also a subtle but important difference in documenting a ‘difference’ between land use or land management, versus a recovery from ‘poor or bad’ management to ‘better or good’

management. That is, there are numerous studies that have compared sites with different land use (e.g., with trees or without trees; or trees versus cropping), however, this is not necessarily the same as studying the changes that occur when a site without trees is monitored for the response when trees are returned to the landscape. Some landscapes may make a full recovery, however, in some cases, historical thresholds and tipping points may prevent a landscape from returning to a functioning system (Laurance et al., 2011). In summary, measuring the process of recovery, as opposed to comparing the response of different land uses, will take a lot longer. Both types of studies were included. However, studies that have monitored the recovery from degradation, or improvement in land management over time, are considered more robust.

Table 6. Inclusion and exclusion criteria for Question 3.5 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	Runoff, suspended sediment and particulate nutrient export studies conducted on hillslopes (paddocks/plots) in GBR catchments.	Gully erosion, streambank erosion, dissolved inorganic nitrogen (DIN), modelling not located in GBR, wetlands, coarse sediment, kelp, streamside management, papers that did not include key terms.
Exposure or Intervention	Must include assessment of a land management practice/s to reduce sediment and particulate nutrient export (e.g., reduced grazing or no tillage farming).	Studies focused on investigating sediment and particulate nutrient sources that have no clear implications for the effectiveness of management strategies/practices.
Comparator	Studies that assess the economic and production implications/outcomes associated with the adoption of improved management practices, BUT only when this was partnered with data on suspended sediment and particulate nutrient export.	General information about best management practices, including climate adaptation, that did not include suspended sediment and particulate nutrient data.
Outcome	Literature that provides conclusions regarding the effectiveness of different management strategies that is supported by observation or strong inference.	Conference papers and reports that were based on modelling only without adequate calibration using measured data.
Language	Studies published in English.	Studies not published in English
Study type		Noting that WaterCAST, E2 and SedNet are old model terms and have been superseded by Source Catchments. This review therefore focused attention on the most recent modelling papers/reports.

Measurement versus Modelling

Due to the cost, logistical challenges and long timeframes involved in measuring improvements in water quality following land management change, a common approach to predicting the effectiveness of practice change is to use modelling. Modelling studies are often conducted because i) there is insufficient time and money available to measure the response of land management practice; ii) there are large areas where there is no monitoring data available; iii) modelling provides a consistent approach across large spatial scales; and iv) modelling allows 'what-if' scenarios to be run to support investment decisions. However, the trade-off is that a lot of the model runs, including many of the ABCD land management scenarios used in the paddock to reef (P2R) program in the GBR catchments (see Carroll et al., 2012), are run without strong published evidence for the predicted outcomes. "*Verification and validation of numerical models of natural systems is impossible…models can be confirmed by the demonstration of agreement between observation and prediction, but the confirmation is inherently partial….models can only be evaluated in relative terms, and their predictive value is always open to question. The primary value of models is heuristic*" (Oreskes et al., 1994). There are numerous papers that have argued about the benefits, challenges and appropriate use of modelling (e.g., Alewell et al., 2019; Jakeman et al., 2006; Sidle, 2021) and it is not the purpose of this document to summarise that literature. However, it is important to note that there are an enormous range of modelling approaches and to quote George Box "all models are wrong, but some are useful". The usefulness of a model often depends on the question being asked, and the level of accuracy required of the answers generated.

Paddock or smaller scale (hillslope or plot) models that have been calibrated using locally derived data are generally considered to be more robust than models that are run using default parameter values from other often geographically distant and diverse locations. When evaluating the effectiveness of land management change, it is common for studies to employ a combination of approaches including field data (e.g., soil and vegetation properties) and modelling (e.g., Ghahramani et al., 2020). Once the models are calibrated using locally collected data, they are then used to run scenarios regarding the likely outcomes of land management practice interventions. It is more challenging to calibrate and validate the data inputs in larger scale and more diverse catchment models. Many reports and published papers in the GBR research space have applied catchment modelling for a range of purposes. In many cases these papers have been enormously valuable, however, the modelled estimates are likely to change as new input data becomes available and new knowledge about the various processes are updated and improved. This may then also lead to the models identifying different 'hot-spot' locations and generating different load estimates.

Figure 7 provides an example of how the integration of water quality monitoring and geochemical sediment source tracing data has dramatically revised the spatial sources and dominant erosion processes predicted by the Dynamic SedNet or Source Catchments model in the Bowen catchment (Bainbridge et al., 2023). This study highlights how the results of large-scale (>5,000 km^2) spatial models can change over time, and confidence in their predicted output increases when supported with local measurements and multiple lines of evidence. It also demonstrates that any subsequent estimates of management practice effectiveness and economic analysis undertaken using these models will also change over time. In theory this can be managed with agreed periodic updates that are well documented and communicated to end-users but this also requires appropriate resourcing for this to happen.

Given that >500 papers were reviewed as part of this formal evidence appraisal process (via Web of Science, Scopus or Google Scholar), within a relatively short resource constrained timeframe, additional ancillary or applied studies that primarily used modelling to help make decisions regarding management effectiveness (e.g., Regional Water Quality Improvement Plans, Reef Water Quality Report Cards) or investment documents (Alluvium, 2016; 2019) were not included. In addition, many of these studies did not meet the requirements and terms of this Evidence Review as they were not discoverable via the key search methods (e.g., Web of Science, Scopus or Google Scholar). They are more 'applied' in nature and were not considered as part of this scientific review process. These approaches have been reviewed elsewhere (The State of Queensland, 2016).

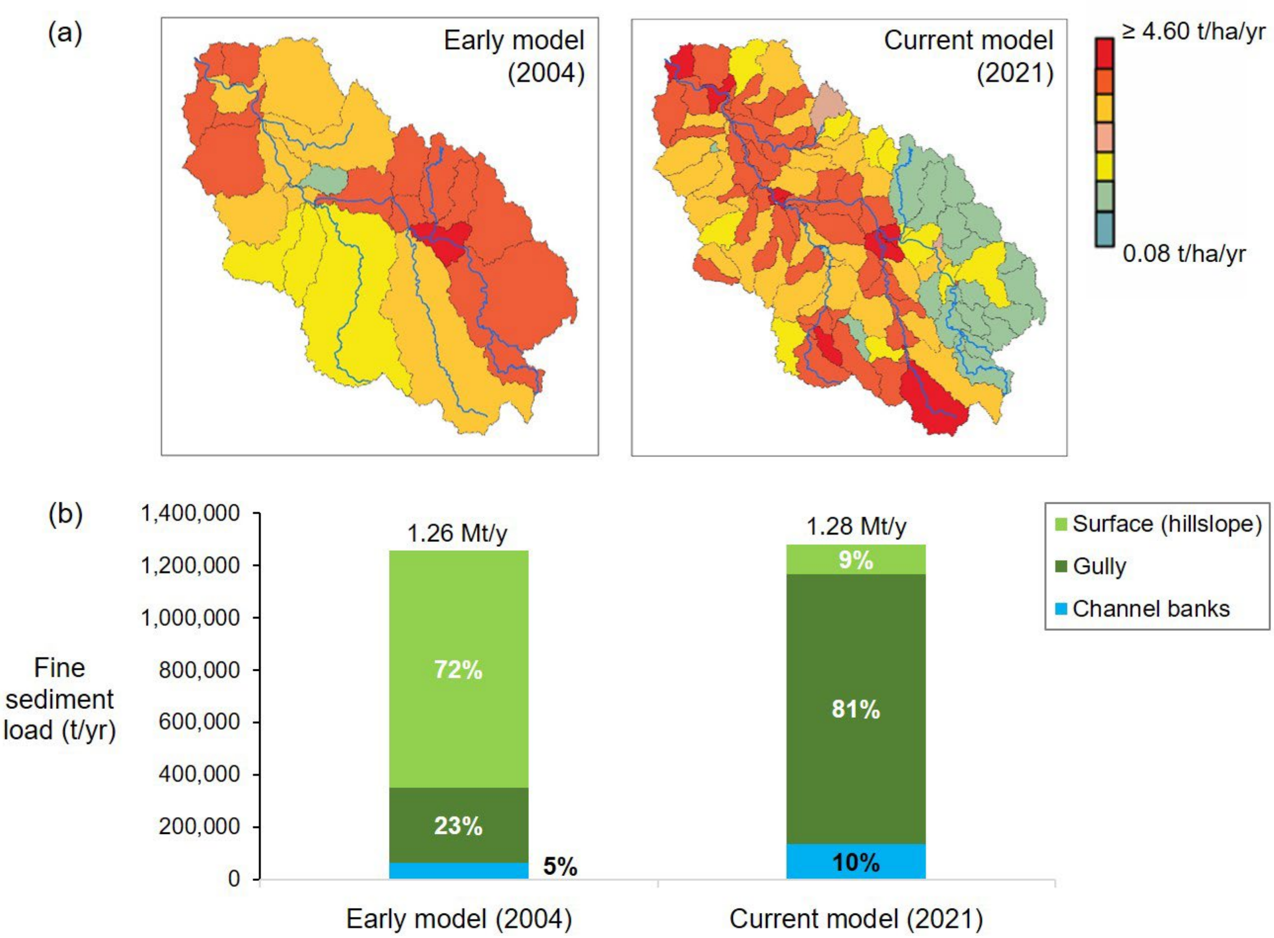

Figure 7. a) Spatial source of fine sediment supply (t/ha/yr) in the Bowen River by tributary link as predicted by the early SedNet model in 2004 that largely used default model parameters and has little calibration with local data (Bartley et al., 2004a) and the current Dynamic SedNet model outputs in 2021 (McCloskey et al., 2021) that included several locally collected datasets such as water quality, geochemistry and radionuclides as part of the calibration and validation process. b) Difference in the ratio of the predicted erosion process (Hillslope, Gully and Streambank) contributing to the Bowen fine sediment loads between the two models (Bainbridge et al., 2023).

Reliability Assessment

Each of the papers included in the review were also subjected to a reliability assessment. This assessment was based on expert opinion and used a range of criteria to determine if a paper had low or poor reliability. Some of the criteria considered, included:

- Identification of any obvious bias in the study.
- Issues with experimental design or data analysis.
- Inadequate model validation.
- Unjustified extrapolation of results/conclusions.
- Unreasonable assumptions.

Any papers that were included in the synthesis, but were considered unreliable, are flagged in pink/red in the text. These papers had something useful to say, and were worthy of inclusion, however, their results should be used with caution.

3. Search Results

Table 7 captures the key search methods and outcomes for this question. [Noting that Table 7 replaces Table 6 and Figure 1 in the SCS template].

Table 7. Search results table summarising the number of papers assessed from each of the search engines as well as manual additions, duplicates and final number of eligible papers.

Land use	Date of searches	Web of Science	Scopus	Google Scholar (first 200 screened)	Manual additions	Total number of papers collated	Duplicates	Initial Screening (after duplicates removed)	Papers removed during screening	# of eligible papers included in evidence appraisal
Grazing	01/09/2022	34 out of 50	36 out of 72	50 of 40,500	1	120	36	84	52	32
Sugarcane	16/09/2022	28 out of 46	31 out of 38	74 of 9,600	4	137	28	109	85	24
Cropping	04/10/2022	17 out 30	16 out of 19	56 of 17,300	1	84	15	69	29	40
Bananas and Horticulture	31/10/2022	17 out of 50	7 out of 12	28 of 2,860	1	52	13	39	23	16
Urban	04/11/2022	12 out of 20	30 out 100	42 of 29,900	1	86	10	76	40	36
Roads	16/11/2022	13 out of 50	10 out 43	30 of 20,200	0	51	6	45	31	14
Total		***120***	***124***	***278***	***7***	***531***	***114***	***422***	***261***	***162****

**Six papers were used across more than one land use, but they have been accounted as different items as the data extraction and evidence appraisal was performed separately for each land use.*

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics across land uses

A total of 530 studies were identified through online searches for peer reviewed and published literature, and only 8 studies were identified manually through expert contact and personal collection, which represented 1.5% of the total evidence (Table 7). Of the 162 studies that were eligible for inclusion in the synthesis of evidence, 46 were based on direct on-ground measurements within the GBR, often at long-term (>5 year) monitoring sites. These papers generally have higher levels of rigour, but the findings are not always applicable across a range of spatial scales and climate conditions. A further 44 studies included measurement data from outside the GBR. Very few of these studies included associated costs and cost-effectiveness of the management practices. A total of 31 papers used modelling as the primary method to evaluate land management changes, however, in many cases, the papers did not clearly articulate if and how data were used to constrain the models, and due to a lack of data on actual land management changes (often relying on assumptions or presumptions) the overall confidence for most modelling studies is lower than for other studies. These modelling studies were the primary vehicle for additional economic analysis of the cost-effectiveness of land management. In general, however, the economic studies undertaken in the GBR are hard to interpret as they often use de-identified data due to privacy concerns and describe non-specific (grouped or lumped) management practice descriptions which make it difficult to determine which practice is working (or not). They are best used to assess the broad range or ranking of likely costs and cost-effectiveness values, and specific values have less reliability due to potential changes in the underlying catchment models. The remaining 41 papers represented review, overview or commentary papers relevant to land management and sediment and particulate nutrient loss. Some of these studies included references from international publications, but where possible, we focused mostly on reviews of Australian studies. The following sections describe the key findings for each of the land uses considered.

a) Grazing

Summary of study characteristics

Table 8 presents a summary of the primary management actions evaluated and the study approaches summarised for the **grazing** land use. Of the 32 papers considered, 15 were based on direct on-ground measurements within the GBR, often at long term (>5 year) monitoring sites. A further four studies included measurement data from outside the GBR. Very few of these studies included associated costs and cost-effectiveness of the management practices. Approximately seven papers used modelling as the primary method to evaluate land management changes. The remaining six papers represented review, overview or commentary papers relevant to grazing land management and sediment and particulate nutrient loss. Of the 32 studies, the majority evaluated changes to stocking rate and pasture utilisation (n=13) or a combination of grazing management strategies (n=10). There were very few studies that directly evaluated strategic rest (n=2), pasture improvement (n=2), or the strategic use of fencing or fire (n=1) on reducing sediment and particulate runoff. The remaining studies were review or secondary type studies (n=4).

Table 8. Summary of the primary grazing management actions evaluated, and the study approach used.

Primary Management action	Measurement	Modelling	Other (e.g., reviews, guidelines etc)	Total
Managing stock and pasture utilisation	8	5	0	13
Ensuring strategic rest of pastures	1	0	0	1
Improving pasture condition	2	0	0	2

Primary Management action	Measurement	Modelling	Other (e.g., reviews, guidelines etc)	Total
Strategic use of fencing (and fire)	1	0	0	1
Planning for droughts	0	0	0	0
Combination of approaches	4	2	5	10
Generic secondary review study	3	0	1	4
Total	**19**	**7**	**6**	**32**

Summary of evidence to 2022

Data measurement studies and grazing management practices

Due to the differences in soil type, climate conditions, timeframe of study and methods applied, it is challenging to directly compare or combine the results from these studies. There are, however, some consistent findings with respect to stocking rates and wet season spelling that were summarised by Moravek et al. (2017a) and built on below:

- Sediment runoff was lower under moderate, sustainable **stocking rates** compared with heavier stocking rates, and management of grazing systems at sustainable stocking rates was generally more profitable than grazing systems operating at heavier stocking rates (Cowie et al., 2007; Hawdon et al., 2008; O'Reagain et al., 2005; 2008; Thornton & Elledge, 2018; 2021; 2022).
- Ground cover levels are closely related to runoff and soil loss with a number of studies showing that runoff and soil loss increase rapidly when the cover drops below 40% (McIvor et al., 1995). However, ground cover levels need to return to ~70% to reduce runoff and sediment loss at sites that have been highly degraded (Bartley et al., 2014b; Sanjari et al., 2009; 2010).
- The Brigalow Catchment Study has shown that clearing brigalow for grazing in the Fitzroy Basin doubled runoff, increased peak runoff rate by 50% and increased TSS loads by 80%. Soil fertility and pasture productivity also declined under grazing compared with brigalow. Overgrazing exacerbated these results, as failure to reduce **stocking rate** with reduced pasture productivity more than tripled runoff, peak runoff rate and TSS load compared with conservatively grazed pasture (Thornton & Elledge, 2022).
- However, at the Wambiana Grazing Trial study site, 10-12 runoff events occurred per treatment over the five-year experimental period where variable **stocking rates** were applied. There were no clear differences between treatments for percentage runoff, sediment loss or water quality, however, in general the heavy stocking strategy does tend to have the lowest cover with the highest median TSS concentrations. The lack of a clear difference was considered to be due to the low rainfall experienced over the trial period as well as the very flat landscape making monitoring runoff challenging.
- **Strategic rest** periods in time-controlled (TC) grazing are seen as the major contributor to soil and pasture recovery after intensive defoliations by grazing animals, leading to an increase in above-ground organic material and thus surface cover over time (Sanjari et al., 2009; 2010;) and deferred grazing is an effective management practice for the rejuvenation of native pastures via increases in native grass densities (Nie & Zollinger, 2012).
- Bare patches were identified as a primary source of erosion and runoff in grazed areas, and there is evidence that improved grazing management practices, in the form of wet season **rest**, are effective in reducing bare ground. However, TSS yields did not decline at the catchment scale due to the disproportionately high yields from hillslopes with persistent low (<10%) cover sites, that did not respond to grazing management, as well as from gullies and streambanks, particularly in high runoff years (Bartley et al., 2010b; 2014b). A combined measurement and modelling study by Jones et al. (2006) assessed the soil loss differences over a 20 year simulation period. The results suggest that soil loss will decline by ~11% (from 3.41 to 3.03

mm/ha) when strategic summer rest is applied, as this leads to an increase in perennial grass composition over time.

- Under long-term **livestock exclusion,** gully sediment yields were 77% lower than those of grazed gullies due to smaller gully extent, and lower erosion rates especially on gully walls (Wilkinson et al., 2018). **Excluding cattle** from previously grazed landscapes can reduce suspended sediment yield by threefold (Hawdon et al., 2008).
- **Sowing perennial grasses and adding lime to soil** can make the existing pastures more sustainable through better use of water and nitrogen, with the liming increasing the number of earthworms. Animal production per hectare was 10–25% higher on pastures with lime. Critical gross margins per dry sheep equivalent (DSE) were lowest ($16/ha) for a long-lived perennial pasture (>15 years), and highest ($20/ha) for a short-lived perennial (5 years). Overall, there were substantial benefits in animal production, improved soil quality and water use from establishing perennial grass pastures with lime on these strongly acid soils (White et al., 2000).
- **Burning of pasture** is commonly practiced in many parts of the world for its perceived ability to improve pasture quality and palatability, reduce woody shrubs, control weeds, and increase nutrient supply (Ghadiri et al., 2011). Pasture burning was found to increase sediment, nutrient and carbon transport. However, 2 m buffers of unburnt pasture were found to remove much of the suspended sediment and decrease enrichment values by 30-50% (Ghadiri et al., 2011).
- It is concluded that recovery of degraded savanna rangelands following reduction in livestock grazing pressure takes decades and is strongly influenced by climate (Ash et al., 2011) and pasture composition (Stokes et al., 2023)**.** Measuring water quality responses to land management change in variable climates requires nested spatial monitoring over long-timescales (Koci et al., 2020).

Costs and cost-effectiveness of practices, variation with climate and production outcomes

Several studies have applied economic modelling to the outputs of the Source Catchments models. Some of these studies included modest links to production outcomes, and no studies explicitly assessed variations with climate. It is often difficult to provide any interpretation of the spatial relevance of the economic data, as most economic studies are required to use de-identified data which only allows interpretation at the subcatchment, rather than property scale. The key outcomes from these studies include:

- A bioeconomic model developed by Star et al. (2010) determined the cost ($/tonne of sediment) incurred by graziers when implementing strategies that increase ground cover and land condition. 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.
- Lower productivity land types were considered to be the cheapest option for sediment reduction, and catchments closer to the coast are more suitable for remediation investment (all other things being equal) (Star et al., 2013). This is because areas close to the coast have higher sediment delivery ratios.
- Star et al. (2017) aggregated land types in the Fitzroy catchment according to land productivity, and gross margins were estimated for enterprises in each group. The study identified that there is a relatively small number of high scoring subcatchments that should be prioritised to achieve the Reef Plan target of a 20% reduction in anthropogenic sediment loads. The key factors driving this result include ground cover, management practice adoption, delivery ratio and cost. The outcomes of the analysis highlight the importance of seeking pollutant reductions where the most effective outcome can be achieved rather than simply targeting an industry or a catchment (Star et al., 2018).

- Another study by Star et al. (2011) suggests that for sediment reduction to be achieved from land regeneration of more fertile land types (e.g., brigalow with blackbutt) the most efficient method of allocating funds would be through extension and education. However, for less productive country (narrow leaved ironbark woodlands) incentives will be required. This is because the low inherent productivity demonstrated through longer regeneration time periods and low gross margins resulted in all scenarios yielding a negative return. This indicates that there is no private incentive for the landholder to undertake land regeneration.
- Land in poor condition may be rehabilitated through grazing land management practices, although this may take years. Land in very poor condition may require mechanical intervention. The cost to rehabilitate land in very poor condition can vary significantly ranging from $14.11/ha to $379.00/ha. Economic outcomes for the rehabilitation of very poor condition (D condition) country vary greatly with land-type and cost of the intervention used (Moravek et al., 2017a).
- Although somewhat out of scope, as it did not present any runoff, sediment or nutrient data specifically, Star et al. (2015) found that although economic modelling indicates that many improved management practices are financially rewarding, landholders remain hesitant to change. Financial returns to landholders can vary substantially across different 20-year periods of a climate cycle, demonstrating that the variability in expected returns may be an important reason why landholders are cautious about changing their management practices. Improved long-term information regarding future climate patterns and their production implications for the particular spatial location of interest will allow better predictions of the private benefits available from changing management practice.
- The results were quite different for a study by Roebeling et al. (2009) and Roebeling and Webster (2007) that considered 15 stocking rates and 11 nitrogen application rates in grazing production in the Tully catchment. All improvements in water quality come at a significant cost to the grazing industry (up to about A$2.5 million per year for a 60% decrease in TSS delivery and up to about A$5.6 million per year for an 80% decrease in DIN delivery), because of limited management practice options for water quality improvement. This is likely due to differences between the wet and dry tropics in terms of land value and (rainfall assisted) recovery potential.

Key conclusions (Grazing)

Based on the published literature, and other recent review documents (e.g., Silburn et al., 2022) the most effective management practices in grazing lands that are demonstrated to reduce fine sediment and particulate nutrient loss include:

- Moderate, sustainable **stocking rates.**
- Ground cover levels maintained above 40% and preferably ~70%.
- Regular periods of **strategic rest** from grazing, which is particularly relevant early in the wet season. Strategic rest should be included in all grazing management systems and be adaptive to climate and pasture conditions.
- Where there are large areas of bare ground, exclude cattle and consider using soil amelioration and sowing perennial pastures to assist recovery.
- If using burning as a management tool, consider having vegetation buffers.

These management practices are fairly generic, however, their effectiveness will vary in different parts of the catchment and under different climatic conditions. The costs and cost-effectiveness of the practices are also highly variable and depend on the site location and type of production system. It is important to also note that cattle prices have increased considerably since many of these studies were published.

Areas of further research

Reports by Moravek et al. (2017b) and Silburn et al. (2022) highlight several high priority areas for future work. These include:

- Continued demonstration of the rehabilitation of land in poor condition using stocking rates and strategic rest to provide biophysical data for economic modelling is needed. Our knowledge of and ability to predict the biophysical outcomes and response times of land condition to grazing management practices is still limited.
- Assessment of the whole-of-business impact of both best management practice (BMP) programs and the specific management practices related to the Paddock to Reef (P2R) water quality framework, including detailed consideration of the impact on business outcomes is needed.
- Continued improvement in parameterising models used within P2R modelling using local data. For example, soil erodibility values currently applied to grazing lands were estimated using an equation derived for cultivated, cropping soils.
- Few studies exist on the economic impact of changing management practices as opposed to operating at different levels of management practice (Moravek et al., 2017a), and even fewer studies exist that have monitored and evaluated the coincident recovery of land condition and water quality. There is not always a “win-win” scenario between reducing sediment and increasing profit, and very few studies have been evaluated at the whole-of-business level (Moravek et al., 2017a). More integrated studies, evaluating land management change, water quality response and the coincident production and economic outcomes are needed. This is useful evidence for landholders, policy and decision-makers.
- Only one of the studies reviewed (Ash et al., 2002) provided economic analysis for changing management practice. The other reviewed studies calculated economic outcomes of operating grazing systems at different stocking rates. Due to this, no inference can be made as to whether changing from one grazing system to another is profitable (Moravek et al., 2017b).
- No studies identified the capital costs of change. Furthermore, no studies gave guidelines on how to implement these practices which might assist in identification of the capital costs of change (Moravek et al., 2017b).
- Only one physical trial exists (O'Reagain & Bushell, 2011) which is able to provide data on animal production differences of alternative grazing management systems to inform economic analysis of wet season spelling or different stocking rate regimes. However, this information is limited to steers and only covers a few land types (Moravek et al., 2017b).
- No study analysed these practices, or the implementation of practices, in a whole-of-business context (Moravek et al., 2017b).
- No studies explicitly linked ground cover to profitability (Moravek et al., 2017b).
- No studies analysed rehabilitation practices, or the implementation of those practices, in a whole-of-business context (Moravek et al., 2017b).
- The review process for this question also highlighted that there are potentially significant un-published datasets within Queensland Government that would provide considerable insights into some of the gaps identified in this study. Support for writing/publishing time would potentially allow these datasets to be written up and published.

b) Sugarcane

Summary of study characteristics

Table 9 presents a summary of the primary management actions evaluated and the study approaches employed for the sugarcane land use. Of the 24 papers considered, 5 were based on direct on-ground measurements within the GBR, using a range of approaches including rainfall simulator and event measurements, although some of the methods used were not very robust (e.g., Brooks, 2008). Very few of these studies included associated costs and cost-effectiveness of the management practices. Approximately five papers used modelling as the primary method to evaluate land management changes. The remaining 14 papers represented review, overview or commentary papers relevant to sugarcane land management and sediment and particulate nutrient loss.

Table 9. Summary of the primary management actions evaluated, and the study approach used.

Primary Management action	Measurement	Modelling	Other (e.g., reviews, guidelines etc)	Total
Timing of plant or ratoon cane	0	0	0	0
Trash blanketing of crop residue retention	1	0	0	1
Bare tracks, headlands or drains	1	0	0	1
Tillage practices and controlled traffic farming	2	1	0	3
Catchment scale change/modelling	1	4	14	19
Total	**5**	**5**	**14**	**24**

Summary of evidence to 2022

Data measurement studies evaluating sugarcane management practices

Due to the differences in soil type, climate conditions, timeframe of study and methods applied, it is challenging to directly compare or combine the results from these studies. There are, however, some consistent findings with respect to agricultural management of sugarcane lands, and these are summarised below:

- A combined monitoring and modelling study in the Johnstone catchment identified that around 50% of the average annual nitrogen loss could be attributed to nitrogen attached to sediment (and organics), or particulate nitrogen (PN) (Hunter & Walton, 1997).
- A study outlined in Visser et al. (2007) and Roth et al. (2004) did not explicitly assess the effectiveness of management actions on erosion, however, it provides an important context or baseline for subsequent studies. In sugarcane areas, water furrows were found to generate the most sediment, however, they were not identified as an important overall source of sediment because of their low hydrological connectivity. Plant cane fields were identified as the most important net sediment source. Drains act as conduits for sediment and can also serve as temporary sinks but were not identified as an important source. Headlands are both significant sinks and also act as a source depending on circumstance (Visser et al., 2007). **In absolute terms, water furrows and plant cane fields by far constitute the most important source of sediment within sugarcane lands, while headlands and minor drains were the main sinks.** These results indicate that significant scope exists to minimise sediment export by targeting appropriate management options at other sugarcane land elements, e.g., the elimination of water furrows in the case of laser-levelling blocks that contain water furrows. Brooks (2008) found that plant cane blocks have much higher sediment runoff compared to ratoon cane based on preliminary turbidity readings, and ratoon blocks, although protected by a trash blanket, still act as a net sediment source. This is because trash does not fully cover all parts of the paddock, if disturbed by ripping or cultivation practices.
- Based on the sediment budget study by Visser et al. (2007), it was estimated by Roth et al. (2004) that even partial adoption of simple measures like the gradual **elimination of water furrows** following laser-levelling provide scope for reducing sediment export by as much as 20%. Repairing eroding drain banks is an equally effective measure in the scenarios tested here (reduction of sediment export by about 16%) but is likely to be far more expensive. Improved drains can lead to a decrease in drain erosion, though they do require an initial capital outlay and an increase in maintenance costs (Roebeling et al., 2004). Moreover, the establishment of spoon shaped drains may lead to a reduction in sugarcane area (Roebeling et al., 2004).
- As outlined in Rayment (2003), historically high annual soil loss rates from row crop sugarcane that ranged between <50- 500 t/ha/y (average loss of 148 t/ha/y) (Prove et al., 1995) have now

been lowered to <5-15 t/ha/y by implementing **soil conservation plans and using green cane trash blanketing** (GCTB) and soil loss rates of 1-4 t/ha/y are possible with GCTB and zero tillage. GCTB is the practice whereby sugarcane is not burnt prior to harvesting, and the green residue is left, unmanaged, on the ground after harvesting.

- Melland et al. (2022) used rainfall simulators to study the impact of **crop residue retention** after harvest (green trash blanketing) on reducing offsite losses of sediment and particulate nutrients. PN, PP and suspended sediment losses in runoff were reduced by crop residue retention. Dissolved inorganic N (DIN) loads (but not concentrations) were also reduced by residue retention. In the same study, DIN and filterable reactive P concentrations in runoff were reduced by subsurface fertiliser placement (Melland et al., 2022).
- In a modelling study by Armour et al. (2009), switching to **green-cane harvesting** reduced sediment export by ~80% and adoption of zero tillage sugarcane was estimated to reduce suspended sediment by 44% with proportional reductions in PN and PP. Restoration of the most degraded 20% of stream sections to 100% vegetation cover decreased bank erosion by 14,000 t (Armour et al., 2009).
- Interestingly Bell et al. (2001) also used simulated rainfall to assess the effects of **trash management, row spacing and soil compaction** on soil hydraulic properties and infiltration in the Bundaberg region. Despite improvements in soil chemical properties, the infiltration capacity under trash blanketing was either similar or only marginally improved relative to that on bare, low carbon soils in burnt sugarcane systems. The lack of improvement can be directly linked to soil compaction and the loss of microporosity, and the high proportion of the ground surface trafficked during harvest under current farming systems. This study suggests that the recovery following improved management of sugarcane may take several years.
- In another rainfall simulator study in the Mackay region, Masters et al. (2008) showed that **controlled traffic farming** (CTF) treatments had significantly less runoff (43%) and lower peak runoff rates (46%) than current practice (CP) treatments. Total sediment loads were also reduced by 44% on CTF treatments compared to CP treatments. The recommended best practice for management of fine sediment in sugarcane lands is no-till green harvested controlled traffic farming (Masters et al., 2008). Controlled traffic involves managing farm machinery (harvesters, haul outs and tractors) so that soil compaction only occurs in the inter-row and permanent (undisturbed) beds are formed to grow the crop on. This involves matching row spacing to machinery wheel widths and confining machinery to the inter-row through use of automatic steering technology in combination with satellite navigation (Roebeling & Webster, 2007).
- Elledge et al. (2016) compared farming using **mound and furrow beds**. TSS loads were lower for mound than furrow beds as a result of differences in cultivation practices. However, TSS loads from both bed formations were relatively high (2.0 t/ha from mound beds and 2.5 t/ha from furrow beds) in comparison to the estimated end-of-catchment load of 0.5 t/ha. Furrow beds with two fill-in processes had higher sediment loads in runoff than mound beds which had no cultivation after planting. However, neither bed configuration overcame the high erosion risk inherent when plant crops have low ground cover. It is recommended that future research should further investigate management practices to reduce sediment loads from plant cane paddocks. This study found that total nitrogen was comprised of 95% total suspended nitrogen; thus, reducing sediment losses would also reduce total nitrogen losses. This may be achieved by implementing practices that overcome low ground cover during the plant cane phase, such as the use of short-term legume crops or mill byproducts.
- A study by Brooks (2008) used rudimentary monitoring to evaluate the effectiveness of seven sediment traps and four sump traps in sugarcane lands. Sediment trapping systems are considered an effective solution in a farm management program to mitigate the effects of paddock cultivation, high rainfall, and slope erosion. The study found that sump traps are ideal for coarse sediment capture but had limited effectiveness on fine sediment (<16 µm) particles (see Question 4.7, Waltham et al., this SCS).

- Carlin et al. (2003) carried out a monitoring study into vetiver grass plantings to assess its effectiveness on reducing stream bank erosion in sugarcane lands. The study was conducted in Pimpama, South East Queensland. Increasing vegetation in the drain and riparian areas would help lower the frequency of drain maintenance and increase sediment trapping during runoff periods. Unfortunately, drought during the study period prevented conclusive results regarding the effectiveness of vetiver planting in the riparian zone of sugarcane drain banks for the improvement of water quality. However, vetiver plantings were found to reduce erosion and act as a biofilter during small runoff events.
- Connolly et al. (2015) identified that riparian zones were not necessarily that useful for reducing particulate N and P as most of the PN and PP was likely coming from agricultural drains. Riparian zones did, however, play an important role in reducing nitrate and nitrite concentrations and loads were significantly lower in streams with greater riparian vegetation which may suggest some removal in this zone.

Costs and cost-effectiveness of practices, variation with climate and production outcomes

Due to the cost and timeframes associated with collecting monitoring data, models are often used to support decision making about remediation investments and provide estimates of likely outcomes (called scenarios) for the relative change in water quality following specific and combined management practice implementation. Several such modelling exercises have been conducted in sugarcane lands and the findings from these studies are summarised below. These models are also used to support economic analysis of the likely costs and cost-effectiveness of various management approaches. It is important to note, however, that very few, if any, of the scenarios presented in these studies have been formally tested and assessed using independent data.

- A study by Bartley et al. (2004b) in Douglas Shire did not explicitly assess sugarcane management options, however, sugarcane **drains** were modelled. It was noted that although the erosion rates in sugarcane lands are now quite low, these floodplain areas would have previously acted as sediment sinks. Due to sugarcane drains and other activities associated with agriculture, they are now a net sediment source.
- Bohnet et al. (2008) modelled six land use change scenarios. These management changes for sugarcane included i) continued sugarcane landscape, ii) agricultural production without sugar cane, iii) sugarcane with established **riparian zones and wetlands**, iv) alternative agriculture with established riparian zones and wetlands, v) enhanced biodiversity with sugarcane, and vi) enhanced biodiversity without sugarcane. Interestingly, the SedNet model predicted either no reduction or a small reduction in sediment loads exported form the Douglas Shire as a result of land use changes proposed in the scenarios. It was suggested that the lack of significant sediment reductions in modelled scenarios indicates the insensitivity of the SedNet model to land use changes in the floodplain part of the landscape.
- A similar study by Roebeling et al. (2006), a spatial environmental-economic study that integrates a land use and value chain model with a hydrological model, indicates possible benefits of land use diversification for both regional income and the resilience of the sugar 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.
- In a sugarcane production modelling study by Roebeling et al. (2009) considerable water quality improvements can be obtained at a negative cost (i.e., at a benefit to the sugarcane industry). 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.
- A modelling study by Star et al. (2018) assessed changes in D to C management and C to B management on fine sediment loss in sugarcane areas [where A and B class pose a lower water quality risk than C and D class management]. The paper found that TSS reduction can range between 62% and 95% depending on the region. Median estimates for the cost of reducing TSS

in sugarcane were reported as ~$44/t in the Wet Tropics and $91/t in the Mackay Whitsunday region.

- A bioeconomic model assessed the cost of implementing the Reef Plan Targets (RPTs) or Ecologically Relevant Targets (ERTs) assigned to either the entire region or within each of five discrete river basins. Key outcomes from the study were that RPTs could be achieved at an annual cost of $3M/year on a whole of region basis. In contrast ERTs could be achieved on a whole of region basis at a net cost of $16M/year. ERTs were not able to be feasibly met on a basin by basin basis (Beverly et al., 2016b). Importantly ERTs cannot be met without substantial costs. This study also demonstrated than an important consideration is the method of allocating available funds. The method of distributing available funds was shown to affect constituent abatement by varying degrees (Beverly et al., 2016a).
- Rolfe et al. (2008) presented a study on the BMPs in sugarcane that are likely to be associated with net production benefits (where it may be easier to encourage adoption)[Noting that it is likely that the BMP's applied in this study have been updated and superseded]. These include **green cane trash blanketing, variety selection, soil health analysis, and nitrogen management**. BMPs likely to be associated with net production costs (where adoption may be more difficult to encourage) are sediment traps, precision farming, controlled traffic and riverbank and streambank stabilisation. BMPs likely to be least acceptable are **double-row harvesting, chemical ripeners and integrated pest management**. These BMPs may require specialised support packages.
- A financial-economic study conducted by van Grieken et al. (2014) found that:
  - There appears to be significant variation in farm gross margins between regions and (to a lesser extent) across farm sizes. This indicates that a single representative farm model is likely to misrepresent the actual financial-economic consequences of changing management.
  - Variation in farm gross margins within regions is relatively modest for the practices evaluated, particularly with the relative economic benefit as a proportion of the average farm gross margin. This tends to highlight the importance of factors such as transaction costs, risk, and other relative (dis-)advantages associated with practice change.
  - The above point also highlights the fact that the direct financial consequences associated with changed practices are potentially difficult to distinguish from other factors impacting on variability in business performance (e.g., price volatility and productivity influences).
  - Economies of scale are evident (between small, medium and large farms, operational efficiencies are higher for larger farms where greater asset utilisation is possible).
  - Changed practices that achieve environmental and economic benefits were identified but trade-offs also exist and may require different policy approaches.
  - For the combinations of practices analysed in this research, a more targeted nutrient management strategy may prove to have the best cost-effectiveness in improving water quality. The extent to which this affects both financial and environmental outcomes varies between regions, soil types, farm sizes and current management systems. The results indicate that moving beyond the existing commercially tested nutrient management strategy is likely to come at a cost to the farmer.
- In a similar study by Rolfe and Windle (2016) modelling results show substantial variation (heterogeneity) in cost estimates, even after allowing for systematic differences in the estimation of both costs and emissions. This is largely due to spatially and thus local climate variability. This confirms that cost-effectiveness should be a key criterion for project prioritisation and funding evaluation. At the Natural Resource Management (NRM)/pollutant level, variations in cost-effectiveness provide some indication about where overall funds can be better invested. At the farm/project level scale, variations mean that there are substantial benefits in prioritising projects within a regional area. The summary estimates at the NRM/pollutant level have been reported at i) end-of-paddock, and ii) end-of-catchment. The latter costs are more expensive, in part because of the transmission losses. Approximate cost-effectiveness thresholds can be set at the average of achieved and predicted costs for end-of-catchment loads, as follows: Sediment: $259/t, Nitrogen (DIN): $150/kg, Pesticide (PSII):

$8,351/kg [Noting that anecdotal feedback was that the cost inputs were not the same across all projects, with some projects including in-kind and others not]. These benchmarks should be treated as average thresholds for allocating project funds, both between and within regions. It is likely that lower cost projects can be achieved through more targeted program design and better assessment of cost-effectiveness. As both modelling and cost information improves, more accurate benchmarks can be established.

- Rolfe et al. (2018) then build on the above study by disaggregating the cost-effectiveness for multiple benefits when a project improves more than one water quality attribute. The paper focused on the economic method, however, the results suggest that much larger reductions in pollutants can be gained by better focusing on cost-effectiveness.
- More recently, Farr et al. (2019) provided a review of current literature pertaining to the cost-effectiveness of land management changes to promote water quality improvement. Their main findings include:
  - Past research indicates that cost and effectiveness estimates vary across different farming systems, soil types, land types, regions and catchments. Studies are often undertaken for different purposes, audiences, and at different timescales within the regions/catchments. As such, inconsistent approaches and reporting of the results mean that the estimates are not always directly comparable. The review has highlighted the importance of timescale, risk and uncertainty, integration with the production system, and links to biophysical models in estimating cost-effectiveness and profitability of land management practice change. Clearly, describing the purpose of the research study and using a consistent and transparent methodological approach is critical for comparative purposes and scientific rigour.
  - Risk and uncertainty are a challenge in the assessment of any future options. It is more likely to be present in the effectiveness and/or the cost of measures. Perceived risk and uncertainty in returns may increase the perceived and real private costs to producers. As such, it would be desirable to apply a range of cost and effectiveness estimates rather than single estimates.
  - Profitability is important and should be included in the evaluation process. The most cost-effective water quality improvement practices may have substantial profitability implications for landholders and may not represent the most profitable option for adoption. Consideration of profitability of management change, in conjunction with social and other key drivers, may also offer insight into landholder adoption rates.

Key conclusions (Sugarcane)

Based on the published literature, the most effective management practices in sugarcane lands that are demonstrated to reduce fine sediment and particulate nutrient loss include:

- In absolute terms, water furrows and plant cane fields by far constitute the most important source of sediment within sugarcane lands. Even partial adoption of simple measures like the gradual elimination of water furrows following laser-levelling provide scope for reducing sediment export by as much as 20%.
- Runoff, soil loss and particulate nutrient losses are reduced with green cane trash blanketing, zero tillage and controlled traffic farming. However, infiltration capacities of soils may take several years to recover following changed management. Mound beds, which had no cultivation after planting, also have better runoff and water quality outcomes.
- Riparian zones in sugarcane lands play an important role in reducing nitrate and nitrite concentrations, however, they were less effective at reducing sediment and particulate nutrients and agricultural drains seem to dominate these sources.
- Repairing eroding drain banks is considered an effective measure for reducing sediment, however, it is more effective for coarse (>63 µm) rather than fine (<63 µm) sediment and is likely to be far more expensive than other options.

- Due to the dominance of slope factors on predicted estimates of sediment and particulate nutrient loss, land use change scenario modelling within relatively flat sugarcane areas predicts modest improvements to TSS, TN and TP following improved management practices.
- Economic modelling studies suggest that a 20% water quality improvement in sediment yields can be obtained at no additional cost to sugarcane farmers. Reductions in water pollution beyond these 20% (TSS) reductions will come at a cost to the sugarcane industry. This finding may have changed more recently with relatively high commodity prices and increasing inflation and associated operational (farm) costs.
- Best management practices that are likely to be associated with net production benefits, and that are likely to have higher adoption levels, include green cane trash blanketing, variety selection, soil health analysis, and nitrogen management. BMPs likely to be associated with net production costs (where adoption may be more difficult to encourage) are sediment traps, precision farming, controlled traffic and riverbank and streambank stabilisation.
- There appears to be significant variation (heterogeneity) in cost estimates and farm gross margins between regions and (to a lesser extent) across farm sizes. This indicates that a single representative farm model is likely to misrepresent the actual financial-economic consequences of changing management.
- At the farm/project scale, spatial heterogeneity means that there are substantial benefits in prioritising projects for remediation investment within a regional area.
- Studies are often undertaken for different purposes, audiences, and at different timescales within the regions/catchments. As such, inconsistent approaches and reporting of the results mean that the estimates are not always directly comparable.
- Perceived risk and uncertainty in financial returns may increase the perceived and real private costs to producers. As such, it would be desirable to apply a range of cost and effectiveness estimates rather than single estimates.

Areas of further research

Unlike the grazing and cropping land uses there are no long-term monitoring sites in the sugarcane landscape. Previously, Sugar Research Australia (SRA) has run longer term trials, however, most recent studies in sugarcane have been conducted using rainfall simulators or Agricultural Production Systems SIMulator (APSIM) modelling. Rainfall simulators are efficient, and provide important input data for modelling, however, this approach does not provide the longer-term assessment of how this land use performs under natural climate conditions which include cyclones, floods and droughts. Long-term farm trials that integrate and evaluate land management change, water quality response and the coincident production and economic outcomes are needed. For further research needs, readers are encouraged to see Section 4.5 – Knowledge gaps.

c) Cropping

Summary of study characteristics

Table 10 presents a summary of the primary management actions evaluated and the study approaches employed for the cropping land use. Of the 40 papers considered for cropping, 25 were based on direct on-ground measurements, using a range of approaches including rainfall simulator and event measurements. Very few of these studies included associated costs and cost-effectiveness of the management practices. Only one paper applied modelling as the primary method to evaluate land management changes (without direct calibration of data). The remaining 14 papers represented review, overview or commentary papers relevant to cropping land management and sediment and particulate nutrient loss.

Table 10. Summary of the primary cropping management actions evaluated, and the study approach used.

Primary Management action	Measurement	Modelling	Other (e.g., reviews, guidelines etc.)	Total
Tillage practices	5	0	0	5
Crop residue (stubble) and burning	2	0	0	2
Crop rotation (or conversion to cropping)	4	0	0	4
Controlled traffic farming	6	0	0	6
Contour banks and mulched rip lines	2	0	0	2
Pasture leys, grass waterways and buffers	4	0	0	4
Combination of above or other	12	1	4	17
Total	**25**	**1**	**14**	**40**

Summary of evidence to 2022

Thomas et al. (2007) outlined how early agricultural practices in Queensland inadvertently led to accelerated soil erosion. During the 1940s, the Queensland Government initiated a soil conservation service that worked with the principles of matching land use with its capability, as well as runoff management using earth structures such as contour banks and grassed waterways. A concerted effort began in the 1960s to develop and adapt farming systems that maximised retention of crop residues to maintain surface cover to complement the earthworks. This led to an increase in the understanding of soil–water–crop interactions that have led to the adoption of no-tillage and conservation farming practices in Queensland. In 2005, the overall area under no-tillage was ~50% of the cropping land in the main grain growing areas of southern and central Queensland but was potentially as high as 85% among some groups of farmers.

Either due to the higher (perceived) commodity prices derived from cropping systems, or the higher erosion rates from bare and fallowed cropping lands, there seemed to be considerably more studies, particularly in the 1990’s and 2000’s, that focused on collecting field data from experimental sites in cropping lands. These studies generally focused on soil attribute data (e.g., soil structure) that influenced crop production, but there were numerous studies that also measured direct runoff or indirect hydrological parameters such as infiltration or soil moisture. These attributes do not necessarily directly represent estimates of sediment and particulate nutrient loss, however, changes in soil hydrology are a good surrogate for estimating the likely water quality benefits from various practices. Runoff is also considerably more difficult to measure than sediment and nutrient concentrations, so it seemed inappropriate to completely ignore this wealth of information. Therefore, many of the papers that deal with changed hydrology in cropping lands are included and briefly summarised below. There are also several global reviews on the general benefits of crop residue management, tillage methods (e.g., Unger et al., 1991), controlled traffic farming (Vermeulen et al., 2010), and several reviews that focus on Australian and Queensland conditions (Silburn et al., 2007a; Tullberg, 2010; Tullberg et al., 2007). Several additional papers were identified as part of the formal review process for this studied (Radford & Thornton, 2011; Silburn et al., 2007b), but they are not summarised below.

Key findings from soil and hydrology data measurement studies that evaluated cropping management practices

This group of studies presents information on changes to **soil and hydrology**. In general, there was no fine sediment and particulate nutrient data presented. The papers were still considered insightful and included in this study.

- Research conducted by Li et al. (1994) found that **controlled traffic farming (CTF)** reduced runoff, improved infiltration capacity and increased crop yield compared with random traffic farming. The optimum practice for reducing runoff was controlled traffic with zero tillage.
- Tullberg et al. (2001) conducted field experiments, using tipping bucket pits at a Gatton experimental farm, on CTF and tillage options. In **controlled traffic** all equipment wheels are restricted to compacted permanent traffic lanes, so that soil in the crop beds and traffic lanes can be managed respectively for optimum cropping and optimum trafficability. Rainfall/runoff hydrographs demonstrate that wheel tracks produced a large and consistent increase in runoff, whereas tillage produced a smaller increase. Mean annual runoff from wheeled plots was 63 mm (44%) greater than controlled traffic plots, whereas runoff from stubble mulch tillage plots was 38 mm (24%) greater than zero tillage plots. Traffic and tillage effects appeared to be cumulative, so the mean annual runoff from wheeled stubble mulch tilled plots, representing conventional cropping practice, was more than 100 mm greater than controlled traffic **zero tilled** plots, representing best practice. This reduced runoff (and increased infiltration) was reflected in an increased crop yield of 16% compared with wheeled stubble mulch.
- Connolly et al. (1997) used a rainfall simulator to measure the hydraulic conductivity of surface seals and infiltration of **bare, tilled soil** in the field. Hydraulic conductivity of surface seals decreased exponentially in all soil groups with the period of cultivation; half of the decline occurred within 2-6 years of first cultivation. Low soil hydraulic conductivity increases runoff. Connolly et al. (1998) then estimated that the period required to return hydraulic conductivity to pre-cultivated levels using ungrazed **pasture leys** ranged from 5 to 40 years, depending on soil type and layer. This is about 2-3 times the period of cultivation that caused the degradation. Similarly, Thomas et al. (2008) used a rainfall simulator to measure infiltration on three surface **cover levels** on crop*s* from 0% to 100%. Infiltration increased with cover and short-term pasture leys did not appear to improve infiltration characteristics of the soil under the conditions of this study, likely due to the relatively short period since the change in management (<2 years).
- Li et al. (2004) and (2007) then continued and extended the sites set up by Tullberg et al. (2001) and further evaluated **traffic and tillage effects** on runoff and crop production under natural rainfall over a period of 6 years on a heavy clay vertosol in Queensland, Australia. Mean annual runoff from controlled traffic plots was 81 mm (36.3%) smaller than that from wheeled plots, while runoff from zero tillage was reduced by 31 mm (15.7%), regardless of traffic. Rainfall/runoff hydrographs show that wheeling produced a large and consistent increase in runoff, whereas tillage produced a smaller increase. Plant available water capacity (PAWC) and mean grain yields increased in controlled traffic plots, compared with wheeled plots.
- Li et al. (2008a) and (2008b) then used the data collected in the above studies to calibrate the PERFECT soil-crop model to model crop, soil and water conditions under different **tillage and traffic systems**. Ranking of management systems in order of decreasing merit for runoff, available soil water and crop yield was 1) controlled traffic zero tillage, 2) controlled traffic stubble mulch, 3) wheeled zero tillage, and 4) wheeled stubble mulch. The effect of traffic is greater than the effect of tillage over the long-term. The best traffic, tillage and crop management system was controlled traffic zero tillage in a high crop intensity rotation, and the worst was conventional traffic and stubble mulch with continuous wheat.
- In a study by Sallaway et al. (1990), data were collected from contour catchments varying from 8 to 16 ha under **different tillage and crop treatments**, over a 4-year period. As expected, the main factor affecting runoff volume was total rainfall, while peak runoff rate was mainly determined by rainfall intensity. The other variables had smaller, interactive effects. The major effects of the management practices were soil water deficit on total runoff and surface cover on peak runoff rate. Maintenance of surface cover by reduced or zero-tillage practices is the most stable and dependable approach during fallow, and early establishment of a growing crop will further decrease both runoff and runoff rate. Benefits from increasing surface roughness by cultivation are generally cancelled by the associated reduction in surface cover.
- Silburn et al. (2007a) evaluated the use of **permanent pasture** or **pasture-ley systems** to help improve the physical and chemical degradation of soils associated with cropping. Pasture

systems are inherently more efficient in using rainfall (they result in less runoff and deep drainage) than cropping, but the economics are dependent on relative prices of commodities and climatic conditions at a given time. When cropping is reintroduced, the benefits of **pasture-ley systems** are best retained by using minimum tillage, stubble retention and controlled traffic, and by optimising fertility and crop productivity.

- In a study by Zhang et al. (2007), a rainfall simulator was used to assess soil structure and runoff and soil loss in two **tillage/stubble management** systems: direct drilled/stubble retained (DD/SR) and conventional tillage/stubble burnt (CC/SB). Under simulated rainfall (100 mm/h) and the removal of surface stubble, both runoff and soil loss were significantly higher under CC/SB compared to DD/SR. The infiltration rate at the end of the experiment under DD/SR was 3.7 times that of CC/SB and sediment loss was 0.04 t/ha for DD/SR in comparison to 1.97 for CC/SB. After 24 years of different stubble and tillage management, significant differences in topsoil structure were observed. As a result, the infiltration rate of simulated rain was significantly greater for DD/SR than CC/SB, which translated to less soil erosion hazard. It was concluded that 24 years of direct drilling and stubble retained practices significantly reduced runoff and soil erosion hazards, due to a fundamental change in soil structure, via higher soil aggregate stability and higher macroporosity of the surface soil.
- The general recommendation in Queensland is that **contour banks** should be present on cropping land with a slope of 1% or greater (Carey et al., 2015), and recently Humphreys (2022) estimated the proportion of cropping land in the Fitzroy Basin that occurs on land with a slope of greater than 1% and proportion of this land where contour banks currently exist. The report does not assess the effectiveness of management practices explicitly but could be used to target potential extension efforts.
- Dalton et al. (1996) conducted trials to assess the effectiveness of vetiver grass on controlling runoff from crop-lands. Only runoff was measured, however, the study suggested that **vetiver grass hedges** may be feasible at land slopes between 0.5 and 2%.

Key findings from runoff, sediment and particulate nutrient data measurement studies that evaluated cropping management practices – including costs and cost-effectiveness of practices, variation with climate and production outcomes (where available)

This group of studies includes information on fine sediment and particulate nutrient data as part of the evaluation of management effectiveness. Information on costs and cost effectiveness of these changes was included when available.

- The Brigalow Catchment study, which is Australia's longest running paired catchment study, evaluated the impact of converting Brigalow to cropping. Several studies have highlighted the general changes to runoff, sediment and nutrient loads following cropping conversion. Cowie et al. (2007) found that clearing brigalow and **converting it to cropping** resulted in a doubling of runoff, a reduction in wheat yield by more than 60% over 20 years, and the leaching of 60% of the root-zone (0–1.5 m) chloride after clearing. More recently Elledge and Thornton (2017) quantified that over a 25-year period the mean annual effect observed as a result of **land use change** from natural Brigalow woodland to cropping systems was a 449 kg/ha/yr increase in TSS and cropping exported nitrogen at a rate of 1.04 kg/ha/yr more than natural Brigalow woodland. However, both pasture and crops increased loads of sediment and phosphorus. Overall crops posed a greater risk to downstream water quality than pasture. Additionally, Thornton and Shrestha (2021) outlined that initial **clearing and burning of Brigalow** scrub resulted in a temporary increase of mineral nitrogen, total and available phosphorus, total and exchangeable potassium and total sulfur in the surface soil (0-0.1 m) as a result of soil heating and the ash bed effect. Soil fertility then declined significantly over the subsequent 32 years. In terms of production outcomes, high productivity of early pasture and crops is attributed to the flush of available nutrients mineralised by fire and the lack of vegetation during the land development phase. Radford et al. (2007) present data showing the productivity of both the cropping and grazing enterprises has declined since establishment of the new land uses. Declines in grain quantity and quality are attributed largely to poor soil N fertility.

- A study by Carroll et al. (1997) evaluated runoff and soil loss on various crop type (sorghum, sunflower and wheat) and management practices (**zero, reduced and conventional tillage practices**) on a vertisol. They found that runoff and soil loss was significantly lower for wheat than sorghum and sunflowers. Zero and reduced tillage management strategies retained more crop stubble and subsequently had significantly lower soil loss than conventional tillage. Zero tillage wheat had the lowest annual runoff and soil loss, while conventionally tilled sunflowers had the highest. Zero tillage combined with opportunity cropping (planting additional crops when the conditions, such as soil moisture, are favourable) to maintain a minimum groundcover that prevents episodic erosion events was identified as the best management practice to reduce runoff and soil loss.
- A study by Carroll et al. (1999) applied experimental data collected at the small plot, furrow, and farm bay scales in irrigated cotton to the GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) model. Several management options were then simulated (**conventional, stubble, cover in tail drains, drip irrigation and stubble + drip irrigation**). Sediment transport from the typical bay with conventional management (i.e., bare, flood irrigated) was substantially more than with the other treatments. Stubble retained and/or drip irrigation were the most favourable treatments for reducing sediment transport at the field scale. Cover reduced sediment transport even in large events, so retaining stubble and using drip irrigation was the most effective management treatment at the bay scale. The combination of stubble retained and drip irrigation strategies almost eliminated sediment transport. The addition of **sediment trap and storage** to conventional management reduced off farm sediment transport by 45%. This was reduced further when improved field management was applied in combination with a sediment trap.
- A study by Melland et al. (2016) and Dang et al. (2018) using rainfall simulation, explored the effects of introducing **strategic tillage (ST) to no-tillage (NT)** farming systems to combat associated management constraints, primarily weed management. Results showed that introduction of ST reduced weed populations and improved crop productivity and profitability in the first year after tillage, however, ST posed higher risks of runoff and associated loss of nutrients and sediment during intense rainfall. On the Sodosol and Dermosol there was 30% and 70% more runoff, respectively, from ST plots than from NT plots, however, volumes were similar between tillage treatments on the Vertosol. Erosion was highest after ST on the Sodosol (8.3 t/ha suspended sediment) and there were no treatment differences on the other soils. Total nitrogen (N) loads in runoff followed a similar pattern, with 10.2 kg/ha in runoff from the ST treatment on the Sodosol. Total phosphorus loads were higher after ST than NT on both the Sodosol (3.1 and 0.9 kg/ha, respectively) and the Dermosol (1.0 and 0.3 kg/ha, respectively). Dissolved nutrient forms comprised less than 13% of total losses. The trade-offs between weed control, erosion and greenhouse gas emissions should be considered as part of any tillage strategy. The impact of ST on runoff and nutrient loads was largely attributed to removal of ground cover by tillage and an increased vulnerability to erosion. An increased risk of runoff, erosion and nutrient loss from Sodosols and Dermosols after ST for weed control in cropping systems typical of the north-eastern growing region are trade-offs that need consideration in ST decisions. "Results showed that introduction of ST reduced weed populations and improved crop productivity and profitability in the first year after tillage, with no impact in subsequent 4 years." (Dang et al., 2018).
- In a 9-year study by Murphy et al. (2013) sediment movement in runoff from dryland grain cropping was measured at the outlet of 2 contour bays where the distance between **contour banks**, referred to as the slope length, was standard (single) (180 m) and triple (450 m) the recommended space. All contour bays were farmed under a zero tilled–controlled traffic farming system. The sediment concentrations (and loads) were higher at the triple spaced site (3.9 mg/L) compared to the single space site (2.6 mg/L). Average annual runoff and sediment yield at the standard slope length was 75 mm and 1.2 t/ha respectively. This was greater than losses from grazing land use (0.1 t/ha/yr) observed during the study, but less than losses from conventional tillage practices (4 t/ha/yr) previously reported from a long-term study in the

region. Total nitrogen concentrations (median 8.3 mg/L) in runoff from the sorghum crop were higher than those reported for other agricultural land uses at similar scales.

- A study by Rohde et al. (1998) assessed soil structural degradation, runoff and soil erosion, and pesticide movement from cotton farms. In the dryland project, downslope **CTF** (1% slope, 550m long) was tested to control runoff and erosion, to increase fallow water storage, and to reduce environmental impacts. Wheat in irrigated cotton systems reduced erosion by 70%. The dryland experiment was constrained by drought, but the bed and furrow CTF system controlled erosion to <7 t/ha/yr by maintaining high ground cover and reducing off-farm transport. Production benefits were good, with a threefold reduction in early season insecticide sprays, while maintaining yield.
- In a study by Silburn and Glanville (2002) improved practices to minimise soil erosion and related agrochemical transport from cotton fields were assessed. Runoff and sediment movement were measured using a rainfall simulator to apply rain to cotton hill–furrow systems with a range of on-ground covers (0–60%), each with and without prior **wheel traffic**. Increasing cover resulted in an increase in the rain required to initiate runoff. Runoff, soil loss, and sediment concentration decreased with increasing cover. Runoff and soil loss were reduced by an order of magnitude with about 50% cover. No traffic gave less runoff and soil loss than trafficked plots but was less effective than cover. Cover and no traffic combined gave least runoff and soil loss.
- Silburn and Hunter (2009) measured the transport of nitrogen (N) and phosphorus (P) in runoff using a rainfall simulator on a cotton hill–furrow system with a range of **on-ground cover** (0–60%), each with and without prior **wheel traffic** in the furrow. The majority of nutrients were transported with sediment, for P for all treatments, and for N from low cover plots. Retaining surface cover and avoiding wheel traffic were both effective in reducing runoff losses of total N and P, especially when used together. Retaining cover gave considerably lower concentrations of total P, and of N and P associated with sediment. To improve water quality, for both sorbed and dissolved forms, the combination of retaining cover and avoiding wheel traffic and subsoil compaction is needed. Similarly, land uses involving high nutrient inputs should be avoided on soils with shallow subsurface restrictions to infiltration, which are thus prone to interflow.
- The study by Thiagalingam et al. (1996) reviewed the results from five short-term (4-8 year) experimental sites in northern Australia. The results suggest that soil moisture and soil temperature were more favourable, and soil movement and soil loss were lower under **no-tillage than under conventional tillage**. Thus, the successful adaptation of no-tillage technology to the commercial production of grain or fodder crops in more intensive mixed farming systems in the semi-arid tropics will hinge on the successful management of pasture and crop residues for mulch, as well as the consistent control of weeds and other pest organisms.
- A study by Yuan et al. (2009) reviewed the effectiveness of buffer strips on sediment trapping capacities in cropping lands. They found that many factors influence sediment trapping efficiency, and the width of a **buffer** is important for filtering agricultural runoff. Wider buffers tended to trap more sediment, and buffers of 4-6 m can generally reduce sediment loading by more than 50%. Sediment trapping efficiency is also affected by slope, but the overall relationship is not consistent among studies. Overall, sediment trapping efficiency did not vary by vegetation type and grass buffers and forest buffers have roughly the same sediment trapping efficiency.
- Freebairn (2004) and Freebairn et al. (1993; 2006; 2009) summarised various studies assessing the differences in soil, runoff and erosion using various cropping management practices. These papers highlight that slope steepness is by far the most important factor determining the inherent erodibility of a paddock, and runoff and suspended sediment losses were considerably lower under pasture than cropping. **Tillage** experiments 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 cropping in

eastern Australia is characterised by high variability and extremes in rainfall and temperature. The data presented generally indicates that production is increased for low tillage crops where stubble is retained. It was also noted that in the future, climate responsive farming systems will have more variable production resembling the cycles of the natural ecosystems they have replaced. In the long term, however, they will be more sustainable both ecologically and economically, provided nutrient inputs match outputs and soil conserving tillage is used.

Interestingly, considerably fewer modelling papers have been conducted in cropping areas than for grazing and sugarcane.

- Littleboy et al. (1992) calibrated and applied the PERFECT soil crop model, using field measurements, then simulated the effect of erosion on productivity for vertisols in selected cropping areas of north-east Australia. An increase in slope resulted in higher rates of erosion and yield decline. **Stubble retention** in **zero-tillage** and **stubble mulched** management practices increases stubble cover during the fallow. Management strategies incorporating these practices resulted in less erosion and lower rates of yield decline. On the other hand, low cover levels, if stubble is burnt after harvest, were shown to greatly increase erosion and decrease productivity.
- Owens et al. (2017) used the paddock scale model (HowLeaky) with the Source Catchments model to assess the effectiveness of improved management practices for reducing off farm losses of sediment, nutrients and pesticides in dryland grain cropping. Although HowLeaky has been extensively validated using measured field data for current conditions, when using models in a predictive mode, it is more useful to consider the order of magnitude of loads and relative differences between management scenarios than absolute numbers. Based on the modelling, the greatest overall reductions in soil erosion can be made by coupling **reduced or zero-tillage** practices with well-designed **CTF** systems. Soil erosion is greater in fallows after chickpea, mungbean and sunflower crops than after sorghum and wheat crops. This is due to the small amounts and more rapid decomposition of stubble after chickpea, mungbean and sunflower crops than after sorghum and wheat crops, leaving less cover to protect the soil surface. Tillage and traffic systems had a secondary level of effect.
- An additional review by Vermeulen et al. (2010) found a productivity improvement of between 5 and 37% as a result of CTF.

Costs and cost-effectiveness of practices, variation with climate and production outcomes

Information regarding production outcomes and costs were integrated into the above text.

Key conclusions (Cropping)

In general, per unit area, cropping lands have higher runoff, erosion and delivery of sediment, and particulate nutrients, than pasture. Based on the synthesis of 40 papers, the most effective management practices in cropping lands that are demonstrated to reduce fine sediment and particulate nutrient loss include:

- Slope steepness is by far the most important factor determining the inherent erodibility of a cropping area, and appropriate contour banks and conservation structures should be implemented on cropping lands >1% slope.
- Although results from experiments can be highly variable, primarily due to seasonal climate conditions, overwhelmingly, published research has shown that management strategies involving retention of crop residues (stubble), reduced tillage and crop rotation can reduce erosion and improve yield. Runoff and soil loss are reduced by an order of magnitude with ~50% ground cover, and retaining cover considerably reduces concentrations of particulate nitrogen and phosphorus.
- Traffic and tillage effects also appear to be cumulative, therefore controlled traffic zero tillage in a high crop intensity rotation is considered cropping best practice and has benefits for water quality as well as improved crop yield (production) outcomes.

- The benefits of using other management options, such as pasture-ley systems, work best when implemented at sites using cropping best practice. Similarly, the effectiveness of irrigation drain sediment traps are improved when combined with cropping best practice. Strategic tillage (ST) is often applied to support weed control in cropping systems, however, while this may reduce pesticide use; runoff, erosion, and particulate nutrient loss are increased.
- Grass and tree buffers have been shown to reduce runoff, sediment, and nutrient losses in cropping lands, with wider buffers trapping more sediment, and buffers of 4-6 m can generally reduce sediment loading by more than 50%.
- The benefits of cropping best practice such as controlled traffic and zero tillage have been demonstrated repeatedly, including improved economic viability, across different soils and mechanisation systems. Adoption of new practices appears to have been related to practical and economic considerations and proved to be more profitable after a considerable period of research and development. However, there are still challenges. Some of the changes (e.g., crop row width and controlled traffic farming) are simple in principle, but complex in practice, and will only occur with the active engagement of the farm machinery industry. There is also the issue that adoption of one practice, for example, zero tillage, may increase weeds and thus greater use of herbicides, which may also degrade downstream marine systems. Finally, the time lags associated with improved practice can be several decades (Radford & Thornton, 2011).

Areas of further research

Given the considerable amount of research that has occurred in cropping systems relative to other land uses, there are no urgent and specific additional areas of research identified as part of this review, however, information on the cost-effectiveness of various practices is required.

d) Bananas and Horticulture

Summary of study characteristics

Table 11 presents a summary of the primary management actions evaluated and the study approaches employed for bananas and horticulture. Of the 16 papers considered, 7 were based on direct on-ground measurements, with 6 of these papers from the GBR region. There were three papers that applied modelling as the primary method to evaluate land management changes (without direct calibration of data). The remaining six papers represented review, overview, or commentary papers that covered issues such as Best Management Practices (BMPs). Very few of these studies included associated costs and cost-effectiveness of the management practices.

Table 11. Summary of the primary management actions evaluated, and the study approach used for bananas and horticulture.

	Primary Management action	Measurement	Modelling	Other (e.g., reviews, guidelines etc)	Total
1	Sources, baseline studies or guidelines	4	0		4
2	Zone tillage	0	1		1
3	Control Traffic Farming and inter-row ground cover	3	0		3
4	Vegetation buffers	3	0		3
5	Social science, grower perceptions of BMPs	2	0		2
6	Economic studies	1	2		3
	Total	**7**	**3**	**6**	16

Summary of evidence to 2022

Sources, baseline studies or guidelines

- King (2021) provided an overview of environmental BMP Guidelines for the banana industry. The guidelines provide options for management of land and soil, biosecurity, water, biodiversity, pesticides, fertiliser use etc. The guide is accompanied by a self-assessment checklist that lists and ranks management practices in terms of industry environmental standards. This assessment includes management practices for the reduction of sediment and nutrient loss, however, conclusions are often not clearly attributable to experimentation or published data both in the checklist and throughout the guideline document.
- Roebeling and Webster (2007) also provide an overview of BMPs for use in horticulture. The BMPs cover drain and road design, fallow, trash and inter-row management, nutrient and soil management, best management and chemical and waste management. The report does not provide explicit evaluations of sediment and particulate nutrient changes following the implementation of the proposed BMPs.
- A study by Stork and Lyons (2012) measured P loads in overland flow from a coastal macadamia plantation under commercial production. This production system was chosen for several reasons. First, such farms use a raised-bed system of production, and second, farms are often on sloping landscapes that are bordered by coastal streams and rivers within 50 km of the coast. Calculated annual losses of total P were 0.32 kg/ha/yr, comprising dissolved inorganic P (DIP, 0.28 kg/ha/yr), particulate P (0.03 kg/ha/yr), and dissolved organic P (0.01 kg/ha/yr). Particulate P loss was calculated as 0.03 kg/ha/yr with DIP accounting for 88% of annual P loss. This paper only presents results collected from a single farm over a 13-month period and the effectiveness of management practices to reduce sediment and nutrient loss were not explored. Concentrations of DIP in runoff were 20–200-fold higher than those found in other coastal catchments in Queensland.

Reduced (Zonal) Tillage

- A study by Armour et al. (2009) applied a long-term, annual-average catchment biophysical model (SedNet/ANNEX) to calculate sediment, N and P loads in the Tully–Murray catchment of north-eastern Australia following the implementation of **zonal tillage** on banana plantations. Zonal tillage is when only the row area is cultivated in preparation for planting and the inter-row area remains undisturbed. The model scenarios estimated that loss of N and P as a result of tillage decreased by 30%. The reduced cultivation as a result of zonal tillage was predicted by the model to reduce suspended sediment from the industry by 65% from 5,700 t/y to 2,000 t/y.

Control Traffic Farming (CTF) and inter-row ground cover

- A study by McPhee et al. (2013) explores the application of controlled traffic farming in areas of complex topography on a vegetable farm in Tasmania. They found that farm layout can dictate success or failure in the adoption of CTF, with the risk of concentrated runoff and consequent erosion in wheel tracks. However, the paper does not assess the effectiveness of this management practice for reducing sediment or nutrient loss.
- Nachimuthu et al. (2013; 2016) carried out a study over a single growing season near Bundaberg. Two vegetable crops (capsicum and zucchini) were grown under four different management practices: i) Conventional – tillage with residual herbicide, ii) Improved—improved practice with plastic mulch, inter-row vegetative mulch, zonal tillage and reduced fertiliser rates, iii) Trash mulch—improved practice with sugarcane-trash or forage-sorghum mulch with reduced fertiliser rates, minimum or zero tillage, and iv) Vegetable only—improved practice with Rhodes grass or forage-sorghum mulch, minimum or zero tillage, reduced fertiliser rates. Results suggest improved and trash mulch systems reduced sediment and nutrient loads by at least 50% compared to conventional systems. The improvement in runoff water quality was accompanied by yield reductions of up to 55% in capsicum and 57% in zucchini under trash mulch systems, suggesting a commercially unacceptable trade-off between water quality and productivity for a practice change. The study has shown that variations around improved

practice (modified nutrient application strategies under plastic mulch, but with an inter-space mulch to minimise runoff and sediment loss) may be the most practical solution to improve water quality and maintain productivity. However, more work is required to optimise this approach and thus reduce the size of any potential productivity and profitability gap that would necessitate an expensive policy intervention to implement.

- A study by Rasiah et al. (2009) explored the effectiveness of inter-row grass cover as an improved management practice in bananas. They found that inter-row grass covers were effective at reducing compaction and improving infiltration caused by wheel traffic stress, however, the study did not directly measure the influence of management practices on sediment and nutrient loss.

Vegetation buffers

- Several published papers by McKergow et al. (2004a; 2004b) that were funded by Land and Water Australia's National Riparian Lands Program, investigated the effectiveness of grass and tree buffer strips in reducing TN, TP and TSS. The study was conducted in the North Johnstone River Catchment, Queensland. Experimental runoff was monitored using San Dimas Flumes to quantify volumes and water quality measures of runoff both entering and leaving riparian buffers. Monitoring was carried out at two banana plantations on both planar and convergent slopes over four wet seasons at four sites with different slopes and buffer widths, and TN, TP and TSS were measured. The grass buffer was able to trap >80% of incoming bedload and between 30 and 50% of the suspended sediment and nutrient loads. An adjacent rainforest buffer acted as a temporary store of bedload, and a source area for suspended material. These studies demonstrate the benefits of grass buffers, particularly on sloping tropical cropped land and identify limitations on the effectiveness of tree buffers, although these may have ecological benefits.

Social science, grower perceptions BMPs

This review identified two studies that have evaluated grower perceptions regarding the application of various best management practices in banana farming and identified high priority practices for the industry (Bagshaw & Lindsay, 2009; Cook et al., 2018). Although neither study presented explicit sediment and particulate nutrient data, a key lesson identified was the need to develop practical, farm scale economic tools to clarify and demonstrate the financial impact of alternative management practices. Demonstrating continued profitability is critical to encourage widespread industry adoption of environmentally sustainable practices.

Costs and cost-effectiveness of practices, variation with climate and production outcomes

There were three studies that applied economic analysis to evaluate the cost-effectiveness of various best management practices in the banana and horticulture sectors.

- Roebeling et al. (2007) applied the LUCTOR crop growth model to generate input-output data for different management practices (MPs) in horticulture (banana) production in the Tully-Murray Catchment. They then used SedNet and ANNEX to model the water quality response of these practices. The modelling indicated that maintaining cover on inter-rows leads to a 60% decrease in fine suspended sediment delivery, however, these results may not be transferable to other systems. The paper identified that the opportunity for cost-effective water quality improvement is largest in sugarcane and horticulture production while opportunities for cost-effective water quality improvement in grazing and forestry are comparatively limited. While inter-row management resulted in reduced TSS loss, a small reduction in profitability was identified.
- A study by Rolfe and Windle (2011) used assessments of successful water quality tenders to reveal opportunity costs of changing agricultural practice to improve water quality inputs to the GBR. Four water quality tenders in the GBR catchments were performed separately: Mackay (sugarcane), Lower Burdekin (sugarcane and grazing), Mary River (dairy) and Kolan River (horticulture). While the study did not assess specific practices, it found that there was high

variability in opportunity costs between agricultural producers, industries, catchments and pollutants. The study indicates that the most cost-effective improvements are associated with the horticulture and dairy sectors (for nitrogen and phosphorus). Opportunity costs for water quality improvements in the sugarcane and grazing industry were determined to be higher.
- A study by Harvey et al. (2016) provided a review of economic studies involving management practices for banana farms. Case studies were conducted for three growers who had made BMP changes in the Innisfail and Tully regions. A Department of Agriculture and Fisheries (DAF) economist visited the farms of the growers and with their assistance developed a detailed whole-farm economic analysis of their banana growing enterprise. The analyses indicated that after BMP changes were made, the case study growers experienced economic benefits, through cost savings on farm. Water quality benefits were also predicted using the HowLeaky model, although the improved water quality effect following the application of the BMP's (broadcast, banded, fertigation) could not be easily represented in the model due to a lack of measured data on the likely water quality improvements. The variance in responses between growers (and case study results) and the additional reasons influencing growers' adoption decisions highlight the uniqueness and complexity of farming systems. This suggests that a "one-size-fits-all" policy or extension approaches that fail to recognise differences between farms and grower circumstances will be of limited effectiveness.

Key conclusions (Bananas and Horticulture)

The key messages to take away from the bananas and horticulture literature identified as part of this review include:

- Bananas and horticulture generally deliver high amounts of TSS, TN and TP relative to other land uses (see Bartley et al., 2012).
- Several environmental best management practice (BMP) guidelines are available for these industries, however, they are not necessarily backed by specific runoff and water quality data, but instead the concepts seem to be borrowed from studies in cropping and sugarcane research.
- It seems that increased demonstration of continued profitability as a result of environmental BMP is critical to encouraging widespread industry adoption of environmentally sustainable practices.
- Several studies suggested that improvements in runoff water quality in horticulture and bananas, using approaches such as trash mulch systems and inter-row management, was accompanied by yield reductions of up to 60%. This indicates that there may be commercially unacceptable trade-offs between water quality and productivity in some cases, and there is likely room for further innovation to ensure that these land uses can be maintained in catchments draining to sensitive marine environments.
- Vegetation buffers are useful for trapping sediment and particulate nutrients, with >80% of incoming bedload and between 30 and 50% of the suspended sediment and nutrient loads being trapped by grass buffer strips. Often this trapping function is temporary, however, and where possible, reductions should be focused on the source.
- Overall, a "one-size-fits-all" policy or extension approach that fails to recognise differences between farms and grower circumstances will be of limited effectiveness.

Areas of further research

There is considerable opportunity in the banana and horticulture land uses for further research including long-term farm trials that integrate and evaluate land management change, water quality response, and coincident production and economic outcomes. Such studies are important for demonstrating to farmers the benefits of improved practices. It would also be useful to demonstrate this at both the farm and regional, scales. This would help demonstrate changes not only to water quality but also communities and livelihoods. These studies do, however, need to be balanced by the fact that these industries represent <0.1% of the catchment area of the GBR, although arguably they contribute higher per unit area sediment and particulate nutrient yields than most other land uses (Bartley et al., 2017).

e) Urban

Summary of study characteristics

Table 12 presents a summary of the primary management actions evaluated and the study approaches employed for the urban land use. Of the 36 papers considered, 24 were based on direct on-ground measurements from a range of urban environments across Australia. **There were no urban management evaluation studies for sediment or particulate nutrients in the GBR region**. These monitoring-based papers generally have higher levels of confidence, but the findings are not necessarily applicable to the urban areas in the humid wet tropics (Cairns and Mackay) and semi-arid tropical regions (Townsville). Very few of these studies included associated costs and cost-effectiveness of the management practices. Approximately seven papers applied modelling as the primary method to evaluate urban management effectiveness (without direct calibration of data). The remaining five papers represented review, overview or commentary papers relevant to urban environments and sediment and particulate nutrient management.

Table 12. Summary of the primary management actions evaluated, and the study approach used for the urban land use.

	Primary Management action	Measurement	Modelling	Other (e.g., reviews, guidelines etc.)	Total
1	Other – baseline studies	0	0	3	3
2	Early-stage construction and sediment management	1	0	0	1
3	Vegetation management + filter strips	0	1	0	1
4	Retention/detention ponds and urban wetlands	13	0	0	12
5	Biofiltration systems	4	1	0	5
6	Reviews of a combination of above	6	0	0	6
7	Other – modelling studies or bespoke solutions/testing (e.g., green walls)	0	5	2	7
	Total	24	7	5	36

Summary of evidence to 2022

There has been considerable work undertaken in Australia on the effectiveness and benefits of various urban water quantity and quality management systems. This work has occurred primarily as part of the CRC for Water Sensitive Cities (https://watersensitivecities.org.au/) and its precursors. As part of this work, there is a wealth of industry knowledge, reports and cost-benefit analysis that is available, but a lot of this information is not peer reviewed research, is site specific and has a very strong southern Australia (temperate) focus. It also often focuses only on Total N and P. However, those interested in Urban environments and their water management are encouraged to visit and https://ewater.org.au/archive/crcch/current_research/programs/urban.html and https://watersensitivecities.org.au.

Studies identifying the key sources of fine sediment and PN in urban areas

There were ~3 papers that did not evaluate the effectiveness specifically but were baseline studies showing the dominant sources with urban areas.

- A baseline study by Goonetilleke et al. (2005) collected water quality data around the Gold Coast using automatic monitoring stations established at the outlet of each area. TSS, TN and TP were measured without hydrological data, and they did not evaluate management actions specifically. However, due to the high variability in concentrations between sites, they highlighted that the effectiveness of structural measures would not be universal, with a significant proportion of nitrogen being in dissolved form.
- Gunaratne et al. (2017) presented a baseline study in the coastal catchment of Roebuck Bay near Broome, north-western Australia, and did not look explicitly at treatment options. The contribution of nutrient export from urban areas was larger from the older Broome town site sub-catchments compared to subcatchments that have been progressively urbanised since 2000. A distinctive seasonal first flush phenomenon, with an initial 30% of runoff volume containing 40–70% of the nutrient load was a key feature. This indicates there are opportunities for storm-water management to minimise impacts through adopting water-sensitive urban design principles.
- Hatt et al. (2004) presented a baseline study that focused on the identification of the elements of urbanisation that contribute most to pollutant concentrations and loads. Drainage hydrological connection (the proportion of impervious area directly connected to streams by pipes or lined drains) is proposed as a variable explaining variance in the generally weak relationships between pollutant concentrations and imperviousness. Fifteen small streams draining independent sub-basins east of Melbourne, Australia, were sampled for a suite of water quality variables. Hierarchical partitioning showed that dissolved organic carbon (DOC), electrical conductivity (EC), filterable reactive phosphorus (FRP), and storm event TP were independently correlated with drainage hydrological connection more strongly than could be explained by chance. Neither pH nor TSS concentrations were strongly correlated with any basin variable. Oxidised and total nitrogen concentrations were most strongly explained by septic tank density. Loads of all variables were strongly correlated with imperviousness and hydrological connection. Priority should be given to low-impact urban design, which primarily involves reducing drainage hydrological connection, to minimise urbanisation-related pollutant impacts on streams.

Early-stage construction and sediment management

- There was only one paper that evaluated early stage construction and sediment management (Rowlands, 2019). This study, from South East Queensland (SEQ), found that the construction phase sediment loads are more than 170 times the loads predicted for the operational phase of land development for urban residential land use. Rowlands (2019) proposed that treatment trains consisting of a temporary construction water dam, a High Efficiency Sediment (HES) and a constructed wetland/ bioretention pond will improve cost-effectiveness of construction projects by saving on imported water costs by facilitating supply of both untreated and treated stormwater, however, specific effectiveness estimates were not provided.

Vegetation management and filter strips

- There was only one paper that evaluated vegetation management and filter strips. Brodie (2011) only assessed runoff, and used the MUSIC model, in SEQ. They found that hydraulic performance of vegetative filter strips is very sensitive to infiltration capacity, and thus soil type. In general, there was very little Australian data available to calibrate the model. It was predicted that a grassed filter strip (50 m wide by 30 m long, 5% slope) is expected to be a feasible runoff reduction option for a Brisbane Residential A subdivision (15 lots/ha) with a 5 ha catchment area. An infiltration rate of at least 50 mm/hr into the filter strip would be required.

Retention/detention ponds and constructed wetlands

There were 13 papers that evaluated the effectiveness of retention/detention ponds and constructed wetlands, and all of these studies focused on collecting measured water quality changes. None of the studies were located in the GBR catchments, however, those from SEQ have similar climate and runoff characteristics to parts of the GBR.

- A comparison of the hydraulic and water quality performance of a bioretention basin, a constructed wetland and a roadside swale was monitored by Liu et al. (2022) near Coomera Waters on the Gold Coast. The study measured water quality and quantity (TSS, TN and TP) at the inlet and outlet of the three sites and the outcomes showed "that a bioretention basin performed better in relation to peak flow and runoff volume reduction while the constructed wetland tended to produce better outflow water quality. The roadside swale had a relatively lower capacity for treating stormwater. These results suggest that a bioretention basin could be the preferred option when the primary requirement is water quantity improvement. However, if water quality improvement is the primary consideration, a constructed wetland could be more efficient". It was noted, however, that the results are highly variable and specific % reductions in TSS, TN and TP were not presented.
- Adyel et al. (2016) collected data over a range of timescales to assess the nutrient attenuation capability of a new constructed wetland in Canning, Western Australia. It was determined that overall the constructed wetland attenuated 62% of the TN and 99% of the TP during dry periods and 54-76% and 27-68% of TN and TP, respectively, during short episodic flow pulses.
- Birch et al. (2006) evaluated a rectangular dry retention pond adjacent to the road at the intersection of a large motorway (M4) and a high volume highway (Prospect Highway) in Sydney, Australia. The study measured TSS, TN and TP concentrations at the inflow and outflow of the retention basin over six storm events. The removal efficiency of the retention basin ranged between -12 and 93 % (mean 40%), -61 and 76 (-5%), and -1 and 59 (28%) for TSS, TP and TN, respectively. The efficiency of the retention pond was highly variable between events.
- Greenway (2005; 2007; 2017) and Greenway et al. (2002) presented results from several field monitoring sites in Brisbane (Golden Pond stormwater treatment wetland system and Bridgewater Creek stormwater treatment wetland system). The studies showed that during a storm event there was little reduction in the concentration of TSS throughout the treatment train due to limited detention time, however, there was a decrease in soluble nutrients. However, the 600 m length of remnant natural channel, lagoons and associated vegetation was most effective for water quality improvement in post-storm and dry weather. Species richness also increased by more than 50% in both stormwater wetlands, compared to the concrete drains.
- A study on the effectiveness of constructed floating treatment wetlands on Bribie Island (in SEQ) was presented by Nichols et al. (2016), Schwammberger et al. (2017) and Walker et al. (2017). They found that although the constructed floating wetlands (CFW) treatment area to catchment ratio was only 0.14%, the results demonstrated a significant removal of both TSS and TP from the stormwater inflows by the CFW. The efficiency ratios for TSS and TP were 81% and 52%, respectively. While the removal rate for total nitrogen was not significant for the CFW evaluated in this study, the efficiency ratio (ER) was still 17%. However, the ERs for nitrate and nitrogen oxide were both 47%. The study results suggest that it may be possible to increase the pollution removal performance of the CFW by upsizing the system and including intermittent re-aeration zones in the surrounding stormwater pond.
- Nu Hoai et al. (1998) conducted a study evaluating the trap efficiency of a constructed wetland in the City of Lake Macquarie, NSW. It focused on lead, but also included sediment data. In the wetland studied, the efficiency was 24–51% for lead and 35–86% for suspended solids during dry weather. Although the trap efficiency was not as high as might be expected, it is encouraging to note that the outflow water had relatively consistent concentrations of lead and suspended solids (<50 µg Pb/l and<10 mg/l suspended solids) which is lower than the levels recommended for recreational water quality criteria. It is worth noting that removal efficiency for suspended solids and associated heavy metals is closely related to input concentration, with

low efficiency measurement at low input concentrations. Notably, it appeared that the effectiveness of the wetland decreased following any medium rain event, with a trap efficiency falling to 14% for lead and 25% for suspended solids.

- A Master's thesis by Parker (2010) studied a constructed wetland, bioretention swale and a bioretention basin in Coomera Waters (SEQ). They were evaluated for their ability to improve the hydrologic and water quality characteristics of stormwater runoff from urban development. The monitoring focused on storm events, with sophisticated event monitoring stations measuring the inflow and outflow from Water Sensitive Urban Design (WSUD) systems. Data analysis undertaken confirmed that the constructed wetland, bioretention basin and bioretention swale improved the hydrologic characteristics by reducing peak flow. The bioretention systems, particularly the bioretention basin also reduced the runoff volume and frequency of flow. The pollutant loads were reduced by the WSUD systems to above or just below the regional guidelines, showing significant reductions to TSS (70-85%), TN (40-50%) and TP (50%). The load reduction of NO_x and PO_4^{3-} by the bioretention basin was poor (<20%), while the constructed wetland effectively reduced the load of these pollutants in the outflow by approximately 90%. The primary reason for the load reduction in the wetland was due to a reduction in concentration in the outflow, showing efficient treatment of stormwater by the system. In contrast, the concentration of key pollutants exiting the bioretention basin were higher than the inflow. However, as the volume of stormwater exiting the bioretention basin was significantly lower than the inflow, a load reduction was still achieved. Calibrated MUSIC modelling showed that the bioretention basin, and in particular, the constructed wetland was undersized, with 34% and 62% of stormwater bypassing the treatment zones in the devices.
- A study by Yang et al. (2022) focused on heavy metals, and also measured TSS and particulate nutrients. It found that the concentrations of zinc, aluminium and iron are particularly high in the constructed wetlands reviewed. This study brings attention to the pollutant profile of established constructed wetlands and the impact of heavy metals on the aquatic environment. The findings from this research revealed that the existing design and management guidelines for constructed wetlands in urban catchments are lacking in reduction targets for metal pollutants, thus improvements are essential to safeguard the water quality and performance of constructed wetlands.

Biofiltration systems

There were five papers that evaluated the effectiveness of biofiltration systems, four papers were based on measurements and one focused on modelling. Biofiltration systems can be used to improve the quality of stormwater by treating runoff using plants grown in a moderately permeable soil. Most biofilters use herbaceous species, but in highly urbanised locations, such as streets, trees may be a more suitable vegetation. These options may be useful in some areas of the GBR, but due to the highly variable climate in many catchments, they will not be suitable in all locations.

- Daly et al. (2012) presents a model that describes the statistical behaviour of the main variables involved in the water balance, and nitrogen removal, of a biofiltration system. The model was tested against field data collected at a stormwater biofiltration system in Melbourne, Australia. By relating the soil water content in the filter media before inflow events to the outflow total nitrogen concentrations, the model also gives estimates of the statistics of nitrogen removal performance as a function of inflow variability. No specific effectiveness values were given for nitrogen removal.
- A study by Denman et al. (2016) investigated the use of four street tree species and an unplanted control in model biofilters. All four tree species are used in urban landscapes in southern Australia and were chosen to investigate potential species differences in biofiltration systems. The trees were grown in a laboratory environment as a randomised block factorial design in soils with three saturated hydraulic conductivity rates. Tree growth increased significantly, except when flooded with stormwater. There was little effect of species on the removal of nutrients from stormwater. Trees were found to have the potential to be effective

elements in urban biofiltration systems, but further field-level evaluation of these systems is required to fully assess this potential.

- Drapper and Hornbuckle (2018) studied a stormwater treatment train consisting of rainwater tanks, pit basket inserts and media filters within a detention tank in a townhouse complex 1 km from Moreton Bay in Ormiston, SEQ. The site was monitored over a 4.5-year period. The paper concludes that the treatment train, and in particular the media filter, provides good removal of total copper and total zinc as well as TSS (61-78%), TP (28-59%), and TN (42-45%) from urban stormwater runoff, with higher inlet concentrations producing better performance.
- The objective of a study by Hatt et al. (2009) was to investigate the hydrologic and pollutant removal performance of three field-scale biofiltration systems in two different climates (Melbourne and Queensland). The study found that suspended solids and heavy metals were effectively removed, irrespective of the design configuration, with load reductions generally more than 90%. In contrast, nutrient retention was variable, and ranged from consistent leaching to effective and reliable removal, depending on the design. To ensure effective removal of phosphorus, a filter medium with a low phosphorus content should be selected. Nitrogen is more difficult to remove because it is highly soluble and strongly influenced by the variable wetting and drying regime that is inherent in biofilter operation. The results of this research suggest that reconfiguration of biofilter design to manage the deleterious effects of drying on biological activity is necessary to ensure long-term nitrogen removal.
- Lucke and Nichols. (2015) evaluated the pollution removal and hydrologic performance of three bioretention basins (that have been in place for 10 years) in Caloundra, Qld Australia. The bioretention basins were subjected to a series of simulated rainfall events with four different synthetic stormwater pollutant concentrations. The basins successfully reduced peak flow, and runoff volumes. TSS removal performance was variable for all tests and no correlation was found between performance and dosage.

Studies evaluating a combination of systems (generally also review papers)

There were ~6 papers that evaluated the effectiveness of a combination of approaches, noting that none of these were located in the GBR catchments, but were from studies in other parts of Australia.

- Ahammed (2017) presented a review paper assessing Water Sensitive Urban Design (WSUD) technologies for stormwater management that included infiltration systems, permeable pavements, bioretention systems, vegetated swales, rainwater harvesting systems, with a focus on TN and TP. In summary:
  - Infiltration systems had TN and TP removal rates of as high as 96-100%.
  - Permeable pavements - several studies identified differing efficiencies for the removal of TSS, TN and TP from stormwater. Removal efficiencies ranged from 28-100 %, 20-60 % and 7-60 % for TSS, TN and TP, respectively.
  - Bioretention systems had maximum removal efficiency for these systems of TSS = 95%; TN = 66%; N = 77% and P = 94%.
  - Vegetated swales reported mean removal rates of 69, 56 and 46% for TSS, TN and TP, respectively.
  - Rainwater harvesting systems have the potential to reduce volume and peak of stormwater runoff.
  - Infiltration systems - several authors suggest a maximum slope of 5-6% for high infiltration rates to be achieved.
  - Permeable pavements - several authors suggest that significant maintenance is required.
  - Bioretention systems - pollution removal efficiencies of bioretention systems depend on vegetation species and symbiotic relationships of bacteria and fungi.
  - Vegetated swales - sandy and sandy loam soils are most effective at removing pollutants as a result of higher surface area. Systems also depend on optimum conditions of healthy vegetation.

  - Permeable pavements are more cost-effective than infiltration systems, like soakable ways, however, existing literature recommends that the evidence of intensive economic analyses on WSUD technologies are rare.
  - Many of the papers reviewed identify additional services provided by WSUD technologies including urban amenity and ecological services.
- Greenway (2004) found the treatment efficiency of a wetland system requires a balance between pollutant loading rate and hydraulic retention time, which is also affected by the water quality and quantity of wastewater effluent or stormwater runoff. The size of a wetland will depend upon the volume of runoff, pollutant characteristics, desired level of treatment and the extent to which the wetland is expected to function as a flood retention basin. Water depth and extent of inundation will determine the types and species of aquatic plants. A combination of emergent, submerged and floating species should be selected. Pre-treatment and detention times are crucial parameters to maximise pollutant removal efficiency. Sedimentation ponds are important in stormwater wetlands to remove particulates, but dense vegetated macrophyte zones are essential to enhance the removal of suspended solids and nutrients.
- Hatt et al. (2006) provides a review of the treatment and recycling of stormwater in Australia. While the paper provides a detailed account of Australian stormwater treatment and recycling processes, information regarding the performance of these systems in reducing sediment and nutrient loss was limited. The review is focused on the need to use stormwater for non-potable requirements, thus reducing the demand on potable sources.
- Hoban (2019) provides detailed descriptions of an extensive number of Water Sensitive Urban Design approaches noting that detailed assessment of performance is limited. Mitigation options evaluated include gully baskets, gross pollutant traps, vegetated swales, bioretention (rain gardens) wetlands, floating wetlands, water smart street trees. For most technologies, there is a relative paucity of reliable field data. This is because in many treatment systems, it is difficult to set up equipment to sample inflows and outflows; it is expensive as it often requires event-based sampling of inflow and outflow throughout multiple storm events and then ensuring appropriate sample handling, chain of custody, and laboratory analyses; there are different criteria for evaluating the efficacy of stormwater practices, including several differing statistical methods to determine percentage removal.
- Malaviya and Singh (2012) presented a review of the effectiveness of constructed wetlands for the management of urban stormwater runoff. The effectiveness of different wetlands was highly variable across studies. The review suggests that some of the most important considerations to improve the effectiveness of constructed wetlands in reducing sediment, nitrogen and phosphorus concentrations are wetland treatment area as a proportion of the basin area which has direct effects on retention time as well as vegetated versus non vegetated wetlands and the species selected for vegetation.
  - Cost-effectiveness indicates that wetland-based stormwater treatments are relatively inexpensive. However, they do generally encompass about 3-5% of the land they drain which is comparatively high in comparison to other stormwater management practices. This can make them untenable in areas where land values are high.
- Roy et al. (2008) reviewed the widespread implementation of WSUD management practices with examples from the US and Australia. The study focused on the impediments to widespread implementation rather than assessment of the effectiveness of specific management practices. While there are numerous demonstrations of WSUD practices, there are few examples of widespread implementation at a watershed scale with the explicit objective of protecting or restoring a receiving stream. This article identifies seven major impediments to sustainable urban stormwater management: 1) uncertainties in performance and cost, 2) insufficient engineering standards and guidelines, 3) fragmented responsibilities, 4) lack of institutional capacity, 5) lack of legislative mandate, 6) lack of funding and effective market incentives, and 7) resistance to change.

Other modelling studies including studies evaluating hydrological response only

There were ~7 papers that evaluated the effectiveness of several bespoke and relatively small-scale solutions (e.g., green walls and biochar) and were based on modelling only.

- Brodie (2007) demonstrates an alternative approach of using the composition of surface type (e.g., road, roof, grassed) within urban catchments to define suspended solids loads in runoff. This paper estimates suspended particle loads from a hypothetical 'residential' catchment located in SEQ. The method uses surface runoff event mean concentrations (EMCs) measured for a sequence of storm events monitored over a 13-month period from 2004 to 2006. Authors predict that the introduction of rainwater tanks will reduce runoff by 18-35%. This paper demonstrates that describing urban catchments by their surface composition, rather than by a more generic land use is a useful approach.
- Di Matteo et al. (2017) presents complex multi-objective optimisation modelling of trade-offs between three main objectives (lifecycle cost, reliability and TSS reduction). The results suggest it can be difficult to tease out individual performance of best management practices investigated as these were considered in terms of all objectives in combination. In addition, while this research presents a useful modelling tool for the design of stormwater harvesting (SWH) systems the results of modelling may be very location/situation specific, and there are no obvious messages for the GBR.
- Friend and Jayasuriya (2014) used the MUSIC model to assesses the feasibility of a number of different structural BMPs for achieving pollutant reductions in stormwater discharged at Indented Head Beach on the western side of Port Phillip Bay, Vic, Australia. The measures chosen for the structural BMPs, include raingardens, bioretention swales and rainwater tanks. The majority of each of the structural measures achieved pollutant reductions well above the targets.
- Nguyen et al. (2018) applied the SWAT model, that was developed in the US, to urban areas in Torrens River catchment, South Australia. Scenarios of three feasible control measures demonstrated best results for expanding buffer zones to sustain stream water quality. The construction of wetlands along the Torrens River resulted in the reduction of catchment runoff, but only slight decreases in TN and TP loads. Overall, the results of this study suggested that combining the three best management practices by the adaptive development of buffer zones, wetlands and stabilised riverbanks might help to efficiently control the increased runoff and TP loads.
- Waltham et al. (2014) applied the WaterCast catchment modelling and TUFLOW Advection Dispersion (AD) receiving water modelling to model diffuse sediment and nutrient loads under past and proposed future land use changes on the Gold Coast (SEQ). The study identified the need for extensive restoration of the upper catchment as well as stormwater treatment if sediment and nutrient loading are to be kept to acceptable levels under proposed development. However, this finding is specific to that study.

Costs and cost-effectiveness of practices, variation with climate and production outcomes

There were very few papers that combined a robust analysis of the reduction of sediment and particulate nutrients in urban areas with cost-effectiveness evaluations. For the few studies that did present cost-effectiveness data, the findings were integrated into the above summary.

Key conclusions (Urban)

Most of the remediation measures employed in urban areas for reducing runoff, sediment and nutrient concentrations are shown to be effective to some degree, however, there were some broad lessons and considerations for tropical systems adjacent to the GBR. These include:

- Loads of all variables, including sediment and particulate nutrients, were strongly correlated with imperviousness and hydrological connection of impervious surfaces.
- Due to the high variability in pollutant concentrations between sites and different types of urban areas (residential versus industrial etc.) the effectiveness of structural measures would not be universal.

- There is a need for extensive restoration of the upper catchment as well as stormwater treatment if sediment and nutrient loading are to be kept to ecologically acceptable levels.
- Most urban treatment options were more effective for sediment than for nutrients.
- For treatments such as bioretention systems to be effective, they need to be the right size for the volume of water that will move through them. If stormwater bypasses the systems, they will not be effective. This is an important consideration for tropical systems that can have a very large range between base and event flows.
- It appeared that the effectiveness of wetlands was optimal in small events and decreased following medium to large rain events with a trap efficiency falling for sediment and nutrients.
- In general, combining treatments, into treatment trains (which are a set of hydrologically linked treatments), are more effective than single treatments.
- Cost-effectiveness indicates that wetland-based stormwater treatments are relatively inexpensive. However, they do encompass about 3-5% of the land they drain which is comparatively high in comparison to other stormwater management practices. This can make them untenable in areas where land values are high. Note that none of this work has been conducted in the GBR catchment area, and it may or may not be applicable.
- For most technologies, there is a relative paucity of reliable field data. This is because for many treatment systems, it is difficult to set up equipment to sample inflows and outflows as it is expensive, often requires event-based sampling of inflow and outflow throughout multiple storm events and there are different criteria for evaluating the efficacy of stormwater practices, including several differing statistical methods to determine percentage removal. This challenge is not unique for urban land uses.
- Overall, there were a limited number of studies that provided any cost or cost-effectiveness data, and there is a challenge in translating any of these results from temperate systems to tropical environments.

Areas of further research

Given there are no known published studies of the effectiveness of urban management systems in the GBR catchment area, there is considerable potential for some data to be collected from urban areas within tropical systems. Importantly, information on the cost of any approach would need to be included. These studies do, however, need to be balanced by the fact that urban areas represent ~0.6% of the of the GBR catchment area and have only a small contribution to TSS, PN and PP loads (Table 1).

f) Roads

Summary of study characteristics

Table 13 presents a summary of the primary management actions evaluated and the study approaches employed for roads as a land use. Of the 14 papers considered, 5 were based on direct on-ground measurements from other parts of Australia, although none were within the GBR. There was only one paper that applied modelling regarding road hydrological connectivity. The remaining eight papers represented review, overview or commentary papers. Very few of these studies included associated costs and cost-effectiveness of the management practices.

Table 13. Summary of the primary management actions evaluated, and the study approach used for roads.

	Primary Management action	Measurement	Modelling	Combo or Other	Total
1	Sources, baseline studies, reviews or guidelines			3	
2	Permeable pavement	1			
3	Management of unsealed roads	4	1	2	

	Primary Management action	Measurement	Modelling	Combo or Other	Total
4	Roadside retention basins, vegetation and buffer strips	1		2	
5	Reducing road hydrological connectivity		1		
6	Economic studies				
	Total	**5**	**1**	**8**	**14**

Summary of evidence to 2022

There have been several research programs over the last few decades that have undertaken research into various aspects of road management including the CRC for Catchment Hydrology Forest Management Program (https://ewater.org.au/archive/crcch/archive/pubs/pdfs/technical199906.pdf) and the Rainforest CRC program. Those interested in more detail on road management and their impacts on water quality are encouraged to seek out these resources. Numerous studies have identified roads as a source of heavy metals, hydrocarbons and other chemicals, however, that literature was not evaluated as part of this review. Other pollutants are addressed in Question 6.1 (Chariton & Hejl, this SCS).

Sources, baseline studies, reviews or guidelines

- Goosem et al. (2010) provides a set of principles and supporting guidelines for implementing best practice planning, design and management for ecologically sustainable roads within rainforests throughout Queensland. These guidelines provide generic advice for avoiding erosion and reducing water quality impacts, however, no specific data regarding the evaluation of road management is presented.
- A recent International review of forest roads by Kastridis (2020) identified that vegetation and organic matter on the road prism (the road surface and its immediate surroundings), established riparian buffers along the streams, and the use of appropriate bioengineering designs for each area significantly decrease runoff generation and sedimentation from roads. From a construction point of view, a reduction in road-related impact could be achieved by reducing the depth of excavations and the use of soil compaction limiting technology during road establishment. The road network design should be more efficient, avoiding hydrologically active zero-order basins. Techniques that minimise the length and hydrological connectivity among skid trails, unpaved roads and streams are crucial. Broad-based dips, immediate revegetation and outsloping of the road base are considered good road construction practices.
- Seutloali and Beckedahl (2015) conducted a review of road-related soil erosion and management issues and available control measures. This was an international review and they highlighted that there is a variety of measures for controlling road–related erosion (e.g., using vegetation, engineering design, erosion control blankets, geotextiles, silt fences, compost/mulch). They found that the most efficient and economic soil erosion control strategy on roadsides is revegetation, although no study has demonstrated a method that is cost efficient and operational across different landscapes.

Permeable pavements

- A study by Ball and Rankin (2010), where experimental data was collected during storm events in an urban area of Sydney, found that in a catchment where a permeable road surface was installed, the effective imperviousness was reduced from 45% prior to reconstruction of the road surface to less than 5% after reconstruction of the road. The water quality (concentrations) from the treatment site was comparable to a typical urban road, however, as the runoff had declined, overall pollutant loads also declined. In summary, the permeable pavement was an effective treatment for load reduction.

Management of unsealed roads

- Craik and Dutton (1987) provided a critical review of the research and monitoring program implemented to determine the effect of runoff and sediment on the surrounding fringing reefs from an unsealed road through the coastal rainforest between Bloomfield and Cape Tribulation in North Queensland. However, the paper did not assess specific management practices to reduce sediment and nutrient loss in road runoff, and no specific data were presented. Similar insights were provided by Francombe (2003) for roads on Cape York, but no water quality data were presented with the paper.
- Forsyth et al. (2006) collected data on surface runoff in response to natural rainfall and sediment and nutrient loads at a pine plantation in SEQ. The study identified that when road and drain maintenance (grading) was performed, runoff and sediment loss were increased from both gravelled and un-gravelled road types. Additionally, the breakdown of the gravel road base due to high traffic intensity during wet conditions resulted in the formation of deep (10 cm) ruts which increased erosion.
- A rainfall simulator study by Riley and Shrestha (2009) attempted to assess how several different road-surfacing techniques on unsealed roads affect sediment runoff and stormwater quality in eastern Melbourne, Australia. Unfortunately, due to the short length of the study, missing data and complications with some treatments, the findings were limited and no clear outcomes were available.
- A study by Connolly et al. (1999) used data collected from a rainfall simulation experiment on forest roads in SEQ and the CREAMS erosion model to assess the potential for hillslopes in SEQ forest plantations to infiltrate concentrated runoff from forested road turnout drains. With respect to the generation of sediment from forest roads, the key findings of their research for forest managers were: i) sediment loads in runoff are directly proportional to road area generating runoff, ii) road surface gravelling reduces sediment generation, iii) consolidated road drains produce less sediment than newly formed unconsolidated drains, iv) grass regeneration on road surfaces reduces sediment production, and v) gravel type has a significant impact on the characteristics of generated sediment.
- Similar to recommendations from the above paper, Loch et al. (1999) provide results from field studies investigating the generation and management of runoff and sediment from forest roads in SEQ. They suggested that:
  - Hillslope infiltration provides the best option for the management of sediment-laden road runoff.
  - Only short lengths of road surface (and therefore low volumes of sediment-laden runoff water) approaching water courses should be directed to water course filter strips.
  - Roads with table drains discharging in the vicinity of watercourses should be gravelled.
  - Table drains should discharge to areas with high infiltration rates and flow spreading should be maximised.
  - Residue retention practices should be adopted during inter-rotational periods to maintain high roughness and infiltration rates.
  - Gravelling, grass cover and consolidation of road surfaces reduced sediment loads.
  - Pushing loose material generated from road maintenance into table drains should be avoided as this material will be easily transported.
  - Fine sediment will be very difficult to remove using vegetated filter strips (VFS) – there is a need to reduce sediment generation, prevent flow concentration and discharge runoff as high as possible in the landscape instead.

Roadside retention basins, vegetation and buffer strips

- Pezzantiti et al. (2012) investigated the performance of a retention basin on the eastern side of the southern expressway in Adelaide. Retention basins are often used to treat road runoff. Measurements were taken at inflows and outflows of the retention basin and water quality parameters measured included TSS, total dissolved solids (TDS), TP and total Kjeldahl nitrogen

(TKN). Average load reductions due to the retention basin were estimated to be from 18% for TDS to 77% for TP.

- In a review paper by Clinnick (1985), they determined that a 30 m buffer on either side of a stream provides adequate protection to the stream environment and wider buffers should be used where slopes exceed 30%. Bracken and Truong (2000) provide some basic (and now outdated) analyses of costs associated with various road management options and compared them to the recommended Vetiver grass, although no runoff, sediment or nutrient data were provided.

Reducing road hydrological connectivity

- Eastaugh et al. (2008) used Lidar and a hydrological connectivity index to model the degree to which a road is hydrologically connected to the stream network in order to inform road decommissioning projects. The focus being that roads that are more 'connected' in the landscape, will produce more runoff, sediment and particulate nutrients. While the method presented is useful for the comparison of different road network management options, as well as assessing the likely result of decommissioning works, the study does not provide specific information regarding the effectiveness of specific management practices for the reduction of nutrient and sediment loss.

Costs and cost-effectiveness of practices, variation with climate and production outcomes

There were no specific studies that addressed the effectiveness of road management for variable climate and spatial locations, and production outcomes were not relevant for this assessment. Publications citing costs and cost-effectiveness information were not present in these searches, and it is likely that this information would need to be obtained from councils and engineering firms.

Key conclusions (Roads)

Most remediation measures employed to reduce runoff, sediment and nutrients concentrations on and around roads are shown to be effective to some degree, and there were some broad lessons and considerations for tropical systems adjacent to the GBR. These include:

- Dirt and gravel roads are a source of sediment and particulate nutrients, whereas sealed roads are a source of runoff (and other contaminants such as heavy metals, hydrocarbons and other chemicals). These contaminants were not explicitly addressed here.
- There are numerous manuals and engineering 'how to' guides for road maintenance (e.g., https://www.tmr.qld.gov.au/-/media/busind/techstdpubs/Contract/routine-maintenance-guideline/RoutineMaintenanceGuidelines.pdf?la=en), however these documents generally do not contain runoff or water quality information and are not published and peer reviewed. Therefore, they were not included in this study.
- Similarly, there is considerable research from the US and elsewhere regarding the effectiveness of various forestry logging management approaches for reducing sediment yield (e.g., snig tracks, filter strips etc.), but less research on rural road networks as a source of sediment and particulate nutrients.
- One of the most efficient and economic soil erosion control strategies on roadsides is revegetation, however, fine sediment will be very difficult to remove using vegetated filter strips alone, and there is a need to reduce sediment generation, prevent flow concentration and discharge runoff as high as possible in the landscape.

Areas of further research

Similar to the research for bananas and horticulture, there are no known published studies of the effectiveness of road management systems in the GBR catchments. Therefore, there is considerable potential for some data to be collected from roads within tropical systems. Importantly, information on the cost of any approach would need to be included.

4.1.1 Recent findings 2016-2022

The body of evidence presented here is represented by considerably more studies published prior to 2016 (see Table 1), with <30% of the evidence from papers published after 2016 for all land uses except Urban. This may be for several reasons including the research and development (R&D) funding environment, the long-term, and therefore often sporadic and delayed nature of publications from such studies, a stronger focus on modelling in recent years, and a change in R&D priorities or focus. For example, gullies and streambanks have been identified as a major source of fine sediment and particulate nutrients to the GBR, and the evaluation of the effectiveness of remediation of these sources has increased in recent years (see Question 3.6. Brooks et al., this SCS). This more recent focus has resulted in a scaling back of studies evaluating surface or plot erosion. Outside of the long-term trial sites such as Brigalow, Wambiana and Virginia Park that continue to publish new findings (O'Reagain et al., 2018; Stokes et al., 2023; Thornton & Elledge, 2021), there are few new studies that have explicitly measured a water quality change following the implementation of best management practices across any land use.

4.1.2 Significance of findings for policy, management and practice

The key recommendations that were consistent across all land uses suggest that:

- There is a general lack of measured runoff and water quality field data, combined with commensurate land management practice information, to demonstrate improvements for many practices.
- Vegetation is a key component to maintaining sustainable landscapes. Implementing management practices that involve the addition or re-introduction of vegetation are generally correlated with improved water quality. In most cases, the more vegetation, the better.
- Hydrologically connected systems will produce more sediment and particulate nutrients (via roads, drains, gullies etc.), and therefore remediation measures should be focused on reducing the hydrological connectivity of flow pathways for all land uses.
- Outputs from models, particularly those that have not had sufficient local calibration using multiple lines of evidence, will have limited temporal value and are best used to show relative and approximate changes in water quality response to land management.
- For studies that have demonstrated an improvement in sediment and particulate nutrient runoff, there is a general lack of data on the cost and production implications of those interventions. There is not always a “win-win” scenario between improving water quality and increasing profit, and very few studies have evaluated changes at the whole-of-business level for most land uses.
- Information on the impact of BMPs on production and costs is of most interest to landholders. This information is considered important for increasing uptake of BMPs across all land uses.

As Australia (and the rest of the world) increasingly move towards carbon net zero and nature positive policies that will (potentially) be supported by Natural Capital Markets, information on the measured changes in biophysical assets will be critical. Strategic investments into additional long-term multi-dimensional measurement studies in the GBR catchments, are needed. The Brigalow Catchment Study in the Fitzroy Basin, which is Australia’s longest paired catchment study, is the only study of its kind in the GBR catchment area. Studies such as Brigalow, that evaluate land use and land management change, alongside soil, runoff and water quality outcomes, while quantifying production and economic implications, are vital for demonstrating the ‘actual’ effectiveness (or otherwise) of land management adjustment. Modelling is useful for predicting likely or approximate outcomes, but it can have large uncertainties. Experimental and monitoring data to validate and reduce the uncertainties in modelled outputs is critical. Investing in long-term monitoring, including the equipment and people to support such studies, is expensive. However, long-term data generally becomes more useful with time, and therefore the benefits of this knowledge are likely to re-pay severalfold into the future. This review has highlighted that long-term on ground measurements of land management change with coincident environmental and economic data, are grossly lacking in the GBR catchments, and additional sites should be established to support future decision making.

4.1.3 Uncertainties and/or limitations of the evidence

There were no studies from the GBR catchment area that were applicable to all aspects of this question. That is, no studies: i) used measured data to evaluate a range of agricultural management practices on fine sediment and particulate nutrient loss; ii) included data on the cost-effectiveness of the practices; and iii) can be broadly extrapolated to other spatial areas under different climate conditions. This is primarily because no study captures all issues over an average rainfall period (~10 years) while comparing to appropriate control conditions across a range of soil, terrain and land use types. The only studies that combine these elements are based on modelling outputs, which have generally low confidence due to a lack of field validation, particularly for remediation approaches. The key long-term monitoring studies that have collected both land (grazing) management and water quality data over at least a 10-year climate period, are from the Brigalow Catchment Study (Fitzroy, QGov), Wambiana Grazing Trial (Burdekin, QDAF) and Virginia Park Research site (Burdekin, CSIRO). These studies provide extremely valuable data and insights into land management practices and their effectiveness on water quality, however, the results need to be used carefully when extrapolating outside of their geomorphological, climatic and economic context. There are no equivalent monitoring sites in any of the other agricultural commodities.

4.2 Contextual variables influencing outcomes

This has been covered in above sections.

4.3 Evidence appraisal

Quantity, Relevance, Diversity, Consistency and overall confidence

A total of 162 studies were included in this review. The **quantity** of papers varied for each land use, ranging from 14 for roads to 40 for cropping (Table 14.). The overall **relevance was Moderate**, with scores ranging from 4.0 for roads up to 6.8 for cropping. Overall relevance was higher for land uses that had more studies based on measured data (e.g., cropping and grazing). Grazing, sugarcane, cropping, and bananas/horticulture were given a **diversity** ranking of 2 as they were derived from a range of study types in space and time (Table 15.), however, urban and roads received a diversity value of 1, as no studies from within the GBR were represented. Due to the broad range and location of studies, all studies were given a nominal **consistency** value of Moderate (value = 2). This reflects the general pattern that improved land management generally leads to improved water quality regardless of the method used, however, the timescales over which this occurs vary widely (hence only Moderate ranking applied). The **overall confidence** of the papers was Moderate for grazing, sugarcane and cropping and Moderate-Low for bananas/horticulture, urban, and roads due to fewer studies, and very few from tropical environments (Table 16).

The **Moderate confidence ranking** was also because there were no studies from the GBR catchments that were applicable to all aspects of this question. That is, no studies used measured data to evaluate i) a range of agricultural management practices on fine sediment and particulate nutrient loss, ii) included data on the cost-effectiveness of the practices, and iii) can be broadly extrapolated to other spatial areas under different climate conditions. This is primarily because no study captures all issues over an average rainfall period (~10 years) while comparing to appropriate control conditions across a range of soil, terrain and land use types. The only studies that combine these elements are based on modelling outputs, which have generally low confidence due to a lack of field validation, particularly for remediation approaches. The key long-term monitoring studies that have collected both land (grazing) management and water quality data over at least a 10-year climate period, are from the Brigalow Catchment Study (Fitzroy, QDERM), Wambiana Grazing Trial (Burdekin, QDAF) and Virginia Park Research site (Burdekin, CSIRO). These studies provide extremely valuable data and insights into land management practices and their effectiveness on water quality, however, the results need to be used carefully when extrapolating outside of their geomorphological, climatic and economic context. There are no equivalent monitoring sites in any of the other agricultural commodities.

Table 14. Type of studies evaluated for each of the land uses.

	Studies based on measured data from GBR region	Studies based on measured data from other parts of Australia	Studies based on modelled data	Other (e.g., reviews, guidelines etc)	Total
Grazing	15	4	7	6	32
Sugarcane	7	0	12	5	24
Cropping	18	10	1	11	40
Bananas and Horticulture	6	1	3	6	16
Urban	0	24	7	5	36
Roads	0	5	1	8	14
Total	46	44	31	41	162

Table 15. Relevance score for each of the land uses evaluated.

	Relevance to the Question 1-Low 2-Mod 3-High	**Spatial Relevance** 1-Low 2-Mod 3-High	**Temporal Relevance** 1-Low 2-Mod 3-High	**Overall** Low: 1-3 Mod: 4-6 High: 7-9
Grazing	2.3	1.7	1.8	5.8
Sugarcane	1.8	1.6	1.6	5.0
Cropping	2.7	2.0	2.2	6.9
Bananas and Horticulture	1.9	1.5	1.5	4.9
Urban	1.7	1.4	1.4	4.5
Roads	1.9	1.1	1.1	4.2

Table 16. Quantity, diversity and consistency scores for each of the land uses evaluated, as well as the overall confidence score. Where n = the number of papers included in the review for that land use.

	Quantity 1-Low 2-Mod 3-High	**Diversity** 1-Low 2-Mod 3-High	**Consistency** 1-Low 2-Mod 3-High	Overall Confidence Limited Mod High
Grazing	n=32	2	2	Mod
Sugarcane	n=24	2	2	Mod
Cropping	n=40	2	2	Mod
Bananas and Horticulture	n=16	2	2	Mod-Limited
Urban	n=36	1	2	Mod-Limited
Roads	n=14	1	2	Mod-Limited

Additional Quality Assurance (reliability)

Each of the papers included in the review were also subjected to a reliability assessment. This assessment was based on expert opinion and used a range of criteria to determine if a paper had low or poor reliability. Some of the criteria considered, included:

- Identification of any obvious bias in the study.
- Issues with experimental design or data analysis.
- Inadequate model validation.
- Unjustified extrapolation of results/conclusions.
- Unreasonable assumptions.

Any papers that were included in the synthesis, but were considered unreliable, are flagged in pink/red in the text. These papers had something useful to say, and were worthy of inclusion, however, their results should be used with caution.

4.4 Indigenous engagement/participation within the body of evidence

There was no Indigenous engagement and/or direct participation during the preparation of this body of evidence.

4.5 Knowledge gaps

Table 17. Summary of knowledge gaps for Question 3.5.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
Continued demonstration of the rehabilitation of land in poor condition to provide biophysical data for economic modelling is needed. Knowledge of, and ability to predict the biophysical outcomes and response times of land condition to management practices is still limited.	Consider setting up more ‘Brigalow’ style studies in a diverse range of environments and land-uses to future proof modelled scenario outputs in 20 years’ time.	Actual measured biophysical and economic data (evidence) on the effectiveness of management actions across a range of key land uses.
Assessment of the whole-of-business impact of best management practice programs. There is not always a “win-win” scenario between reducing sediment and increasing profit, and very few studies have been evaluated at the whole-of-business level.	Demonstration that good environmental stewardship is financially beneficial to the landholder.	Knowledge and information to support various investment programs and understand the full cost of program implementation.
The need to quantify the distribution and density of roads in the GBR catchment. This could be divided into sealed and unsealed roads.	At the moment there is no published information on road densities in the GBR, so it is difficult to know if they pose a threat or not, relative to other sources.	This may provide information or insights on a yet undetected erosion and pollutant source.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
The review process for this question highlighted that there are potentially significant unpublished datasets within Queensland Government that would provide considerable insights into some of the gaps identified in this study. Support for writing/publishing time would potentially allow these datasets to be written up and published.	Suggest contacting members of the P2R team for specific details.	There has obviously been considerable investment in data collection and research related to many topics presented in this review, but not all the data has been written up and documented. A relatively modest investment into 'writing up' time could save considerable investment in new data collection for some land uses.
Estimates of TSS, PN and PP by land use need to be published and peer reviewed.	There are various modelled estimates of TSS, TN and TP by land use available in reports. However, they also include contributions from streambanks, they are not published in the formal literature, and it is not clear that an independent assessment of the modelled outputs has been checked against measured data for each land use.	Published data on constituent loads by land use would help understand the relative proportions from each industry and therefore guide remediation and R&D investment.

5. Evidence Statement

The synthesis of the evidence for **Question 3.5** was based on 162 studies undertaken mostly in the Great Barrier Reef catchments (with Australian literature also included if relevant), published between 1990 and 2022. The synthesis includes a *Moderate* diversity of study types (29% observational from Great Barrier Reef, 27% observational from broader Australia, 25% reviews and 19% modelling), and has a *Moderate* confidence rating for all land uses (based on *Moderate* consistency and *Moderate* overall relevance of studies across land uses).

Summary of findings relevant to policy or management action

The most effective management practices for reducing sediment and particulate nutrient loss from the Great Barrier Reef 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). Agricultural areas downstream of dams and closer to the coast lead to higher rates of sediment and particulate nutrient delivery to the coast, therefore the spatial location of sites needs to be considered when estimating management practice effectiveness and translating between the farm site, and ecosystems downstream. 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.

Supporting points

- The greatest proportion of total fine sediment loads exported to the Great Barrier Reef are from grazing areas, followed by ‘other’ land uses (nature conservation, forestry, roads, dairy), sugarcane, cropping, urban and bananas/horticulture. Cropping, urban and bananas/horticulture can generate high loads per unit area, but the overall areas are relatively small.
- In **grazing** lands (32 studies), effective practices include moderate and adaptive stocking rates, minimum ground cover levels maintained above 40%, but are most effective when ≥70%, regular periods of strategic rest from grazing (especially in the early wet season), cattle exclusion from fragile land-types, soil amelioration and pasture establishment to assist recovery of large areas of low cover or bare ground, and consideration of vegetation buffers (especially near drainage areas and when using fire as a management tool). The effectiveness of these management practices varies spatially and under different climatic conditions.
- In **sugarcane** lands (24 studies), effective practices include the gradual elimination of water furrows following laser-levelling and repairing eroding drain banks (more effective for coarse sediment), green cane trash blanketing, zero tillage and controlled traffic farming. Other practices associated with higher overall costs include sediment traps, precision farming, and river and stream bank stabilisation. There is significant heterogeneity in cost estimates and farm gross margins between regions and (to a lesser extent) across farm sizes.
- In **cropping** lands (40 studies), effective practices include the use of contour banks and soil conservation structures on cropping lands >1% slope, retention of crop residues (stubble), reduced tillage, crop rotation and retaining ground cover to reduce erosion and improve yield. The additional benefits of cropping best practice have been demonstrated repeatedly, including improved economic viability and productivity, across different soils and mechanisation systems.
- **Banana and horticulture** (16 studies) practices generally align with cropping and sugarcane. Grass buffer strips can provide between 30 and 50% trapping efficiency for fine sediment in

bananas. There is limited information on the economic outcomes of practices and production outcomes.

- In **urban areas** (36 studies, all external to the Great Barrier Reef), effective practices aim to reduce runoff and are linked to improving filtration, hydrological connectivity of impervious surfaces, and greater runoff retention times. Combining treatments into treatment trains (which are a set of hydrologically linked treatments) is more effective than single treatments. For most technologies, there is a relative paucity of reliable field data and few studies that provided any cost or cost-effectiveness data.
- For **roads** (14 studies, all external to the Great Barrier Reef), effective practices include revegetation on roadsides, engineering drainage design, and specific erosion control measures such as the use of erosion control blankets, geotextiles, silt fences and compost/mulch. For unsealed roads, road surface gravelling can also be effective, however, this varies with gravel type. While there are guidelines for road management relevant to construction and maintenance, there are limited studies of the water quality and cost outcomes of treatments. The distribution, density and water quality impacts of roads is not documented.
- Overall, the evidence for all land uses was limited by a lack of measured (as opposed to modelled) runoff and water quality field data combined with land management practice and cost information to demonstrate improvements for many practices.
- There is high variability in the cost-effectiveness of practices at the farm/project scale which is driven by several factors including a wide range of different practices and economic returns, location within the landscape and factors relating to sediment mobilisation and delivery. The way that cost-effectiveness is assessed between projects and programs is also inconsistent. Therefore, there are substantial benefits in prioritising projects for investment at the regional scale based on the key metrics of interest (e.g., sediment reductions) before applying cost-effective metrics at smaller scales.
- Information on the best management practices for reducing sediment export and their impacts on agricultural production and profitability (all land uses), roads and urban systems is a significant knowledge gap and is considered important for increasing uptake of practices to improve water quality outcomes across all land uses in the Great Barrier Reef catchment area.

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 3.5

Theme 3: Sediments and particulate nutrients – catchment to reef

Question 3.5 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?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Rebecca Bartley	CSIRO	Research Scientist	Lead Author	All Sections
2. Bruce Murray	CSIRO	Research Technical Officer	Contributor	Searches and data extraction