2022 Scientific Consensus Statement

Question 3.4 What are the primary biophysical drivers of anthropogenic sediment and particulate nutrient loss to the Great Barrier Reef and how have these drivers changed over time?

Question 3.4.1 What evidence is there to link low groundcover, vegetation and tree clearing with poor water quality and runoff?

Question 3.4.2 What is the relationship between land condition and sediment and particulate nutrient runoff for management of Great Barrier Reef catchments?

Scott N Wilkinson[1], Bruce Murray[1], Ian P Prosser[2]
[1]CSIRO Environment, [2]Centre for Applied Water Science, University of Canberra

Citation

Wilkinson SN, Murray B, Prosser IP (2024) Question 3.4 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? In Waterhouse J, Pineda M-C, Sambrook K (Eds) 2022 Scientific Consensus Statement on land-based impacts on Great Barrier Reef water quality and ecosystem condition. Commonwealth of Australia and Queensland Government.

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

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

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Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

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

What is the Scientific Consensus Statement?

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

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

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

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

Method used to address the 2022 SCS Questions

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

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

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

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

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

Two methods were developed for the 2022 SCS:

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

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

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

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

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

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

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

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

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

Guidance for using the synthesis of evidence

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

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

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

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

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

Peer Review and Quality Assurance

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

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Acknowledgements

Rob Richards (Evidentiary), Jane Waterhouse (C_2O Consulting) and Mari-Carmen Pineda (C_2O Consulting) are thanked for guiding the drafting process and reviewing drafts. Thanks to Marie Vitelli (AgForce) and Bronwyn Bosomworth (Department of Environment and Science) for submitting literature for consideration in this synthesis.

Executive Summary

Questions

Primary Question 3.4 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?

Secondary Question 3.4.1 What evidence is there to link low ground cover, vegetation and tree clearing with poor water quality and runoff?

Secondary Question 3.4.2 What is the relationship between land condition and sediment and particulate nutrient runoff for management of Great Barrier Reef catchments?

Background

Poor water quality is a primary threat to the health of Great Barrier Reef (GBR) ecosystems (Question 1.2/2.1, McKenzie et al., this Scientific Consensus Statement (SCS)) and improving water quality can assist ecosystems to cope with multiple stressors including climate change impacts (Question 2.4, Uthicke et al., this SCS). Sediment and particulate nutrient exports increase nutrient availability, attenuate light penetration through the water column and settle on substrate including coral and seagrass, which together reduce coral diversity, increase mortality and suppress reef recovery from disturbances (Question 3.2, Collier et al., this SCS). Land uses affect the mean annual sediment and particulate nutrient exports through biophysical drivers. An understanding of the primary biophysical drivers is required so that management practices and erosion stabilisation actions can be identified and designed to either mitigate them or to adapt to and work with them. The biophysical drivers of natural erosion and nutrient export include climate (e.g., rainfall), terrain (e.g., surface slope), lithology (soil properties), and vegetation (e.g., biomass, structure, and cover), and the drivers of anthropogenic exports typically represent modifications to these. Drivers of anthropogenic exports may affect erosion and/or the delivery of sediment and particulate nutrients through the river system to the GBR coast. This question identifies the primary biophysical drivers, including those in the secondary questions of ground cover, tree clearing, increase in runoff volume and land condition.

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 Summary method was used.
- Search locations included Web of Science, Scopus, and Google Scholar, supplemented by author databases.
- The main source of evidence was studies within GBR catchments since the primary biophysical drivers of anthropogenic exports may vary depending on the underlying natural sediment and nutrient exports and on land use characteristics.
- Across the primary question and two secondary questions, the initial searches identified 1,774 items of evidence, including 225 items which were duplicated between the questions. Of those, 100 were eligible for inclusion. An additional 35 items were added manually (26% of the total included), obtained from literature submitted to the Scientific Consensus Statement, from citations within the eligible searched items and from the authors' personal collections. All studies were accessible.

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

Method limitations and caveats to using this Evidence Summary

For this Evidence Summary, 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 GBR derived studies were included except for a small number of reference experimental studies or global reviews which provided robust tests of associations observed within GBR catchments.
- Only studies published since 1990 were included, with one exception.

Key Findings

Summary of evidence to 2022

A total of 135 items of evidence were relevant to the question including the secondary questions. Of these, 36% were observational, 28% were experimental, 22% were review studies, and 14% were modelling studies.

Key findings include:

- Anthropogenic sediment and particulate nutrient export rates per unit area are larger in wetter climates, steeper terrain and erodible soils.
- The two most important primary biophysical drivers of anthropogenic sediment and particulate nutrient export to the Great Barrier Reef are vegetation degradation and surface disturbance.
- Vegetation degradation is caused by tree clearing (or more generally, land clearing) associated mainly with grazing and cropping land uses, by low ground cover primarily from overgrazing and drought, and by changes in the structure and function of vegetation including a shift to non-native grass species. Gully and streambank erosion have been greatly accelerated by vegetation degradation and collectively deliver 77% of the sediment and 40–50% of the particulate nutrient export, from a very small proportion of the catchment area. Streambank erosion rates are several times higher where riparian tree cover has been removed. Hillslope erosion rates increase sharply as cover declines below 30–50% because low ground cover exposes soil to erosion by rain splash and scour and increases the efficiency of sediment transport from hillslopes to streams. Vegetation degradation within stream channels, floodplains and wetlands also reduces sediment deposition in those areas.
- Surface disturbance, including trampling by cattle, tillage in cropping areas, unsealed roads and construction earthworks, is also an important biophysical driver especially where it occurs around gullies and streambanks and in areas of erodible soils. Actions that reverse vegetation degradation and prevent surface disturbance can reduce export through reducing erosive forces and increasing erosion resistance, especially when actions are targeted within gully networks and riparian zones. Road and urban construction can be a major driver of sediment yields locally, particularly in steeper and wetter areas.
- Soil degradation is a less significant driver at GBR scale but is widespread. It includes compaction, decline in soil fauna, carbon rundown, and ongoing erosion increases runoff generation and hillslope soil loss, particularly in more erodible soil types including duplex soils.
- Increased runoff contributes to gully and streambank erosion once they are established but is unlikely to be as significant in causing increased sediment exports as other biophysical drivers associated with grazing and cropping land uses such as reductions in ground cover and surface disturbance.
- Runoff concentration on hillslope surfaces associated with interception by gully networks, cattle tracks, road drains or urban stormwater systems etc., is a less significant driver although important in some settings. It can be a driver of elevated sediment and particulate nutrient delivery from hillslopes into the stream network. Concentration on hillslopes can also enhance gully formation driven primarily by vegetation degradation. The fine spatial scale at which it operates, and limited evidence increase the uncertainty about the significance of this driver.

- An increase in runoff detention in large reservoirs is the only driver studied which has substantially decreased anthropogenic sediment and particulate nutrient exports to the Great Barrier Reef. For example, construction of the Burdekin Falls Dam in 1987 decreased sediment export from the Burdekin River basin by 35%. This driver is less effective at capturing fine particulate matter, has negative impacts on freshwater ecology, and is much more costly than interventions which stabilise erosion directly.
- Land condition is a measure of forage productivity based on forage composition, ground cover, and soil surface characteristics. While land condition can indicate differences in erosional status between the extremes of very low and very high ground cover, it has not been consistently related to hillslope soil loss within these extremes and it is difficult to measure.
- Climate change is projected to increase the magnitude of large floods, the severity of droughts and alter fire regimes, all of which may exacerbate vegetation degradation and gully and stream bank erosion processes to increase future export volumes and concentrations. Therefore, the need for vegetation protection in areas of sediment supply will become increasingly important. The overall effect of climate change on sediment and particulate nutrient yields has received limited attention to date and remains poorly understood due to complex interactions with vegetation and land use.
- Other drivers include wildfire, which can exacerbate sediment and particulate nutrient yields in cases when large rainfall events follow soon after. This driver has been studied only in the Normanby River catchment and it is likely to be minor at the GBR scale because it is uncertain if fire frequency has increased. Grazing and tree clearing have reduced available biomass in many areas. Wildfire is likely to increase in frequency and extent because of global warming.
- Changes in the biophysical drivers over time are most well documented in the Burdekin and Fitzroy River basins. Significant events have included: surface disturbance associated initially with the introduction of livestock and subsequently with alluvial mining such as in the Upper Burdekin catchment, progressive and ongoing vegetation degradation associated with expansion and intensification of livestock grazing which increased Burdekin basin sediment export to record levels by the 1950s, historical and ongoing land/tree clearing including but not limited to the Brigalow bioregion which resulted in Fitzroy River basin sediment export increasing around the 1950s, expansion of cropping and road and urban earthworks. More recent construction of large dams has had a smaller effect on exports than the cumulative effect of other drivers. Ongoing vegetation degradation including land/tree clearing, and surface disturbance, appear to be contributing to expansion in coastal water quality impacts in recent decades, especially where they occur in areas prone to or experiencing gully and streambank erosion.

The biophysical drivers have increased erosion rates primarily by reducing the resistance through vegetation degradation including land/tree clearing, surface disturbance and geomorphic instability associated with gully and streambank erosion. Climatic forcing (drought and extreme rainfall) has also contributed and is likely to contribute further in coming decades. Each of the biophysical drivers identified arises from specific conditions and acts somewhat independently although many interdependencies between them are noted, for example vegetation degradation (especially land/tree clearing) is associated with surface disturbance, and these both lead to soil degradation.

Recent findings 2016-2022

Approximately 30% of the evidence items were published in 2016 and subsequently. This current question has addressed biophysical drivers in much greater detail than they were covered in previous Scientific Consensus Statements and has consolidated understanding of the evidence of the biophysical drivers which was previously contained within individual evidence items. The question has synthesised understanding about the magnitude of effect that individual drivers have had on individual erosion sources, and the temporal changes in biophysical drivers.

Significance for policy, practice, and research

Actions that improve vegetation cover and function within gullies are a priority to reduce exports, such as revegetating gullies and redistributing grazing pressure away from gullies. Streambank erosion can be addressed by revegetating riparian zones in extensive reaches to reduce the scour energy and build erosion resistance. Reversing upslope vegetation degradation may reduce runoff volumes to reduce gully and streambank erosion, but this effect is much smaller than the effect of local vegetation on erosion resistance. Widespread weed incursions make reversing vegetation degradation a challenging prospect without active intervention and so targeting the most actively eroding elements within catchments is a priority. Hillslope erosion is elevated by the current prevalence of poor land condition and is much higher than average where ground cover is low either at broad scales during droughts, or permanently in vulnerable areas. Vegetation degradation and tree clearing are continuing and appear to be increasing the exports over time, especially where they occur in areas prone to or experiencing gully and streambank erosion, making protection of vegetation in these areas a priority. Actions that address vegetation degradation also address some causes of soil degradation.

Reducing the frequency of surface disturbance can reduce hillslope erosion. For example, reduced tillage is known to reduce erosion on cropping land. Rotational grazing and controlling livestock access to riparian zones each constrain surface disturbance as well as addressing vegetation degradation, and soil degradation in the long term.

Runoff retention in large dams has reduced exports to the GBR by ~30–40% from what it would otherwise be, noting that very fine sediments including those from basalt soils appear to be poorly trapped by dams. Further dam construction may reduce sediment and particulate nutrient exports but will not outweigh the effects of other drivers. Dams are also very expensive relative to practice changes or erosion controls and have detrimental impacts on natural flow regimes and freshwater ecosystems.

Climate change is projected to increase the magnitude of large floods and the severity of droughts, and will exacerbate vegetation degradation, gully and streambank erosion processes, increasing the importance of vegetation protection in areas of sediment supply.

More prominent monitoring of indicators related to the primary biophysical drivers would improve understanding of their effects on exports. Relevant indicators include tree clearing, the incidence of poor ground cover within and around gullies and streambanks, and vegetation composition and condition in priority catchments.

Further research on the effect of land uses on tree clearing extent, vegetation and soil degradation, particularly around gullies and streambanks and contributing hillslopes would improve understanding of the effect of current management practices and the global warming trajectory on these biophysical drivers to firm up the baseline against which water quality improvement is assessed. Further research is needed into the reversibility of the effects of the primary biophysical drivers on sediment exports, to understand practice change outcomes. Inconsistency in the evidence regarding reservoir trapping effectiveness on fine-textured sediments and particulate nutrients indicates that further investigation is also needed there.

Key uncertainties and/or limitations

With only one quarter of the evidence items involving experiments, and some observational studies including either drivers or exports but not both in their scope, there were a substantial number of studies in which the drivers had to be identified or the size of their effects assessed through triangulation against other studies based on spatial location or time of occurrence. Some of the observational studies have been based on short load monitoring records considering the variable climate, which contributes to uncertainty in the relative importance of different drivers being established. There have been few studies of gully and streambank erosion rates in any region to refine the significance of each driver on sediment and particulate nutrient yield today. Fewer studies referenced particulate nutrient exports than sediment exports. The effect on exports of increased climate variability associated with global warming is little studied, and will likely exacerbate vegetation degradation, runoff scour, erosion and deposition in complex ways. These limitations reduce the precision of the conclusions, although not their findings.

Evidence appraisal

The body of evidence had a Moderate confidence rating assigned, based on overall High consistency of results, and Moderate overall relevance to the question. While the qualitative influence of the primary biophysical drivers is very well established, the precise quantitative influences in specific GBR situations is moderately understood. There were few experimental studies of the primary biophysical drivers, and many of the observational field studies covered either sediment concentrations or yields at various scales but not drivers, and so the identification of drivers relied on being able to triangulate changes in drivers and exports that were coincident in time or space. The spatial coverage of GBR catchments was focused on the Fitzroy and Burdekin regions, few in the Wet Tropics and Cape York regions, and very limited in the Burnett Mary and Mackay Whitsunday regions. However, the biophysical drivers identified were consistent with those in other regions of the world and there is little reason why studies are not equally relevant in comparable climate and soil zones in adjacent regions.

There was a large number of evidence items which was sufficient to identify each of the drivers listed, and vegetation degradation and surface disturbance drivers had a good quantity of evidence.

1. Background

Poor water quality is a primary threat to the health of Great Barrier Reef (GBR) ecosystems (Question 1.2/1.3/2.1, McKenzie et al., this Scientific Consensus Statement (SCS)) and improving water quality can assist ecosystems cope with multiple stressors including climate change impacts (Question 2.4, Uthicke et al., this SCS). Sediment and particulate nutrient exports increase nutrient availability, attenuate light penetration through the water column and settle on substrate including coral and seagrass, which together reduce coral diversity, increase mortality and suppress reef recovery from disturbances (Question 3.2, Collier et al., this SCS). To reduce fine sediment and particulate nutrient exports to the GBR lagoon requires that their magnitude and primary sources are identified (Question 3.3, Prosser & Wilkinson, this SCS). These sources have been addressed and mitigated through land management practices (Question 3.5, Bartley & Murray, this SCS) and stabilising areas of concentrated erosion (Question 3.6, Brooks et al., this SCS). Biophysical drivers are the means through which land uses affect sediment and particulate nutrient exports. An understanding of the primary biophysical drivers of the exports is essential to ensure that management practices and erosion stabilisation can be effective and well targeted.

1.1 Questions

Primary question	**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?
Secondary questions	**Q3.4.1** What evidence is there to link low ground cover, vegetation and tree clearing with poor water quality and runoff?
	Q3.4.2 What is the relationship between land condition and sediment and particulate nutrient runoff for management of Great Barrier Reef catchments?

The present ecosystem impacts of sediment and particulate nutrients are caused by their high mean annual loads exported from river basins to the GBR. Sediments are derived from water erosion processes, either erosion of surface soil from hillslopes or subsoil from denuded areas of deep degradation, gully or streambank sources (Question 3.3, Prosser & Wilkinson, this SCS). The soil particles can be mobilised by surface runoff or, in the case of streambank and gully erosion, channelised flow. To become exports, sediment and particulate nutrients are transported from source areas through the river system to the GBR, and so exports can change through changes in either erosion and/or in delivery efficiency. Erosion and sediment transport are naturally occurring geomorphological phenomena which can be affected by anthropogenic (human) changes to land use and management of the land use and the river system.

This Question addresses the primary biophysical drivers (or controls or factors or causes) of anthropogenic sediment and particulate nutrient exports to the GBR. It focuses on diffuse (non-point) source water-borne pollution, of which the main process and catchment sources have been identified in Question 3.3 (Prosser & Wilkinson, this SCS). Each land use may have a characteristic mix of biophysical drivers, each of which have unique effects on erosion and deposition processes.

River basin sediment and particulate nutrient loads are dependent on the natural river basin drivers of erosion, being climate (rainfall, temperature and humidity), terrain (surface slope, relief, drainage), lithology (soil depth, erodibility, texture, nutrients, structure) and vegetation (e.g., biomass, structure and cover) (Brodie et al., 2008; Carlson et al., 2019; Mariotti et al., 2021). Spatial variations in each of these natural drivers influence spatial variations in area-specific rate of exports to the GBR between and within river basins. For example, within the Burdekin River basin higher sediment yields are observed from steeper and wetter catchments than flatter and drier ones (Furuichi et al., 2016).

This Question addresses the changes in each of these natural drivers by land use and management which drive anthropogenic sediment and particulate nutrient exports. Examples include removal or degradation of vegetation, mining or earthworks changing runoff pathways, compaction by livestock or exposure by erosion changing soil properties, and changes in rainfall intensity and drought severity. In addition to drivers affecting (increasing) erosion rates, drivers of anthropogenic sediment and particulate nutrient exports also include those affecting (increasing) transport of sediment from hillslopes to streams and sediment delivery to the coast through decreasing sediment trapping (deposition) in river systems.

The impacts of sediment on GBR ecosystems are predominantly caused by the fine fractions of sediment, such as that with particle size <20 µm (refer to Questions 3.1, 3.2 and 3.3, this SCS). This fraction carries almost all particulate nutrients, but they can also be attached to particles coarser than 20 µm and generally <63 µm, which are collectively defined as silt and clay. Therefore, sediment <20 µm is what this investigation of biophysical drivers is oriented towards, but it does not exclude coarser fractions. Particulate nutrient loss from hillslopes, yields from catchments, or export to the GBR is nitrogen (N) and phosphorus (P) attached to soil and to sediment particles in river water. During the erosion process, some nitrogen and phosphorus remain attached to particles, and some are transported as colloids which are subsequently measured as dissolved (e.g., Judy et al., 2018). During transport in the river system there are interactions and transformations between particulate and dissolved pools of nitrogen and phosphorus. Nutrient transformations within rivers and reservoirs are addressed in detail by Question 4.5 (Burford et al., this SCS).

The spatial scope of the biophysical drivers is the river basins and catchments therein draining to the GBR coast. Sediment and particulate nutrient export is defined as the mean annual rates of load at the GBR coast over decades, irrespective of climate-related temporal dynamics of the exports and drivers. The nature and form of relationships between drivers and yields at stream and river locations within catchments is indicative of that between drivers and export to the GBR, although deposition within river systems in reservoirs and on floodplains must be accounted for when determining the efficiency of delivery to the coast (Question 3.3, Prosser & Wilkinson, this SCS). The potential for time lags between specific driving events and export to the GBR is recognised. Changes in the biophysical drivers over time considers decadal time periods depending on available evidence rather than event dynamics.

Secondary question 3.4.1: What evidence is there to link low ground cover, vegetation and tree clearing with poor water quality and runoff?

This question focuses on the evidence for a link between vegetation (ground cover and tree cover or other characteristics) and water quality, and runoff quantity. As such it focuses on specific aspects of vegetation degradation. Evidence can be in the form of proximal or remote measurements, or modelling that is supported by measurements.

Secondary question 3.4.2: What is the relationship between land condition and sediment and particulate nutrient runoff for management of Great Barrier Reef catchments?

Land condition in Queensland grazing lands is generally taken as relating to the status of existing vegetation (e.g., cover and composition) in relation to the potential for the site in terms of vegetation establishment, growth, amount and survival. Soil structure and nutrient status can also be considered as part of land condition due to their influence on vegetation. Based on this definition, land condition is relevant for the management only of grazing (range land) and to a lesser extent cropping land uses. It is not a relevant consideration for land disturbed by roads or mining, for example. Sediment and particulate nutrient runoff is interpreted as the losses of these pollutants from hillslopes to streams (e.g., tonnes per hectare per year (t/ha/y)).

1.2 Conceptual diagram

The conceptual diagram shows how the biophysical drivers of anthropogenic sediment and particulate nutrient exports represent land use-induced modifications to the natural drivers of exports. The drivers are associated with land uses, which define characteristic but specific combinations of drivers. The drivers manifest as specific erosion and deposition processes to determine the net export to the GBR. The specific focus here of the biophysical drivers affecting erosion and deposition processes, and hence the export, overlaps with the adjacent SCS Questions, which focus on quantifying the anthropogenic export to the GBR including erosion sources (Question 3.3, Prosser & Wilkinson, this SCS), and modifications to land uses which are effective in reducing erosion rates (Question 3.5, Bartley & Murray, this SCS).

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	**Q2.2** What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)? (Covers the climate changes occurring in the catchments over time.) **Q2.3** What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef? (Covers how land use is changing over time.) **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? (Quantifies anthropogenic sediment and particulate nutrient export, characteristics and primary sources in terms of catchments, land uses and landscape elements (hillslopes, gullies and streambanks).) **Q3.5** What are the most effective management practices (all land uses) for reducing sediment and particulate nutrient loss from the Great Barrier Reef catchments, do these vary spatially or in different climatic conditions? What are the costs and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices? (Effective management practices for reducing export to the GBR, cost-effectiveness, spatial variations, production outcomes; practices can act on the catchment processes and biophysical drivers.)

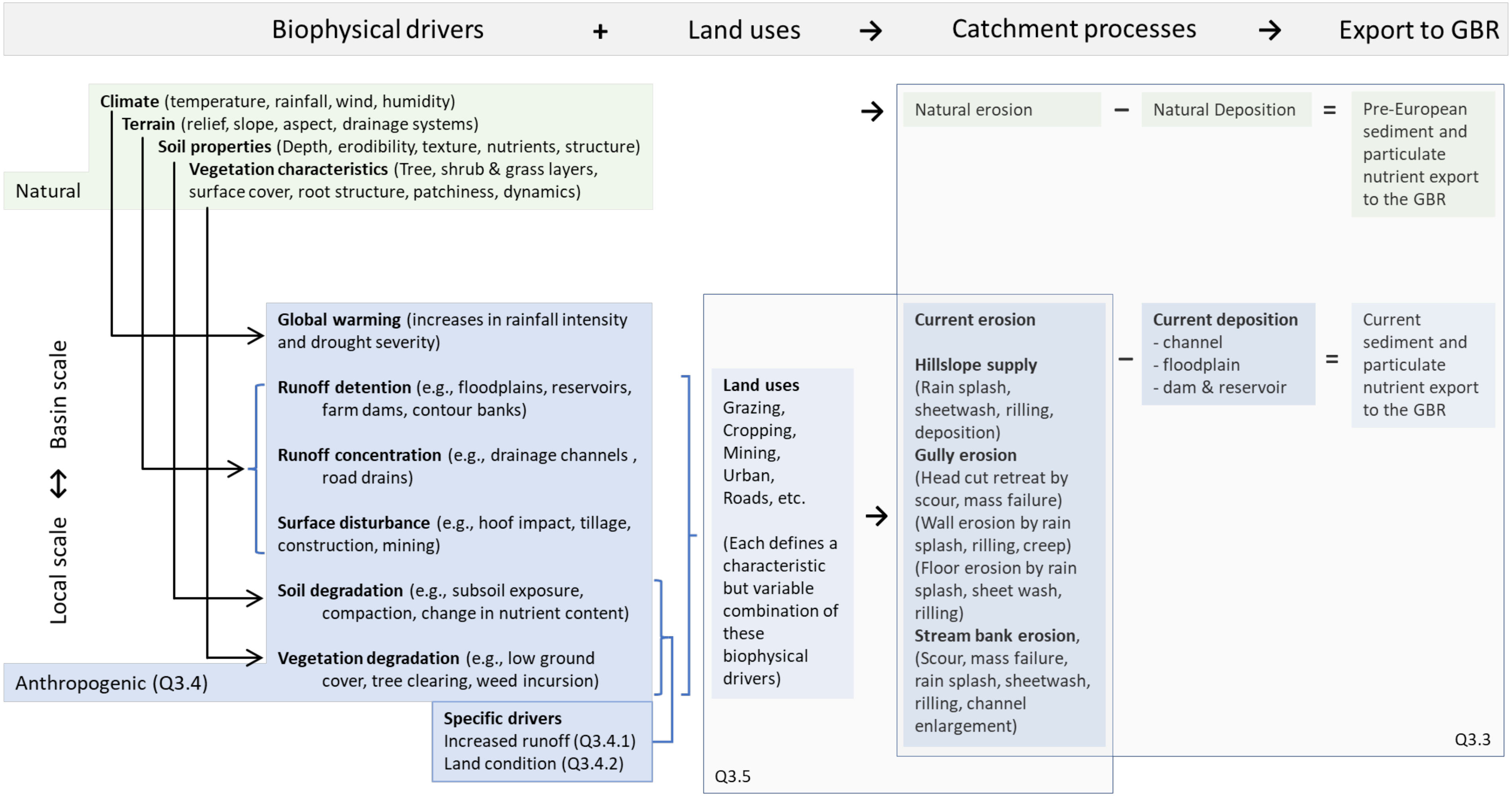

Figure 1. Conceptual diagram of how biophysical drivers relate to land uses, catchment erosion and deposition processes and export to the Great Barrier Reef.

2. Method

A formal Rapid Review approach was used for the 2022 SCS synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[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 Summary method was used.

2.1 Primary question elements and description

The primary question is: ***What are the primary biophysical drivers of anthropogenic sediment and particulate nutrient export to the GBR and how have these drivers changed over time?***

The secondary questions are:

- ***What evidence is there to link low ground cover, vegetation and tree clearing with poor water quality and runoff?***
- ***What is the relationship between land condition and sediment and particulate nutrient runoff for management of GBR catchments?***

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?

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[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

Table 1. Description of question elements for Question 3.4.

Question S/PICO elements	Question term	Description
Subject/ Population	Anthropogenic sediment and particulate nutrient export to the GBR	Increases in exports, loads or yields of fine sediment and sediment-attached nitrogen and phosphorus to the GBR associated with land uses introduced since the arrival of Europeans, primarily from diffuse sources from agricultural areas including grazing lands. Fine sediment is sometimes colloquially referred to as total suspended solids (TSS), which in GBR catchments is predominantly silt and clay but can also contain some sand.
	Sediment and particulate nutrient runoff	Associated processes include erosion, sediment transport, deposition and connectivity. 3.4.1: water quality, runoff, infiltration 3.4.2: sediment, particulate nutrient, runoff
Intervention, exposure & qualifiers	Primary biophysical drivers	Causes, factors, controls of the increases in exports. Relevant physical drivers include changes to natural drivers of river basin exports including: Global warming effects on climate including temperature, wind, humidity and rainfall. Changes to surface water flow such as through human disturbance of the land surface and river system including infrastructure. Changes to (degradation of) soil properties and function. Changes to vegetation function such as through vegetation removal or degradation of composition. The main emphasis is on drivers of diffuse source water-borne pollution from rural areas, mainly agricultural areas given their dominance by area, but mining and urban land uses are also considered briefly. 3.4.1: Specific drivers of vegetation degradation including ground cover, vegetation and tree clearing. 3.4.2: Specific driver of land condition being vegetation status in relation to the potential for the site, including as affected by soil degradation.
Comparator	Change in biophysical drivers over time	The anthropogenic increases to loads defines a focus on changes in biophysical drivers relative to pre-development times. Changes in biophysical drivers relative to earlier decades of European land uses.
Outcome & outcome qualifiers		Only primary drivers are considered, not all drivers or second-order drivers. Response, sensitivity, relationship, anthropogenic.

Table 2. Definitions for terms used in Question 3.4.

Definitions	
Anthropogenic load	The additional load of sediment and nutrients carried by rivers in present and historical times compared to the load carried prior to introduction of European land uses.
Drivers	Causes of or factors determining change. These affect sediment and particulate nutrient loads through physical processes.
Export(s) to the GBR	Mean annual loads (t/y) to the tidal limit excluding estuaries, from all river basins in the six Natural Resource Management (NRM) regions draining to the GBR coast.
GBR catchments	The 35 river basins that span from Jacky Jacky River at the northern end of Cape York to the Mary River north of Brisbane. These river basins are described in the Bureau of Meteorology (BoM) Geofabric using boundaries defined by the Australian Water Resources Management Committee.
Grazing pressure	The amount of forage consumption by livestock relative to plant growth.
Particulate nutrient	Particulate nutrient is nitrogen and phosphorus attached to soil and sediment particles in river water.
Runoff concentration	The concentration of surface runoff on hillslopes from being dispersed across the surface to being confined to a narrow path such as in a gully, drain or cattle track.
Sediment	Sediment refers to the finer fractions with particle size <20 µm (refer to Questions 3.2 Collier et al., and 3.3 Prosser & Wilkinson, this SCS). This fraction carries almost all particulate nutrients and impacts on turbidity of coastal waters. It comprises the clay and fine silt components of sediment.
Yield	Sediment or particulate nutrient delivery to locations within catchments, such as the bottom of a hillslope, to streams, or catchment outlets.

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 in:

- Web of Science
- Scopus
- Google Scholar

b) Search terms

Table 3 shows a list of the search terms used to conduct the online searches.

Table 3. Search terms for S/PICO elements of Question 3.4.

Question element	Search terms
Subject/Population	Great Barrier Reef Sediment, suspended solids, particulate nutrient, particulate nitrogen, particulate phosphorus, water quality
Exposure or Intervention	Biophysical, driver, cause, factor, process, runoff, flow, discharge, infiltration, climate, rainfall, runoff, discharge, drainage, disturbance, earthworks, construction, infrastructure, dam, reservoir, impoundment vegetation, degradation soil “land use”, agriculture, grazing, rangeland, cropping, arable, mining, urban, roads
Comparator (if relevant)	NA
Outcome	Loss, load, yield, export, erosion, deposition
1st secondary question element	Search terms
Subject/Population	Great Barrier Reef, Queensland water quality, runoff
Exposure or Intervention	Ground, cover, vegetation, tree clearing, shrub, composition, diversity
Comparator (if relevant)	NA
Outcome	NA
2nd secondary question element	Search terms
Subject/Population	Great Barrier Reef, Queensland, Australia Sediment and particulate nutrient, runoff
Exposure or Intervention	Land condition
Comparator (if relevant)	NA
Outcome	NA

c) Search strings

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

Table 4. Search strings used for electronic searches. Bold words in the secondary questions denote those not included in the primary question.

Search strings
3.4: **Web of Science and Scopus** “Australia” AND “great barrier reef” AND (sediment OR “suspended solids” OR “particulate nutrient” OR “particulate nitrogen” OR “particulate phosphorus” OR “water quality”) AND (loss OR load OR yield OR export OR erosion OR deposition) AND (biophysical OR driver OR cause OR factor OR process OR change) AND (climate OR rainfall OR degradation OR disturbance OR earthworks OR construction OR infrastructure OR dam OR reservoir OR impoundment OR drainage OR soil OR vegetation OR runoff OR discharge OR “land use” OR grazing OR agriculture OR mining OR road OR urban) **Google Scholar advanced search** Exact phrase: “great barrier reef” With all of: sediment, land, use At least one of: nutrient, water quality, erosion, deposition, rainfall, degradation, reservoir, drainage, soil, vegetation, runoff, discharge, grazing, road, urban
3.4.1: **Web of Science** Australia AND (“great barrier reef” OR **Queensland**) AND (sediment OR “suspended solids” OR “particulate nutrient” OR “particulate nitrogen” OR “particulate phosphorus” OR “water quality” OR runoff OR infiltration) AND (loss OR load OR yield OR export OR erosion OR deposition) AND **(ground** OR **cover** OR **vegetation** OR **“tree clearing”)** **Google Scholar** "Great Barrier Reef" AND (Australia OR Queensland) AND (vegetation OR ground cover) AND (sediment OR "suspended solids" OR "particulate nutrient" OR "particulate nitrogen" OR "particulate phosphorus" OR "water quality")
3.4.2: **Web of Science** (“great barrier reef” OR **Queensland** OR **Australia**) AND (sediment OR “suspended solids” OR “particulate nutrient” OR “particulate nitrogen” OR “particulate phosphorus” OR “water quality” OR runoff OR infiltration) AND **(“land condition”** OR **“rangeland condition”)** **Google Scholar** (“great barrier reef” OR **Queensland** OR **Australia**) AND (sediment OR suspended OR solids OR water quality OR runoff OR infiltration) AND **(“Land condition”** OR **“rangeland condition”)**

d) Inclusion and exclusion criteria

Initial screening of titles and abstracts: The reproducibility of the initial exclusion process across authors was tested by two authors discussing the test results for 50 references near the top and 50 near the middle of the returns for Question 3.4 (Web of Science). There was agreement in 99 of these publications about whether to include or exclude. Differences in assessment were discussed for the remaining study and minor refinements were made to the exclusion criteria, that studies where the effect of drivers was not directly covered were only excluded if there was insufficient spatial or temporal information within the study to triangulate the drivers with effects reported elsewhere.

Table 5 shows a list of the inclusion and exclusion criteria used for accepting or rejecting evidence items in the second screening based on reviewing the full text.

Table 5. Inclusion and exclusion criteria for Question 3.4 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	Sediment or particulate nutrients	Study not within GBR catchments (not applied for 3.4.2 due to the small number of search returns for that sub-question). Water quality attributes are not defined specifically enough to establish the relevance to sediment or particulate nutrients.
Exposure or Intervention	Biophysical drivers of anthropogenic sediment or particulate nutrient loads. Results include both the subject (exports) and intervention (drivers) OR Results include either subject or intervention and Discussion makes links to the other quantified elsewhere, with sufficient spatial or temporal information to triangulate and establish the relationship. 3.4.1: Results also include vegetation degradation, ground cover, tree clearing, runoff increase, concentration of runoff, detention of runoff. 3.4.2: Results also include land condition.	Does not study catchment processes or biophysical drivers e.g., marine focus, or only loads and sources, or only management outcomes but not processes, or no substantive new evidence. Drivers are not part of the study scope and there is insufficient spatial or temporal information on exports to triangulate the effect of driver(s). 3.4.2: Study had a focus on urban, mining or road land uses, or on reservoir deposition.
Comparator (if relevant)	Impact, factor, driv*, process, caus*, change	Does not study the effect on generation, transport or loads. Does not study an anthropogenic change.
Outcome	Driver has anthropogenic effect.	
Language	English	
Study type		Publications from prior to 1990 (not applied for 3.4.2 due to the small number of search returns for that secondary question).

3. Search Results

A total of 1,774 studies were identified through online searches for peer reviewed and published literature. Of these, 100 studies were eligible for inclusion in the synthesis of evidence (Table 6; Figure 2). An additional 35 studies were identified manually through expert contact and personal collections, which represented 26% of the total evidence. All studies were accessible.

Table 6. Search results table, separated by A) Academic databases, B) Search engines and C) Manual searches. The search results are provided in the format X of Y, where X is the number of relevant evidence items retained from the second screening and Y is the total number of search returns or hits.

Date (d/m/y)	Search strings	Sources	
A) Academic databases		Web of Science	Scopus
18/01/2023	*"Australia" AND "great barrier reef" AND (sediment OR "suspended solids" OR "particulate nutrient" OR "particulate nitrogen" OR "particulate phosphorus" OR "water quality") AND (loss OR load OR yield OR export OR erosion OR deposition) AND (biophysical OR driver OR cause OR factor OR process OR change) AND (climate OR rainfall OR degradation OR disturbance OR earthworks OR construction OR infrastructure OR dam OR reservoir OR impoundment OR drainage OR soil OR vegetation OR runoff OR discharge OR "land use" OR grazing OR agriculture OR mining OR road OR urban)*	*96 of 370*	*93 of 197*
19/01/2023	*Australia AND ("great barrier reef" OR Queensland) AND (sediment OR "suspended solids" OR "particulate nutrient" OR "particulate nitrogen" OR "particulate phosphorus" OR "water quality" OR runoff OR infiltration) AND (loss OR load OR yield OR export OR erosion OR deposition) AND (ground OR cover OR vegetation OR "tree clearing")*	*99 of 513*	*84 of 212*
19/01/2023	*("great barrier reef" OR Queensland OR Australia) AND (sediment OR "suspended solids" OR "particulate nutrient" OR "particulate nitrogen" OR "particulate phosphorus" OR "water quality" OR runoff OR infiltration) AND ("land condition" OR "rangeland condition")*	*14 of 23*	*10 of 16*
B) Search engine (Google Scholar)			
18/01/2023	***Advance Search*** *Exact phrase: "great barrier reef"* *With all of: sediment, land, use* *At least one of: nutrient, water quality, erosion, deposition, rainfall, degradation, reservoir, drainage, soil, vegetation, runoff, discharge, grazing, road, urban*	*36 of 684 (first 200)*	
23/01/2023	*(Great Barrier Reef) AND (vegetation OR cover OR ground or tree) AND (sediment OR "suspended solids" OR particulate OR "water quality")*	*52 of 2340 (first 200)*	

23/01/2023	*(“great barrier reef” OR Queensland OR Australia) AND (sediment OR suspended OR solids OR water quality OR runoff OR infiltration) AND (“Land condition” OR “rangeland condition”)*	*14 of 14*
Total items online searches		***100 (74 %)***
C) Manual search		
Date	Source	Number of items added
	Author personal collections	*27*
	SCS literature submissions	*3*
	Cited in searched items	*3*
Total items manual searches		***35 (26 %)***

Two additional items were included as background information only. Figure 2 shows the final search results.

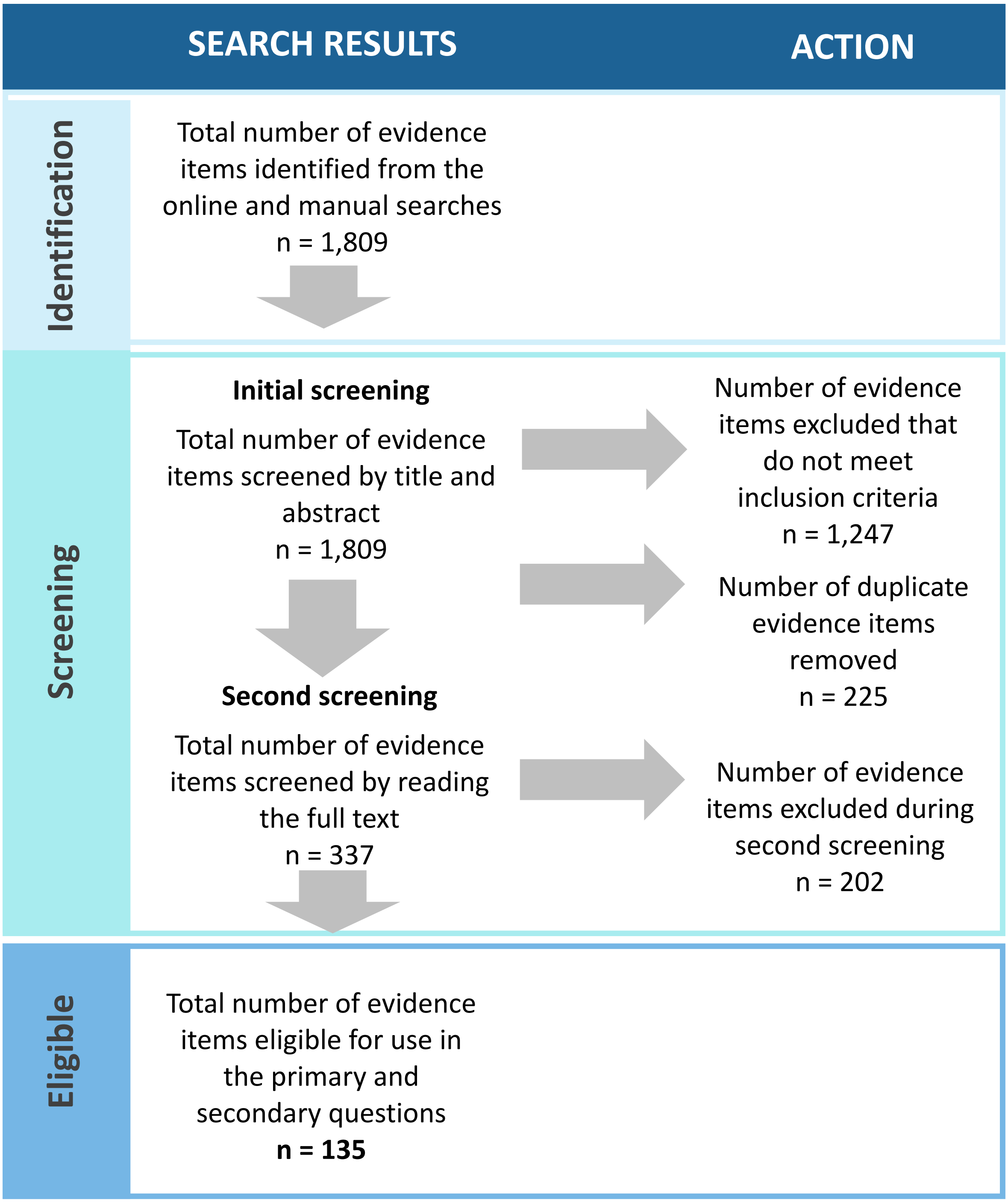


Figure 2. Flow chart of results of screening and assessing all search results.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

For the primary question 3.4, there were 81 eligible studies included. For the secondary question 3.4.1, there were 77 studies included from the search strings, including 44 studies that were additional to those for the primary question. Of the studies included in 3.4 that were not included in search results for 3.4.1, we found that 50 were also relevant to 3.4.1. For the secondary question 3.4.2, a total of 20 studies were included, including 10 studies additional to both the primary question and 3.4.1. Seven biophysical drivers of anthropogenic sediment and nutrient exports to the GBR were identified from the literature, in addition to those drivers identified in the 3.4.1 and 3.4.2 questions. Vegetation degradation was the most common driver considered (Table 7) and a large majority of those 57 studies noted the involvement of low ground cover or vegetation and tree clearing. Other drivers prominently studied were surface disturbance (e.g., from cattle trampling, tillage or road earthworks and use), and (changes in) runoff detention. Runoff concentration, soil degradation, global warming and wildfire had 1 to 6 studies each. Sediment was much more frequently studied than particulate nutrients. The most common land use studied was grazing (53%), followed by no specific land use (29%) and cropping (13%).

Approximately half of all studies addressing the primary question were observational in design, meaning that they quantified sediment or particulate nutrient catchment yields or exports and linked them to drivers without a controlled (experimental) manipulation of variables. Secondary studies, mainly reviews, were somewhat less common, while experimental or modelling studies were uncommon. In contrast, studies addressing 3.4.1 were mainly experimental, comparing between treatments or against a non-treated control. Approximately half of the studies addressing 3.4.2 were secondary in nature, mainly reviews, while the remainder were either observational or experimental. Many of the studies which referred to particulate nutrients were primarily focused on sediment. A small subset of studies were focused on runoff volume but not sediment or particulate nutrients. Observational and experimental field studies were focused on the Fitzroy and Burdekin regions, few in the Wet Tropics and Cape York regions, and very limited in the Burnett Mary and Mackay Whitsunday regions.

Of the observational studies, quantifying sediment loads from discharge and concentration observations at river stations was key in 15 studies. Most of these studies were at plot and hillslope scales, with a smaller number at a range of catchment scales. Sediment source tracing and dating have been key for identifying erosion processes and spatial patterns of sediment supply and delivery (13 studies), and these predominantly occurred at larger catchment scales. Field measurements of gully and streambank erosion have also contributed (11 studies). Coral chemistry was a less common variable for investigating sediment exports in relation to biophysical drivers (6 studies). Most of the review studies did not make substantive new conclusions but synthesised generally consistent findings made across multiple case studies. However, many of those case studies especially those dating from the 1990s were not otherwise included in the compilation due to their specific focus on agricultural sustainability rather than water quality and so the reviews extended the pool of evidence.

A total of 35 studies were added manually, either because they were very relevant studies or because they represented reference experimental studies or global reviews which provided robust tests of associations between drivers and exports that were observed within GBR catchments.

Table 7. Number of evidence items for each driver, for sediment and particulate nutrients, and for land use categories. The numbers of duplicate items between questions are also listed.

Question	Driver	Total	Pollutant		Land use			
			Sediment	Particulate nutrients	Generic	Grazing	Cropping	Other
3.4	Vegetation degradation	60	77	19	31	45	8	2
	Soil degradation	5						
	Surface disturbance	12						
	Runoff concentration	4						
	Runoff detention	13						
	Global warming	4						
	Other (wildfire)	2						
	Change in drivers over time	15						
	3.4 total excl. duplicates	**81**						
3.4.1	3.4.1 search (low ground cover, vegetation and tree clearing, runoff)	77						
	3.4 search	50						
	3.4.1 additional to 3.4	44						
	3.4.1 total excl. duplicates	**94**	91	27	15	51	10	3
3.4.2	**3.4.2 total (land condition)**	**20**	14	3	1	19	0	0
	3.4.2 additional to 3.4 and 3.4.1	10						
Total	**Overall total excluding duplicates**	**135**	**115**	**32**	**42**	**77**	**18**	**7**

4.1.1 Summary of evidence to 2022

The evidence is structured around the biophysical drivers of anthropogenic sediment and particulate nutrient loss listed in Figure 1, with additional sections for each of the secondary questions. The drivers addressing the primary question are addressed in order from those acting locally to basin wide, and the secondary questions are inserted into that order at logical points. A separate section addresses the aspect of the primary question regarding changes in the drivers over time.

1. Vegetation degradation

a) General effects

Vegetation degradation refers to deviations in the amount, structure or function of vegetation from the natural state. More intensive land uses which change vegetation by a greater degree tend to have larger sediment yield per unit area; for example, cropping results in higher sediment yields than grazing (Bartley et al., 2012; Hughes et al., 2010; Packett et al., 2009; Thorburn et al., 2013). Grazing is the most widespread land use associated with vegetation degradation in GBR catchments because it occupies around three quarters of the total catchment area. Differences in grazing pressure result in variable degrees of vegetation degradation within grazing land. Vegetation degradation also results in anthropogenic yields of larger magnitude in areas with greater vulnerability to erosion associated with natural drivers of climate, terrain and soil erodibility (Thorburn & Wilkinson, 2013). Such areas include riparian areas where terrain is steeper and runoff volumes are large. Such areas typically have larger underlying natural erosion rates.

Historical grazing has directly caused low ground cover (Bastin et al., 2012). Observational studies and the GRASP pasture model have concluded that the proportions of pasture biomass accumulated at the end of each wet season that are consumed in the following dry season have been higher than can be sustained by native grasses, resulting in their replacement by invasive species, often exotic to the area (Lebbink & Fensham, 2023; McKeon et al., 1990; Thorburn & Wilkinson, 2013). While invasive grasses are in general capable of providing levels of ground cover as high as endemic species provided grazing pressure does not inhibit plant growth, they often provide poorer resistance to hillslope erosion and sediment delivery to streams under typical grazing conditions. This is because, firstly, some invasive species produce less forage biomass, which reinforces the degradation process unless stocking rates are greatly reduced (Ash et al., 1997; Lebbink & Fensham, 2023). Secondly, while invasive grasses typically spread rapidly at the end of droughts when bare ground is widespread, they can be less drought tolerant (Lebbink & Fensham, 2023). Thirdly, the physical traits of invasive grasses can include shallow roots and lower production of persistent woody litter, leaving the soil exposed for sheetwash erosion and making the surface more efficient for transport of runoff and sediment (Carlson et al., 2019).

The effect of vegetation degradation is considered further below, initially in relation to tree clearing and then in relation to each of the primary erosion process sources identified by Question 3.3 (Prosser & Wilkinson, this SCS); hillslope, gully and streambank erosion. The effect of vegetation degradation on sediment storage in river channels, floodplains and reservoirs is also considered, since these deposition processes naturally retain sediment and particulate nutrients within catchments (McCloskey et al., 2021), and so reductions in their rates can result in increased exports to the GBR. Removal of tree cover, reduction in ground cover and increases in runoff are special cases of vegetation degradation addressed by the secondary question 3.4.1, which are incorporated into this section.

b) What evidence is there to link tree clearing with poor water quality? (Secondary Question 3.4.1)

Tree clearing initiates and is associated with changes to multiple biophysical drivers associated with the resulting changes in land use. Tree clearing for cattle grazing and cropping is noted as a major cause of anthropogenic sediment exports to the GBR by many of the early studies focused on changes in marine water quality (Brodie & Mitchell, 2006; Brodie et al., 2007; Haynes & Michalek-Wagner, 2000; Haynes & Morris, 2004; McCulloch et al., 2003). However, these studies did not establish causal links between water quality decline and tree clearing specifically. Below we consider specific spatial and temporal relationships between tree clearing and elevated sediment loads.

Between 1962 and 1978 around 46,000 km^2 of the Fitzroy River Basin was cleared of forest and scrublands, representing ~37% of the grazing land use area (Packett, 2020). Some of the cleared area was sown to pasture grasses and some was subsequently cropped. Several observational studies have identified that this phase of tree clearing clearly resulted in increased sediment export to the GBR. For example, the basaltic content of Keppel Bay beach ridge sediment deposits laid down from 1908 onwards contained an increase in basaltic sediments (Brooke et al., 2008). This is supported by evidence from multiple locations within the Fitzroy River Basin that the local timing of tree clearing and establishment of cropping was associated with increases and subsequent declines in the contributions from basalt soils to stream systems locally (Hughes et al., 2008; 2009; 2010). For example, at one location in the Fitzroy River Basin where tree clearing occurred in the 1980s, a temporally coincident increase occurred in the proportion of sediment supplied from the soils prevalent in the area cleared of trees (Douglas et al., 2010). An experimental study confirms that catchments with cropping and grazing land uses both export higher quantities of sediment and phosphorus than do comparable virgin Brigalow catchments on a per hectare basis (Elledge & Thornton, 2017).

Tree clearing in wet tropics locations with krasnozem soils has resulted in increases in sediment concentrations and yields of approximately one order of magnitude (Neil et al., 2002). These soils have a high nutrient content, and so indicate that tree clearing also has large effects on particulate nutrient exports, especially in wet climates and fertile soils. Where tree clearing in this environment was followed by cropping, increases in sediment yield at field scale were up to 33 times the yield prior to clearing. The lowest suspended sediment concentrations in the Tully River catchment are associated with forest and grazing land uses, and the lowest particulate nutrient concentrations are observed in forests (Bainbridge et al., 2009). Therefore, reducing either ground cover or tree cover increases sediment and particulate nutrient exports in that environment.

Evidence linking vegetation degradation and each erosion process specifically (hillslope, gully and bank erosion) is discussed in the following subsections.

c) Hillslope erosion

What evidence is there to link low ground cover with poor water quality? (Secondary question 3.4.1)

Low ground cover is one indicator of the extent of vegetation degradation which accelerates all erosion processes. Although less than one quarter of sediment export to the GBR is derived from hillslope erosion (Question 3.3, Prosser & Wilkinson, this SCS; McCloskey et al., 2021), hillslope erosion occurs over a very large proportion of GBR catchments. Periods of poor vegetation cover on hillslopes and correspondingly high risk of sheetwash and rill erosion result from a combination of strong rainfall variability and commonly high stocking rates (Hairsine, 2017). Overgrazing during droughts is a primary cause of increased hillslope soil erosion, alongside tree clearing (Haynes & Morris, 2004). The potential for sediment yield at a given location increases as cattle stocking rates increase, due to the increased vegetation degradation (Wilkinson et al., 2014b). It is noted that gully and streambank erosion, discussed in subsequent sections, are larger sediment sources than hillslopes at river basin scale and the severity of those processes is a stronger determinant of mean annual catchment sediment yield than is ground cover on hillslopes (Bartley et al., 2010a; 2014a; McCloskey et al., 2021).

A link between low ground cover on grazed hillslopes and poor water quality in runoff is well established by observational and experimental field studies at multiple sites in the Fitzroy and Burdekin River catchments. For example, heavy grazing of established pasture on hillslopes in the Brigalow Catchment Study in the Fitzroy River basin resulted in 2.5 times more bare ground, 3.6 times more runoff and higher loads of total suspended solids (TSS), nitrogen and phosphorus than from pasture grazed conservatively within the known long-term carrying capacity (capacity to produce forage) (Thornton & Elledge, 2021). The observed relationship between ground cover levels and hillslope erosion rates is non-linear, with erosion increasing sharply as cover declines below 30–50% (depending on the study), so that the sediment concentration of runoff is several times larger on areas of 10–20% cover relative to areas of 50–80% cover (Bartley et al., 2010b; Bosomworth et al., 2018; Eyles et al., 2018; McIvor et al., 1995a; Roth, 2004; Silburn et al., 2011). This observed non-linearity is consistent with the ‘cover factor’ relationship between cover and gross erosion in the Universal Soil Loss Equation that is used to model hillslope erosion across GBR catchments and globally (McCloskey et al., 2021; Silburn, 2011a; 2011b; Thorburn & Wilkinson, 2013; Wilkinson et al., 2014a).

Lower ground cover provides less protection from direct raindrop impact, as demonstrated by mobilisation of larger amounts of sediment at low cover levels including higher proportions of larger sand particles (Eyles et al., 2018; Scanlon et al., 1996; Silburn et al., 2011). Vegetation also increases the resistance to entrainment of soil particles by protecting the soil surface from scour and by providing carbon to maintain the stability of soil aggregates (Torri & Poesen, 2014). Cover of grass pasture or tree litter each provide similar control over runoff and erosion, since they both reduce the energy of raindrop impact and provide surface roughness and litter to slow and pond runoff. Arising from these studies, a minimum of 70–75% ground cover has been identified as being required to most effectively protect the soil surface from rain splash and scour erosion and to sustain biota that maintain soil structure (Bartley et al., 2014b; Roth, 2004; Sanjari et al., 2009).

Sediment source tracing studies indicate that large proportions of hillslope sediment supply are derived from areas that have chronically low ground cover (Karfs et al., 2009; Wilkinson et al., 2015). Studies of instrumented hillslopes indicate that the spatial arrangement, species composition and pasture biomass are all critically important in determining how ground cover influences runoff and erosion (Bartley et al., 2014a; Wilkinson et al., 2014b). Hillslopes with relatively high mean cover, but with small patches bare of vegetation can have much higher sediment loss than similar hillslopes that do not contain bare patches (Bartley et al., 2006; 2010a; 2010b; Ludwig et al., 2005;). This is consistent with the non-linear relationship observed between sediment yield and cover noted earlier. When bare patches occur low on hillslopes in areas of flow concentration (such as upslope of some gullies) they can be especially significant contributors of sediment to streams (Kinsey-Henderson et al., 2005). Low ground cover patches have a smooth, hard surface (McIvor et al., 1995a), which is more efficient than rougher vegetated surfaces for delivering sediment eroded from upslope to streams. Buffer strips with high levels of grass cover at the bottom of planar hillslopes with otherwise poor cover can be sufficient to trap sand bedload but not the fine silt and clay which is of interest here (McKergow et al., 2004).

Dryland cropping has rates of sediment loss per hectare that are several times higher than grazing. This has been observed in multiple studies in the Fitzroy River basin at hillslope scale (Carroll et al., 1997; Elledge & Thornton, 2017), and at catchment scale (Bartley et al., 2012; Hughes et al., 2009; 2010; Packett et al., 2009). In Wet Tropics catchments, observed sediment concentrations downstream from routinely ploughed sugarcane areas are also higher than in grazed areas (Johnson et al., 2000; Rayment, 2003). In cultivated areas therefore, sheetwash or hillslope erosion generally dominates sediment budgets, in contrast to grazing areas where gully erosion dominates (Hughes et al., 2009). However, as well as producing lower cover levels, the surface disturbance from tillage is likely to also contribute significantly to higher sediment yields from cropping land (see later section on Surface Disturbance).

As on grazed hillslopes, non-linear relationships are also observed between cover and sediment yield in cropped fields, with much higher sediment yields occurring below 30–50% cover (Carroll et al., 2000; Hulugalle et al., 2002). Cropping land sediment yields are higher where and when cover is low or non-existent, such as during fallow and tillage (Carroll et al., 1995; 2010; Hulugalle et al., 2002). Coverage of dryland crop residue can somewhat reduce sediment and particulate nutrient yields relative to bare fallow (Carroll et al., 1997; Melland et al., 2022), and it substantially reduces sediment yield from sugarcane fields (Visser et al., 2007) (see Question 3.5, Bartley & Murray, this SCS). Hillslope monitoring of terrain recently constructed from mine spoil also indicates rapidly increasing sediment yield when ground cover levels are less than 40–50% (Carroll et al., 2000; Carroll & Tucker, 2000; Loch, 2000; So et al., 2018).

A sensitivity analysis of parameters in the SedNet model in the Burdekin River basin identified that predicted annual sediment loads were sensitive to vegetation cover inputs especially in years of lower cover, suggesting that cover is a major control on sediment erosion and delivery from hillslopes and entire river basins during these times (Wilkinson et al., 2014a). However, other possible causes of high sediment concentrations in years during and immediately following drought were noted including weathering of bare soil surfaces and temporary fine sediment storage in stream channels (possibly from gully and streambank erosion). A recent plot rainfall simulation study (Bosomworth et al., 2018) and a recent hillslope observational study (Brooks et al., 2014) also indicate that sediment yields from hillslopes are lower than predicted by the Universal Soil Loss Equation model using current datasets for ground cover and soil erodibility, further suggesting that high sediment export to the GBR during and following droughts has causes other than low ground cover. Therefore, further investigation is required of processes at hillslope and small catchment scales to test the basin-scale significance of low ground cover in post-drought sediment exports.

A small subset of hillslope studies report relationships between hillslope nutrient yields and ground cover, and these relationships have similar form to those for sediment (Melland et al., 2022; Roth, 2004;

Silburn & Glanville, 2002; Silburn & Hunter, 2009). Soils with higher clay fractions generate greater loads of N and P (Bosomworth et al., 2018).

There are several studies in which low ground cover is correlated with higher suspended sediment concentrations and loads at regional scales, but these provide less robust evidence of a causal relationship than studies at the scale of hillslopes or small catchments. For example, the Tully-Murray catchment has lower sediment concentrations than surrounding catchments with similar rainfall amounts and land uses (Bainbridge et al., 2009). However, differences in climate, terrain and soil type between these catchments may be confounding factors, since increased sediment yield is also associated with wetter climate, steeper terrain and more erodible soil types (O'Reagain et al., 2005). Sediment yields are more sensitive to changes in ground cover in wetter and steeper landscapes than in flatter and drier areas (Bartley et al., 2015).

Even though ground cover is an important indicator of hillslope runoff and erosion, other vegetation factors influencing soil surface conditions must be considered when developing management strategies to reduce runoff and erosion (Scanlon et al., 1996). These include vegetation biomass and composition (Wilkinson et al., 2014b), which are discussed further in the later subsection on land condition.

What evidence is there to link low ground cover, vegetation and tree clearing with runoff? (Secondary question 3.4.1)

Here we address what effect low ground cover, vegetation and tree clearing have on runoff as a driver of increased sediment yield from scour and sediment transport on hillslope surfaces, or from gully and streambank erosion, independent of the effect that vegetation degradation has on hillslope erosion directly.

A study of coral geochemistry indicates that the variability of Burdekin River water discharge, but not necessarily the overall volume, increased at a similar time to the introduction of European land uses (Lough et al., 2015; Waterhouse et al., 2016). In particular, the frequency of high flow events increased from 1 in every 20 years prior to European land uses (1748–1847) to 1 in every 6 years reoccurrence (1948–2011). This change coincided with a shift towards greater El Niño–Southern Oscillation (ENSO) variability and rapid warming in the southwest Pacific. However, a contribution from vegetation degradation to increased variability in Burdekin River discharge also appears likely. For example, an association was observed between tree clearing in the Upper Burdekin catchment and a decrease in the river base flow and increase in discharge during large rainfall events, though not mean annual discharge (Pena-Arancibia et al., 2012). Similarly, vegetation degradation is observed to substantially increase runoff volume, duration and peak rate at small catchment scales (Koci et al., 2020b). Therefore, an increasingly variable runoff regime is likely to be one of the results of vegetation degradation and a contributing factor to increased erosion in the Burdekin watershed (Bartley et al., 2014b), given the dependence of gully and streambank erosion on event runoff.

In the Fitzroy River basin, long-term monitoring indicates that the clearing of Brigalow vegetation for either pasture or cropping approximately doubles runoff at the paddock scale. This has been consistently observed since 2007 (Thornton et al., 2007; Thornton & Yu, 2016) and recent studies incorporating additional years of monitoring have confirmed this finding (Elledge & Thornton, 2022; Thornton & Elledge, 2018; 2021; 2022). Lower levels of pasture ground cover are associated with increased runoff across a 10 ha catchment (Connolly et al., 1997). In contrast with the Burdekin River basin, broadscale tree clearing in the Brigalow bioregion was found to increase mean annual runoff by 40–58% (Siriwardena et al., 2006). It can be speculated that this may be associated with groundwater having a larger role in modulating temporal patterns of runoff generation in the Fitzroy River basin, due to deeper soils and lower-relief landscapes, which contributes to the difference in behaviour relative to the Burdekin River basin.

Considering the above, it is likely that increased runoff volumes make a modest contribution to anthropogenic sediment and particulate nutrient exports at GBR scale. However, the observed changes to runoff at basin scale are more subtle than changes to sediment yields (Bartley et al., 2014b; Pena-Arancibia et al., 2012). Changes in coral geochemistry (Barium (Ba)/Calcium (Ca) ratio and luminescence residuals) from pre-development values have been evident during both wet and dry periods, indicating that drivers of anthropogenic sediment exports are chronic, such as persistent catchment degradation, rather than acute only within large rainfall events (D'Olivo & McCulloch, 2022). More variable rainfall patterns due to human induced climate change may also contribute, both directly and indirectly by causing vegetation degradation.

Studies in southeast Australia and globally demonstrate that infiltration capacity is much higher under trees than in cleared areas, reducing surface runoff volumes during rainfall (Ellis et al., 2006; Leguédois et al., 2008). Plant roots are known to increase soil porosity (Torri & Poesen, 2014). Tree clearing reduces use of groundwater by vegetation, resulting in additional runoff in large events when groundwater stores are full (Roth et al., 2002). Decreased storage and use of groundwater following tree clearing is consistent with the observed increases in runoff variability following tree clearing (Pena-Arancibia et al., 2012). Evapotranspiration 'pumps' water back to the atmosphere via leaves (Larsen et al., 2013), suggesting that the amount of vegetation rather than simply ground cover is important for controlling runoff. Recent measurements indicate that water use by woodland trees is smaller than previously thought (Owens et al., 2019), indicating that their effect on infiltration capacity is relatively more important. Alongside vegetation degradation, soil degradation will also help to drive increased runoff (see Section 2 – soil degradation).

Studies of hillslope runoff provide insight into how low ground cover, independent of tree cover, can increase runoff volume, peak rates and frequency. Instrumented plots and hillslopes in the Fitzroy and Burdekin catchments indicate that ground cover, biomass and soil surface condition each play a significant role in reducing hillslope runoff (Bartley et al., 2017; McIvor et al., 1995a; 1995b; Scanlon et al., 1996; Silburn & Glanville, 2002). This behaviour is observed more strongly in smaller events than large events (Bartley et al., 2014a; McIvor et al., 1995a). The surface infiltration capacity of hardsetting or crusting soils declines at ground cover levels below 75% (Roth, 2004). This relatively high threshold indicates that runoff is controlled more by vegetation biomass and soil surface characteristics than by cover per se (Fraser & Stone, 2016). Deep rooted perennial native grasses tend to provide macropores that reduce hillslope runoff more than the stoloniferous grass Indian Couch (*Bothriochloa pertusa*) (Bartley et al., 2014a; Roth, 2004). Hillslope-scale runoff to streams is more heavily influenced by the presence of bare areas near the bottom of hillslopes than by hillslope average cover (Bartley et al., 2014a).

Numerous plot, hillslope and small catchment studies have observed an association of higher hillslope sediment yields with higher runoff volumes and peak rates. For example, cropped, and grazed hillslopes have greater runoff volume, peak rate and frequency compared with Brigalow hillslopes (Elledge & Thornton, 2017), and higher sediment and nutrient loads (Thornton & Elledge, 2018; Tiwari et al., 2021). Similarly, more heavily grazed hillslopes and small catchments have higher sediment yields and runoff than areas with light grazing (Koci et al., 2020b; Thornton & Elledge, 2018). However, these associations do not confirm increased runoff as a primary cause of increased sediment loads. For example, longitudinal studies of removing cattle grazing have observed large reductions in hillslope sediment yield while surface runoff levels continued unchanged (Bartley et al., 2010b; 2014a; Hawdon et al., 2008). On low relief landscapes where gradients are too low to form channelised rills and gullies, the erosive power of overland flow is very small compared with that of rain splash erosion, and so sediment yield is determined by vegetation cover and surface disturbance rather than runoff volume (Johns et al., 1984).

In summary, increased runoff is unlikely to be as significant in causing increased sediment exports as other biophysical drivers associated with grazing and cropping land uses such as reductions in ground cover and surface disturbance. The significance of increased event runoff on gully and streambank erosion is discussed in sections below.

What is the relationship between land condition and sediment and particulate nutrient runoff for management of Great Barrier Reef catchments? (Secondary question 3.4.2)

Land condition relates to "the status of present vegetation in relation to potential vegetation for the site" (McIvor et al., 1995b), or the capacity to produce forage for grazing relative to the potential capacity of the land type (Hunt et al., 2014). Assuming that capacity to produce forage can impact the forage biomass and ground cover existing at a given time in grazed areas, land condition conceptually therefore influences the erosion risk associated with a given stocking rate (Thorburn & Wilkinson, 2013). However, the degree of prediction provided is uncertain.

A variety of land condition assessment methods have been published but "all methods include … the herbage composition and some include other vegetation and soil characteristics" (McIvor et al., 1995b). Factors supporting forage production are commonly accounted for, as are the influence on state of current vegetation removal by grazing or fire, and the physical services provided by the community structure (Tongway & Hindley, 2004). Metrics used typically include i) the degree that forage is perennial, palatable and productive ('3P' composition) as an indicator of the capacity to respond to rainfall at different times of the year or larger climate disturbances such as drought, ii) vegetative ground cover or grass basal area, iii) soil surface condition (e.g., evidence of infiltration and stability versus runoff and erosion), and iv) the amount of weeds or woody thickening (Beutel et al., 2021; Hunt et al., 2014; McIvor et al., 1995b). The specific metrics used are typically adapted to local vegetation structure (McIvor et al., 1995b). Condition is commonly reported in classes of A, B, C and D where A is best condition (Beutel et al., 2021; Hunt et al., 2014; McIvor et al., 1995b; Tongway & Hindley, 2004).

The inclusion in land condition assessment of indicators of surface infiltration and hence surface runoff which accelerates hillslope sediment delivery and gully and streambank erosion, means it can be expected that sediment export to the GBR is better predicted by land condition than by vegetation cover alone (Roth, 2004). This is important because infiltration capacity is high when ground cover is >75%, but particularly when it occurs together with the presence of perennial tussock grasses, and soil biological activity (Roth, 2004; Wilkinson et al., 2014b). However, given that propensity for erosion is only one of many components in land condition assessment, variability can be expected in the relationship between land condition and sediment and particulate nutrient yield. Unfortunately, relationships between land condition and sediment or particulate nutrient yield from hillslopes or more broadly, have not been directly quantified. Several studies have covered components of land condition and indicators of erosion or sediment yield, with mixed results:

1. One study assessed land condition using indices representing vegetation, soil and site conditions (McIvor et al., 1995b). The soil index was intended to indicate surface infiltration capacity and occurrence of erosion and hence sediment yield. Across 10 locations, the soil index for D class plots was lower than that for A class plots in 7 out of 10 cases (McIvor et al., 1995b). The soil index declined monotonically between class A and lower classes for 3 of 10 plots and two of those 3 plots displayed monotonic decline in both years of monitoring. It is noted that some autocorrelation is expected between each of the input indices and resulting land condition.
2. Another study of soil surface condition measured sediment and nutrient concentrations in plot runoff, observing that sediment concentrations in runoff were higher from plots with poor soil surface condition (termed erosional surfaces), than from plots with better soil surface condition. However, this relationship was observed only at bare to low cover levels. Nutrient concentrations were not systematically related with soil surface condition at any cover level (Roth, 2004).
3. A longitudinal study of the response to reduced grazing pressure observed an increase in ground cover and in the proportion of vegetation that was perennial tussocks (indicating an improvement in the vegetation component of land condition). It noted an accompanying decline in TSS concentration in hillslope runoff but not in hillslope sediment yield, with runoff volumes remaining high in wet years later in the study. Catchment sediment yield also did not decline (Bartley et al., 2014a).
4. A land condition assessment study rated hillslope erosion severity in terms of degree of subsoil exposure and vegetation cover, categorising all sites in A condition as having Very little soil erosion evidence, and finding that the occurrence and proportion of sites with Minor soil erosion or greater categories of erosion was progressively higher at B, C and D condition sites. The Moderate erosion category occurred at only C or D condition sites, and Severe erosion occurred only at D condition sites (Hassett, 2022). Of the four studies this was the only one to indicate a reasonably strong relationship with indicators related to sediment yield, although not with sediment yield directly.

These studies indicate that land condition is not reliably related to hillslope soil loss but that it can indicate differences in erosional status between the extremes of very low and very high ground cover. At low ground cover levels, land condition may indicate spatial patterns in hillslope sediment yield (Roth, 2004). However, such patterns may be related to differences in runoff volume from upslope. Spatial heterogeneity in condition between terrain units is acknowledged based on differences in soil water accumulation, implying that landscape-scale soil loss may be poorly indicated by landscape averages of land condition (Tongway & Hindley, 2004). A similar dependence on spatial arrangement in the relationship between hillslope erosion and low ground cover was noted in an earlier section.

Other methodological issues may also complicate detecting a relationship between land condition and sediment and nutrient loss. Land condition assessments are complex (Roth, 2004), and the land surface condition component (the component most related to erosion) is difficult to assess correctly (Hassett, 2022). Since land condition can change through climatic sequences, regular assessment is required, which suggests that a remote sensing approach would be advantageous (Karfs et al., 2009; Pahl, 2015). To date, ground cover alone can predict condition correctly at more than 60% of A and D condition sites but cannot predict B or C condition reliably, indicating that a multi-parameter approach is required (Beutel et al., 2021). Poor prediction of ground cover under tree cover is a particular problem (Karfs et al., 2009).

It appears unlikely that gully and streambank erosion would be well related to land condition averaged across properties or catchments, although together these processes supply more than three quarters of GBR sediment exports (Question 3.3, Prosser & Wilkinson, this SCS). However, gully and streambank erosion are related to vegetation cover and characteristics within those landscape elements (Thorburn & Wilkinson, 2013; Wilkinson et al., 2018). The next sections consider the effect of vegetation degradation on gully and streambank erosion more broadly.

d) Gully erosion

Gully erosion is the largest sediment source in GBR catchments, supplying an estimated 54% of sediment export to the GBR (Question 3.3, Prosser & Wilkinson, this SCS). Gully and streambank erosion have been identified as key processes that elevate sediment yields from grazing land and from past alluvial mining areas (Lewis et al., 2021). Paddock-scale sediment yields from grazing land with gullies are several times to an order of magnitude higher than land without gullies (Brodie & Mitchell, 2006; Neil et al., 2002). The area occupied by gullies is estimated to have increased ~10-fold since European settlement in parts of northern Australia (Shellberg et al., 2010). As well as being a significant sediment source, gully erosion can provide pathways for accelerated movement of particles down hillslopes to streams (Rayment, 2003).

The timing of gully initiation indicates that vegetation degradation is an important driver of this erosion process. For example, extensive and active gully networks along steep banks in the Mitchell River catchment adjacent to the GBR catchments were initiated in the decades immediately following the introduction of intense cattle grazing which had large impacts on vegetation in the riparian zones (Shellberg et al., 2016). Gully erosion is observed to be more extensive in areas with higher stocking rates and vegetation that is degraded in composition and has lower cover (Wilkinson et al., 2018). Over time, increases in the grazing pressure from increased sheep and cattle numbers and introduction of larger cattle breeds combined with drought and flood cycles, probably resulted in a threshold being reached whereby the land became susceptible to gully initiation because of factors such as reduced ground cover, soil compaction, and tree clearance (Hughes et al., 2009).

Gullies have larger extent in cleared land than in nearby intact forest of equivalent topography, indicating that where clearing has occurred there has been more incision and sediment yield than in comparable locations protected from grazing and left in a forested state (Walker et al., 2020). Experimental studies in southeast Australia and globally have confirmed that the initiation of gully erosion is sensitive to vegetation degradation (Prosser & Slade, 1994; Prosser et al., 1995). These observations are consistent with a global review which found that gully head cuts extended to smaller catchment areas and slopes, resulting in larger gully extents and larger sediment yields, in tilled soils on cropland and grazed rangeland compared with areas having permanent vegetation cover at higher levels such as in pasture and native grassland and forest (Torri & Poesen, 2014). That global review provided functions relating gully extent to vegetation cover, which have been used to demonstrate the additional gully lengthening likely to result from clearing existing tree cover (Shellberg, 2020).

Once gully erosion is initiated, the instability from high surface gradients in drainage lines results in high sediment yields continuing for many decades (Hairsine, 2017; Hughes et al., 2009). The rate of wall erosion within established gullies is inversely related to gully wall vegetation cover (Wilkinson et al., 2018) and is especially high where gullies remain denuded of vegetation (Daley et al., 2021). Gully erosion has persisted for over 100 years in many locations and while the rate of gully extension declines in the longer term as upslope catchment areas decline, even then it remains a major catchment sediment source (Wilkinson et al., 2018). In summary, degradation of vegetation in gullied areas and the resulting geomorphic instability is a historic and ongoing driver of sediment and particulate nutrient export. It can be expected that gully erosion rates will continue to adjust as the land use intensity and vegetation function continues to change.

Gully head cut erosion occurs where surface runoff enters gullies (Koci et al., 2020a; Walker et al., 2021). Once gullies have formed, their rate of expansion becomes correlated with annual runoff volumes (Koci et al., 2021; Wilkinson et al., 2018). On that basis, a doubling in event runoff from vegetation degradation on hillslopes would itself result in a doubling in gully erosion rate. This can be compared with a tenfold increase in gully extent since 1850 (Shellberg et al., 2010) to conclude that vegetation degradation itself is the largest primary biophysical driver of gully erosion, with accompanying increases in runoff volume being a contributing driver.

e) Streambank erosion

Direct access of cattle to streams and resulting degradation of riparian vegetation has long been identified as a contributor to anthropogenic exports of sediment to the GBR (Haynes & Morris, 2004; Packett, 2020). Deep-rooted intact riparian vegetation provides bank stability but 60% of native riparian vegetation in the tropical cropping zones of the GBR catchments was cleared by 2003 (Hairsine, 2017). Clearing of riparian vegetation has been common on coastal floodplains and in upland grazing areas. A survey of 118 frontage country sites mainly in the Burdekin River basin found that 80% were in C or D land condition (Hassett, 2022; p88).

There are several mechanisms by which degradation of vegetation on streambanks, bars and benches within the channel can increase streambank erosion. Vegetation protects the soil surface from rain splash and from disturbance by livestock. It also protects the surface from scour by stream flow both locally and by slowing flow in the channel more broadly. Vegetation elevates the soil's cohesive strength to reduce mass failure of the bank (Abernethy & Rutherfurd, 1998; Paul et al., 2018). In headwater areas, riparian trees can provide woody debris in the channel that increases the hydraulic resistance of the channel and banks. In middle reaches, the main role of riparian vegetation is to strengthen the bank substrate by tree roots. In lower reaches, where channels are often wider and banks higher, vegetation maintains steeper bank geometries (Abernethy & Rutherfurd, 1998; Bartley et al., 2017). Vegetation that includes a combination of grasses and dense woody plant cover is particularly effective, and continuous intact riparian vegetation is also important to river stability (Prosser, 2018).

Several studies have demonstrated the substantial impact of vegetation degradation on streambank erosion and sediment loss. Removal of riparian vegetation accelerates bank erosion by one to two orders of magnitude (Prosser, 2018). In the Daintree River, areas where riparian vegetation has been removed had a streambank erosion rate 6.5 times higher than where there was intact vegetation (Bartley et al., 2008). Sites in the Fitzroy with poorer riparian condition had poorer water quality (Chua et al., 2019). A survey of 435 riparian sites found that at sites with heavy grazing pressure, there was nearly twice the rate of occurrence of streambank instability at moderate or severe levels (>31% of the site) relative to sites with moderate or light grazing pressure. Sites with heavy grazing pressure had approximately three times the rate of occurrence of soil erosion in riparian zones categorised as heavily disturbed and severe compared with sites with Moderate or Light grazing pressure (Hassett, 2022). In this context, grazing pressure refers to the amount of forage consumption by livestock relative to plant growth. These findings are supported by numerous studies globally including in southeast Queensland, that remnant riparian tree cover greatly reduces streambank erosion rates (Bartley et al., 2017).

As for hillslope and gully erosion, the effect of degradation of riparian vegetation on bank erosion at a location is dependent on the nature and extent of degradation and also on natural drivers such as stream power, river channel sinuosity and presence of erodible soils (Bartley et al., 2017; Prosser, 2018). For example, the Mulgrave River displays little sign of excessive bank erosion even though trees have been removed and the native riparian vegetation is largely replaced by weeds (reported in Tsatsaros et al., 2013).

Alongside hillslopes, gully and streambank erosion supply approximately 40–50% of particulate nutrient exports to the GBR (McCloskey et al., 2021), and so vegetation degradation is a primary biophysical driver of anthropogenic particulate nutrient exports.

f) Decline in function of sediment deposition processes

Vegetation provides hydraulic roughness which slows flow within channels and on floodplains (Brodie et al., 2007; Larsen et al., 2013). Therefore, removing or degrading vegetation can reduce the capacity to retain fine sediments within catchments and so increase exports to the GBR. However, much of the sediment erosion and delivery occurs during large events, and so the magnitude of these effects is likely to be smaller than the effects of vegetation degradation on erosion processes.

Reduction in channel deposition

Significant deposition occurs within some floodplain river channels. Sediment dating studies on the Normanby (Pietsch et al., 2015) and Fitzroy Rivers (Hughes et al., 2010) have determined that storage of fine sediment can be considerable in some areas (up to 55% by volume of bench material), with sediment residence time typically greater than a century. Therefore, removal or degradation of riparian vegetation in these areas can be regarded as a driver for reduced deposition and thus increased exports to the GBR. It has not been established how widespread the situation of river benches being significant stores of sediment is (Prosser, 2018). Enlargement of river channels caused by vegetation degradation, and floodplain drainage systems, can increase flow velocities and therefore the concentration of flood peaks. Enlargement of river channels through erosion confines larger amounts of hydraulic energy and thus sediment transport capacity within the channel, reducing the opportunity for sedimentation within river systems and so increases loads to the coast (McJannet et al., 2012).

Reduction in floodplain deposition

In some rivers including the Tully and Murray Rivers, a large proportion of flood water naturally passes over bank. In this case, degradation and removal of floodplain vegetation which would otherwise slow the passage of flows is likely to have significantly increased the downstream fluxes of sediment (Wallace et al., 2009). However, the replacement vegetation may still have some roughness impact, such as sugarcane when it is fully grown (Larsen et al., 2013). River enlargement and channelisation caused by degradation of riparian vegetation reduces the occurrence of overbank flooding (Prosser, 2018), and thus the opportunity for floodplain deposition.

However, in terms of sediment exports, this effect of floodplain vegetation degradation is likely to be small relative to its impacts on local erosion processes. Most GBR floodplains are relatively ineffective in trapping sediments because naturally a small proportion of total flow is delivered over bank; most GBR rivers exceed minor flood levels for fewer than three days per year (Wallace et al., 2012). For example, there is relatively little modern sediment trapped on the lower Fitzroy River floodplain as a result of the large size of the channel and fine nature of the sediments, rather than degradation of floodplain vegetation (Smith et al., 2008).

Reduction in wetlands, estuarine and coastal deposition

Vegetation, especially emergent vegetation growing through the water column, has the capacity to slow down water flow, mitigate erosion and promote sedimentation or trapping in wetlands (Coops et al., 1996). Therefore, deposition within vegetated channel margins can be stabilised and resistant to remobilisation (Pietsch et al., 2015). However, the catchment scale effect of vegetation degradation in riverine wetlands to reduce sediment and particulate nutrient exports is small relative to overall increases in upstream sediment yields for two reasons. First, wetlands sufficiently connected to river systems to receive substantial sediment inputs also receive substantial throughflow of water, which reduces deposition, and second, in larger wetlands without emergent vegetation, deposited material remains available for remobilisation in subsequent large events (McJannet et al., 2012). Estuaries along the GBR coastline are mainly too small to have much effect on sediment and particulate nutrient exports to the GBR (Neil et al., 2002).

2. Soil degradation

The considerable proportion of land condition assessments indicating C and D condition in the Burdekin and Fitzroy regions indicates that soil degradation is likely to be widespread (Hassett, 2022). Cumulative soil erosion over more than a century of grazing has removed the A horizon of the soil profile in some denuded areas including sodic duplex soils, resulting in the current soil surface having a high bulk density, which reduces infiltration capacity and moisture water holding capacity and increases the rates of runoff by up to 5–10 times that of areas of >50% ground cover (Silburn et al., 2011). Rain splash, sheetwash and rill erosion can be significant sediment sources within gullies in erodible soil, and prevent degraded soil from recovering (Daley et al., 2023). Soil compaction by vehicle tracks also increases surface runoff (Silburn & Glanville, 2002).

Cattle grazing directly affects the soil to increase hillslope runoff generation and soil loss through surface pulverisation and compaction by hooves (Johns et al., 1984; Roth, 2004). The role of pulverisation is particularly important in ‘hard-setting’ soils prone to forming erosion resistant crusts at low cover levels (Johns et al., 1984), such as red chromosol soils on Granodiorite lithology (Roth, 2004). Grazing also affects soil indirectly by reducing plant size and number and the litter layer (Johns et al., 1984), thus reducing soil faunal activity such as earthworms which normally creates macropores for infiltration and surface roughness to slow runoff (Ludwig & Tongway, 2002; Roth, 2004) and increasing hillslope sediment delivery. Further, removal of vegetation reduces input of carbon to the soil which is important for maintaining the stability of aggregates that create macropores to allow infiltration (Johns et al., 1984; Roth, 2004; Torri & Poesen, 2014).

In summary, soil degradation is caused mainly by vegetation degradation and other drivers and acts to reinforce their effect on sediment and nutrient exports. It can be assumed that this means it is a widespread contributor to exports, but this has not been studied consistently across GBR catchments beyond land condition assessments.

3. Surface disturbance

a) Hillslope erosion

Sediment yield from hillslope surfaces is dependent on either prior detachment of soil particles from the crust such as by animal activity, or on rain splash erosion which is increased by vegetation degradation (Johns et al., 1984). Experimental studies indicate that surface trampling by livestock leads to accelerated hillslope erosion on its own (Roth, 2004). Coral cores show altered geochemistry consistent with increased sediment supply within a year or two of the commencement of livestock grazing (primarily sheep) in the inland southern part of the Burdekin basin in 1854–1856 (Lewis et al., 2007). It is likely that surface disturbance would have been at least as important as vegetation degradation during this time given the rapidity of the response. Catchment-based longitudinal observational studies also indicate that ongoing surface disturbance by hoof impact can be a large contributor to hillslope sediment yields independent of vegetation cover or tree clearing. For example, Hawdon et al. (2008) observed a 50% reduction of sediment yield within one year relative to a control exposed to ongoing grazing. In another study, reductions in suspended sediment concentrations and yields of more than 60% within 2 years of cattle removal were observed without any accompanying increase in ground cover levels (Bartley et al., 2010b; 2014a).

Surface disturbance is often accompanied by removal of vegetation cover such as tree clearing followed by overgrazing, and this combination greatly alters the capacity to retain runoff and soil (Ludwig & Tongway, 2002). However, sheetwash and rill erosion from grazed pasture/woodland is a comparatively minor contributor of sediment to the river network, and subsoil channel erosion is the main contributor in these areas (Hughes et al., 2010).

In addition to removal of the cover of trees and ground vegetation, high sediment yields in cropping areas are associated with surface disturbance by periodic tillage (Thornton & Elledge, 2022). Catchment sediment yields have been observed to double following the conversion from livestock grazing to cropping (Hughes et al., 2009; 2010). Sediment yielded from cropping areas tends to be surface soil material (Hughes et al., 2010), also consistent with surface disturbance by tillage being an important driver. Geochemical tracing results indicate that cropping areas on basalt lithology can be dominant sediment sources at basin scales (Douglas et al., 2006). Cropping is also associated with large increases in sediment yields in Wet Tropics catchments (Rayment, 2003). Multiple observational studies have found that soil erosion is reduced by reducing surface disturbance on cropping land by controlling wheel traffic (Brodie & Mitchell, 2006; Eberhard et al., 2017) or reducing the frequency of tillage (Carroll et al., 1997). Cropping tends to occur in areas of moderate to high soil fertility and so these sediment yields are associated with particulate nutrient yields.

Therefore, surface disturbance is a large biophysical driver of GBR sediment and nutrient yields from hillslopes. Cattle trampling and tillage are likely to be the largest effect of surface disturbance in GBR catchments, given the large spatial extents of these land uses relative to others associated with intense surface disturbance in GBR catchments such as mining or roads or urban (Lewis et al., 2021). However, surface disturbance by road construction and vehicular traffic on unsealed roads can also cause significant yields in some areas. For example, road surface runoff and tracks and fence lines were assessed as supplying a comparable amount of sediment as sheetwash and rill erosion across grazing land in the Normanby River basin (Howley et al., 2021). Construction of new urban areas can be an important source of suspended sediments locally due to the surface disturbance involved, especially on steep slopes in wet climates (Tsatsaros et al., 2013).

b) Gully and streambank erosion

Surface disturbance in proximity to drainage lines and streams is especially influential on sediment yields given that three quarters of catchment sediment yields are derived from these areas. In the upper Burdekin catchment, surficial and alluvial gold mining was a likely contributor to a sediment pulse which commenced around 1860 coincident with when this form of mining was widely occurring in the area, although a decline in sediment yield after such mining largely ceased was not confirmed (Bartley et al., 2018), suggesting that expansion of grazing may have supplied a comparable amount of sediment. Globally, it has been observed that roads and mines can have sediment yields several orders of magnitude larger than undisturbed lands if they are hydrologically connected to river systems (Carlson et al., 2019).

Where surface disturbance such as that associated with tree clearing exposes dispersible subsoils then rill and gully erosion can be initiated (Ludwig & Tongway, 2002). Surface disturbance by cattle tracks in riparian zones can also be a significant cause of erosion, through erosion of the track surface and by initiating gullies in the riparian area. One study in the Fitzroy estimated that cattle tracks may supply up to 30% of fine sediment loads (Packett, 2020), although the representativeness of the small sample area was unclear, as was whether this rate of erosion was historical or ongoing. However, studies in southeast Australia have also found that direct cattle access to streams causes streambank erosion (Brodie & Mitchell, 2006). Herbivorous feral animals, particularly pigs, disturb soil in riparian vegetation and near waterholes and can be a locally significant cause of surface disturbance affecting these processes (Roth et al., 2002).

4. Runoff concentration

Concentration of surface runoff from being dispersed across hillslopes into more defined pathways by linear features was identified as a significant driver of erosion and sediment loss by a small number of studies. Roads, and cattle trails are hydrological conduits driving gully extension (Koci et al., 2020a; Packett, 2020). Alluvial gullies have been identified as being formed from severely eroded cattle ramps and trails in or near streambanks in some areas of the Fitzroy River basin with erodible soils. Alluvial gullies often occur where trails intercept and concentrate hillslope runoff (Packett, 2020). In turn, gully networks increase runoff concentration (Walker et al., 2021), potentially increasing hillslope sediment delivery.

Floodplain drains also reduce the function of floodplain surfaces and vegetation to trap sediment supplied from local floodplain sources (Wallace et al., 2009). However, this effect is likely to be relatively small. Sediment transport connectivity between sugarcane fields and floodplain drains is increased, but connectivity remains generally low in most but not all situations (Visser et al., 2007). Floodplain drains in sugarcane areas can be either sources or sinks, or both at different times and locations depending on their catchment area, shape and vegetation cover and whether the source of runoff was local (runoff into the drain) or catchment-wide (backwatering from the river) (Visser et al., 2007).

Urban development concentrates runoff to locally increase the connectivity of surfaces to streams, resulting in increased runoff frequency, volume and intensity (Bartley et al., 2017). For example, impervious surfaces and roads increase the frequency and intensity of runoff (Carlson et al., 2019). Thus, runoff concentration can be important in some settings and the fine scales at which it operates may have contributed to it being overlooked relative to broadscale drivers.

5. Runoff detention

Anthropogenic increases in runoff detention by construction of hydraulic structures can reduce sediment export to the GBR by slowing runoff and enabling deposition which reduces sediment and particulate nutrient export to the GBR. Examples include hillslope contour banks, constructed wetlands, farm dams and reservoirs. This biophysical driver can reduce the effect of other biophysical drivers such as vegetation degradation which increases runoff, erosion and sediment delivery from hillslopes and gullies, or degradation of riparian vegetation which can reduce sediment deposition in river channels. Hillslope contour banks and constructed wetlands are described in Question 3.5 (Bartley & Murray, this SCS). Here the focus is on farm dams and reservoirs, which are not typically constructed specifically for water quality improvement, but which do affect the biophysical functioning of catchments including sediment delivery.

In calculating sediment and nutrient exports, the SedNet model accounts for the effect of farm dams within the hillslope sediment delivery ratio, and their effect has not been isolated from that of other drivers of hillslope sediment delivery such as rainfall intensity, hillslope gradient, vegetation, soil surface condition or gully network extension (McCloskey et al., 2021). No process studies of farm dam deposition could be identified in GBR catchments.

Reservoir trapping and floodplain deposition are the two largest deposition processes within GBR catchments (McCloskey et al., 2021). As a consequence of these two processes, exports to the GBR are slightly less than half of all sediment eroded within the catchments (McCloskey et al., 2021). Trapping of fine sediment in reservoirs is the largest sediment sink within the GBR catchments. It is estimated in the SedNet model based on the storage capacity of the reservoir, the longest impoundment length from the dam wall at full capacity and the discharge rate of the reservoir, modified to calculate the percentage daily trapping efficiency (Lewis et al., 2013; Wilkinson et al., 2014a). Numerous earlier studies also report sediment deposition in reservoirs and floodplains (e.g., Fentie et al., 2013), but these estimates have been superseded by improvements in modelling methods, which are described above.

Particulate nutrients use the same trapping models as fine sediment, meaning that any imbalance between additional nutrient adsorption from the water column onto sediment in the reservoir and desorption into the water column is neglected. These components are likely to be minor but have not been studied in GBR catchments.

The largest reservoir in the GBR catchments is Lake Dalrymple, as formed by the Burdekin Falls Dam, with a maximum capacity of 1,860,000 ML and an upstream catchment area of 114,220 km^2. This represents 88% of the total Burdekin River catchment area (129,700 km^2) and 27% of the total GBR catchment area (Hairsine, 2017). Since construction of the Burdekin Falls Dam in 1987 it has reduced peak daily discharge at the mouth of the Burdekin River (Lewis et al., 2018). The dam traps on average 66% of the suspended sediment inflows (Lewis et al., 2013). It is estimated that the Burdekin Dam has reduced the TSS export from the Burdekin River basin by ~35% compared to the pre-dam case (Lewis et al., 2009), but due to increases in erosion the basin export remains more than five times larger than the estimated pre-development load (McCloskey et al., 2021). The Fitzroy Basin has numerous impoundments. While almost all of these are small relative to their inflow, they cumulatively have a large effect on sediment delivery from upstream tributary catchments. This is represented in SedNet modelling by river sediment delivery ratios that are significantly smaller than 1.

Several studies have observed that deposition associated with runoff detention in impoundments varies between types of sediment depending on particle size and chemistry. In the Fitzroy, the small impoundments tend to retain little sediment from basalt lithologies (Douglas et al., 2006), which stays in suspension and is transported relatively efficiently and is identified in coastal sediments (Brooke et al., 2008; Smith et al., 2008). More efficient transport of finer sediment particles through the Burdekin Falls Dam has also been observed (Furuichi et al., 2016) and modelled (Lewis et al., 2013). Finer sediment particles such as clays have a higher content of particulate nutrients than silts. Therefore, it is likely that reservoirs have less effect on particulate nutrient exports to the GBR than they do overall on exports of sediment <20 µm. Their sediment trapping effect may be somewhat overestimated in some locations such as the Fitzroy River basin.

It has been noted that the sediment trapping function of dams can be offset by their effect on downstream river channel morphology, where a decline in bedload material can result in bank erosion and channel deepening (Larsen et al., 2013). However, no observational studies in GBR catchments were located. Gully and streambank erosion have resulted in increased bedload supply in most rivers and so such dam-driven erosion is likely to occur only in the immediate reach downstream of the dam before local erosion and tributary inflows outweigh this effect.

6. Global warming

The significance of global warming to date is likely to have been minor relative to vegetation degradation and surface disturbance but can be expected to increase progressively in coming decades. No study was located of the historic changes in flood and drought severity caused by global warming. However, the largest sediment fluxes occur during drought-breaking floods (McCulloch et al., 2003), and large events dominate long-term sediment yields (Koci et al., 2020b). A sensitivity analysis of the SedNet model has identified that streambank erosion and sediment export to the GBR is more sensitive to bankfull discharge (discharge associated with flow that fills the river channel) than to any other parameter (Fentie et al., 2005). Therefore, global warming increases in both flood magnitude (associated with occurrence of severe tropical cyclones and deep monsoon troughs) and drought severity can be expected to increase sediment and particulate nutrient exports (Brodie et al., 2008). The magnitudes of large floods and the condition of vegetation at that time will determine climate change effects on exports.

Climate projections indicate larger changes in rainfall variability than in mean conditions (Question 3.3, Prosser & Wilkinson, this SCS). The effects of global warming will therefore include increasing the magnitude of large floods, exacerbating vegetation degradation during droughts, and increasing the frequency of fire and expanding its occurrence into areas that have not historically been prone to fire. More severe droughts will increase the risk of further vegetation and soil degradation in grazing and cropping land. The multiple effects of climate change on vegetation and discharge interact in complex ways with the multiple effects of land use, and there is little knowledge about the topic. Climate change will raise the importance of understanding the effects of large floods, droughts and fire on sediment exports.

7. Other

A small number of studies identified other drivers. Wildfire can trigger sediment and particulate nutrient mobilisation, particularly if the following rainfall event is large (Howley et al., 2021). However, this is here regarded as a natural biophysical driver and there was insufficient evidence that it is a significant biophysical driver of anthropogenic sediment and particulate exports because it was noted only in two studies in the Normanby catchment. Across much of the GBR catchments it is likely that fire frequency is today lower than it was in pre-development times due to the reduction in standing biomass by livestock and fire suppression activities in more intensive land uses.

8. How have these drivers changed over time?

Some general patterns in land use history extend across the GBR river basins, while the historical timing and intensity in land uses and associated biophysical drivers of sediment and particulate nutrient exports has been somewhat unique to each catchment. Time series of land use extent and characteristics in each Natural Resource Management region and catchment are documented by Lewis et al., 2021. Temporal coincidence between land use change and sediment exports is a common means by which the biophysical drivers were identified from the studies. The consistent historical increase in Ba/Ca (indicator of sediment impact) relative to luminescence data (indicator of freshwater impact) for the inshore corals from the Cairns, Townsville and Rockhampton regions points to a generalised ongoing increase in sediment loads in the inshore areas of GBR impacted by changes in land use and human expansion (D'Olivo & McCulloch, 2022), suggesting that the cumulative effect of all drivers may be increasing. Tree clearing has continued in recent decades (Reside et al., 2017). Average ground cover is an indicator of the incidence of low ground cover which has been tracked for decades and shows no substantial change during that time (Figure 3).

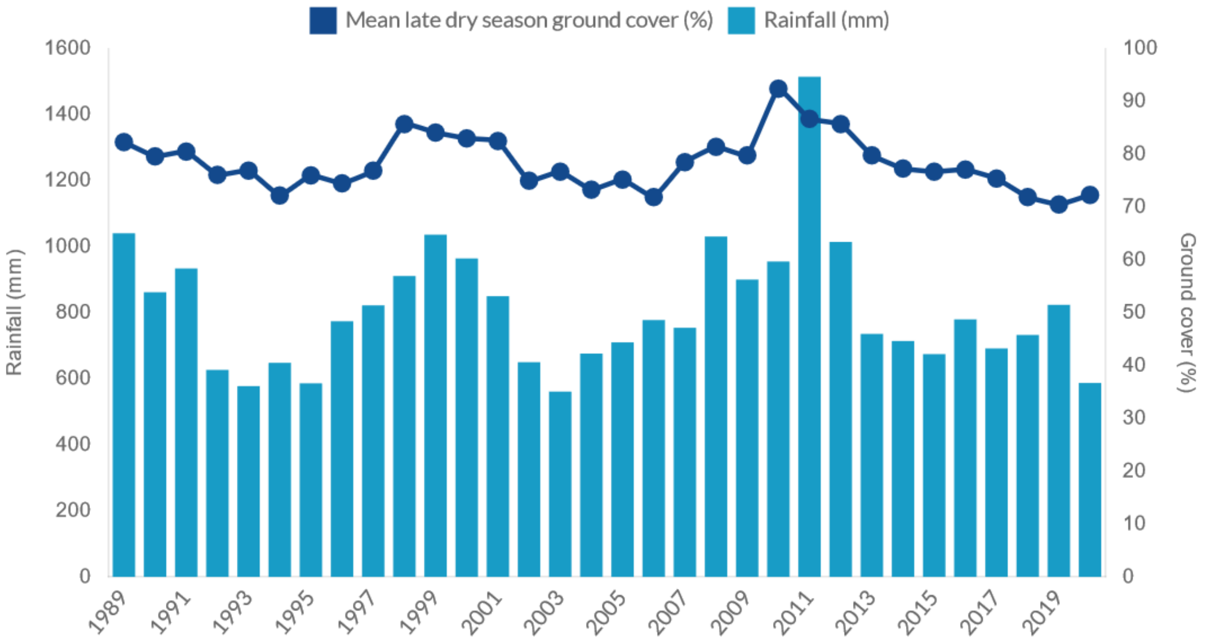


Figure 3. Spatially averaged late dry season ground cover (right hand axis) and annual rainfall (left hand axis) for the combined GBR catchment area. Reproduced from the 2020 Reef Water Quality Report Card (Australian & Queensland Government, 2022).

River basins for which some historical changes in sediment exports are relatively well known include the Burdekin and Fitzroy River basins. In those cases, there is sufficient information on land use history to make some inferences about how drivers have changed over time:

Upper Burdekin catchment:

- Sediment yields within the upper Burdekin catchment increased within years of the commencement of livestock grazing and surficial gold mining around 1860 (Bartley et al., 2018), presumably partly as a consequence of the associated degradation of vegetation.
- Smaller sediment yields during 1900–1950 were inferred by a decline in rates of local deposition, possibly associated with a decline in the extent of surficial gold mining, but this is uncertain due to limitations of that method. A decline in terrigenous effect was not observed in coastal coral chemistry (Lewis et al., 2021), which indicates that temporal changes in surface disturbance by mining did not have a larger effect than that of all other drivers such as vegetation and soil degradation and geomorphic changes.
- Sediment yields then increased from 1950 to record levels in some areas (Bartley et al., 2018) during a period when livestock numbers increased (Lewis et al., 2021). *Bos indicus* cattle breeds

became widespread from the 1960s, and the relative drought hardiness of this breed resulted in the carrying capacity of land being significantly exceeded (McKeon et al., 1990).

Burdekin River basin:

- The specific contributions of grazing and mining land uses to the biophysical drivers which elevated sediment loads from the Burdekin remain elusive and difficult to reconcile but each have been important at certain times (Lewis et al., 2021).
- Coral cores show increased Manganese (Mn) coinciding with commencement of livestock grazing (primarily sheep) in the inland southern part of the basin in 1854–1856, indicating the rapid effects of surface trampling and vegetation degradation on erosion of topsoils. This indicator occurred before gold mining expanded rapidly from 1867 (Lewis et al., 2021). Suspended sediment concentration in flood plume waters at locations in the central GBR doubled from around 1870. The multiple biophysical drivers came into effect progressively, such as surface disturbance by mining and soil degradation as vegetation degradation and erosion progressed.
- The spatial influence of the Burdekin sediment discharge increased further from the 1930s onwards (D'Olivo & McCulloch, 2022), suggesting a further increase in biophysical drivers of sediment export since that time.
- Recent decline in variability of coral chemistry observed at locations in the central and northern GBR may be caused by the reduction in suspended sediment loads reaching the coastal water due to the construction of the Burdekin Falls Dam in 1987 and increased retention of sediment since then (D'Olivo & McCulloch, 2022; Lewis et al., 2018). However, despite the presence of the dam, the net effect of the biophysical drivers is continued increased sediment exports relative to pre-development times. This is consistent with reservoir modelling of sediment deposition, and with budgets constructed from discharge and sediment concentration monitoring which both indicate that anthropogenic erosion in the Burdekin River basin exceeds the effect of the dam in trapping sediment by several times (Bainbridge et al., 2014; Lewis et al., 2009; 2013).
- Within the central GBR lagoon a strengthening of the inverse relationship between terrestrial runoff and coral calcification over the recent period 1969–2008 has been attributed to an overall decrease in water quality reflecting a combination of increasingly degraded catchments and greater variability in rainfall and river discharge (D'Olivo et al., 2013). The cattle herd in the Burdekin almost doubled during this period (Lewis et al., 2021), which is likely to have added to vegetation degradation and surface disturbance.
- Current anthropogenic loads are relatively large in the east and north of the basin, and one study found it is uncertain whether there has or has not been an increase in the flatter and drier inland parts of the basin (Mariotti et al., 2021).
- In summary, multiple datasets of different types are consistent with sediment delivery from the Burdekin River basin to the GBR initially increasing with the introduction of livestock and mining, remaining elevated over time (and even increasing) with the increases in cattle and cropping (Lewis et al., 2007), and declining slightly with the construction of the Burdekin Falls Dam (Lewis et al., 2021).

Fitzroy River basin:

- The residuals between luminescence and Ba/Ca for coral HMP01 [off Fitzroy] indicated a marked increase in suspended sediment concentration around 1920, some 30 years after European land uses commenced (D'Olivo & McCulloch, 2022). This delayed response may indicate progressive loss of water retention capability due to a decline in vegetation cover and condition.
- The effect of surface disturbance by tree clearing and subsequently by cropping tillage on sediment yields increased during the 1950s. Reductions in tillage since the 1970s are likely to have reduced sediment yield from cultivated land since then, but evidence is unclear (Hughes et al., 2010).
- Almost continuous historical increases in Ba/Ca variability at locations off the Fitzroy, reaching a maximum around the 1980s (D'Olivo & McCulloch, 2022), indicate a progressive and cumulative increase in drivers over many decades.

- Interannual variability in rainfall amount and spatial location makes it difficult to detect changes in sediment export from the Fitzroy River basin to the GBR since the 1960s, although the total suspended sediment concentration at a given flow rate has significantly increased in recent years which suggests that the drivers of anthropogenic erosion have continued to increase (Yu et al., 2013).

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

Approximately 30% of the evidence items were published in 2016 and subsequently. This current question has addressed biophysical drivers in much greater detail than they were covered in previous Scientific Consensus Statements. This Evidence Summary has consolidated understanding of the evidence of the biophysical drivers which was previously contained within individual evidence items, and synthesised evidence developed over the past five years about the magnitude of effect that individual drivers have on individual erosion sources. In particular:

- Studies of land use history, sediment tracers and coral geochemistry have added to understanding about the temporal changes in drivers.
- The effect of tree clearing and grazing pressure on hillslope erosion and land condition is better understood.
- The effect of vegetation degradation and low ground cover on gully erosion is now better understood.
- The effect of vegetation degradation on streambank erosion is somewhat better understood.
- Understanding of the historical changes in biophysical drivers has been consolidated.

4.1.3 Key conclusions

This iteration of the Scientific Consensus Statement used methods that were more ‘top-down’ than previous iterations to set the structure and to compile relevant studies. Previous iterations have not explicitly identified the biophysical drivers of anthropogenic sediment and particulate nutrient exports to the GBR. These exports are the net effect of all the drivers described here. It can be difficult to attribute the overall anthropogenic exports to individual drivers which often occur simultaneously. For example, land/tree clearing is often associated with subsequent reductions in ground cover and surface disturbance such as by tillage or cattle hooves. Anthropogenic sediment and particulate nutrient exports are also the result of multiple biophysical drivers associated with land use interacting with the natural drivers of climate, terrain, lithology and vegetative cover. However, sufficient quantitative and process studies have been made to identify the primary biophysical drivers as described below:

- The two most important primary biophysical drivers of anthropogenic sediment and particulate nutrient export to the Great Barrier Reef are vegetation degradation and surface disturbance.
- Vegetation degradation, including tree clearing (or more generally, land clearing), low ground cover and changed grass structure (towards non-native grass species), is the most frequently identified driver of sediment and particulate nutrient exports and is a primary driver. It has triggered geomorphic instabilities by causing large expansion of gully erosion and streambank erosion, and increased hillslope erosion. Vegetation degradation can also elevate sediment and particulate nutrient exports by reducing hydraulic roughness and therefore deposition within river channels, floodplains and wetlands, but this has a minor effect on exports.
- Surface disturbance is a primary biophysical driver of comparable importance to vegetation degradation, including cattle trampling and tillage. It is especially influential where it occurs around gullies and streambanks, given that gully and streambank erosion supply more than three quarters of GBR sediment. Surface disturbance around roads and urban construction earthworks is also locally significant.
- Several other drivers related to land use make smaller but still important contributions. Soil degradation triggered by vegetation degradation increases runoff generation and hillslope sediment loss, particularly in some soil types. Increases in runoff volume have elevated sediment supply from gully erosion, but by an amount several times smaller than from

vegetation degradation. Runoff concentration by roads, tracks and fence lines can exacerbate the effects of vegetation degradation and surface disturbance on gully erosion.

- An increase in runoff detention in large reservoirs is the only driver studied which has substantially decreased anthropogenic sediment and particulate nutrient exports to the Great Barrier Reef. For example, construction of the Burdekin Falls Dam in 1987 decreased sediment export from the Burdekin River basin by 35%. This driver is less effective at capturing fine particulate matter, has negative impacts on freshwater ecology, and is much more costly than interventions which stabilise erosion directly.
- Changes in the biophysical drivers over time are most well documented in the Burdekin and Fitzroy River basins. Significant events have included: surface disturbance associated initially with the introduction of livestock and subsequently with alluvial mining such as in the Upper Burdekin catchment, progressive and ongoing vegetation degradation associated with expansion and intensification of livestock grazing which increased Burdekin basin sediment export to record levels by the 1950s, historical and ongoing tree clearing including but not limited to the Brigalow bioregion which resulted in Fitzroy River basin sediment export increasing around the 1950s, expansion of cropping, dam construction and road and urban earthworks. More recent construction of large dams has had a smaller effect on exports than the cumulative effect of other drivers. Ongoing vegetation degradation including land/tree clearing, and surface disturbance, appear to be contributing to expansion in coastal water quality impacts in recent decades, especially where they occur in areas prone to or experiencing gully and streambank erosion.
- Climate change is projected to increase the magnitude of large floods, the severity of droughts and alter fire regimes, all of which may exacerbate vegetation degradation and gully and stream bank erosion processes to increase future export volumes and concentrations. Therefore, the need for vegetation protection in areas of sediment supply will become increasingly important. The overall effect of climate change on sediment and particulate nutrient yields has received limited attention to date and remains poorly understood due to complex interactions with vegetation and land use.
- Wildfire can exacerbate sediment exports and is likely to increase in importance because of global warming.

4.1.4 Significance of findings for policy, management and practice

Means to reduce exports of sediment and particulate nutrients

Ongoing vegetation degradation and hillslope erosion are much higher than average where ground cover is low either at broad scales during droughts, or permanently in vulnerable areas. The likelihood of overgrazing is elevated by historical declines in land condition. Hillslope erosion is lower if high ground cover and biomass levels are maintained in all years including in vulnerable areas, which may require major destocking during droughts or maintaining lower herd sizes on an ongoing basis. Vegetation degradation and tree clearing are continuing and appear to be adding to the exports over time. Past vegetation degradation on hillslopes cannot be completely reversed while current land uses continue. Revegetating bare patches which deliver disproportionately large sediment yields is a priority given that erosion rates are much higher at cover levels below 30–50%, especially in steeper and wetter catchments and in soils that are erodible or have high nutrient contents.

Gullies and streambanks together supply three quarters of sediment and 40–50% of particulate nutrients from a very small proportion of the total GBR catchment area. Vegetation degradation has elevated gully and streambank erosion primarily through its local effect to reduce resistance to erosion. The relationship between gully erosion and vegetation cover within gullies indicates that actions that improve vegetation cover within gullies are a priority to reduce exports, such as revegetating gullies and redistributing grazing pressure away from gullies (Question 3.6, Brooks et al., this SCS). The geomorphic instability evident in some major river channels also indicates that exports derived from streambank erosion can be addressed by revegetating riparian zones in extensive reaches to reduce the scour energy and build erosion resistance. Upslope vegetation degradation has also increased runoff volumes to accelerate gully and streambank erosion, but this effect is much smaller than the effect of local vegetation degradation reducing erosion resistance, and it would take major improvements in vegetation cover and composition to correct. Vegetation provides hydraulic roughness which slows flow and enhances deposition within channels, floodplains and wetlands, although the effect of vegetation degradation on this function has generally only had a minor effect on sediment export and controlling erosion is the primary function of vegetation which affects sediment export. Widespread weed incursions make reversing vegetation degradation a challenging prospect without active intervention and so targeting the most actively eroding elements within catchments is a priority.

Surface disturbance is a major driver of anthropogenic sediment and nutrient exports, with cattle trampling in grazing areas, tillage in cropping areas, and tree clearing being the most widespread causes. Minimising these activities is therefore a priority. For example, cattle trampling may be reduced by rotational grazing and by excluding livestock from streams. Reduced tillage practices are described in Question 3.5 (Bartley & Murray, this SCS). Tree clearing should be avoided, particularly in areas prone to gully and streambank erosion. The expectation of larger flood magnitudes and more severe droughts associated with climate change increases the importance of stabilising and revegetating streambanks and gullies, including by excluding livestock and establishing riparian buffers which can also reduce the concentration of runoff into gullies and streams.

Soil degradation is caused by vegetation degradation and enhances its effects on exports. Managing the disturbance of, and drainage from, cattle tracks and unsealed roads to reduce sediment delivery to streams is important in some catchments. Alluvial mining still occurs at small scale in some catchments and has a large impact locally.

Runoff retention in large dams has reduced exports to the GBR by ~30–40% from what it would otherwise be. If dams were constructed or enlarged downstream of catchments with high sediment and particulate nutrient yields, they could reduce exports to the GBR further, noting that basaltic and other fine-textured soils appear to be poorly trapped by dams. However, dam construction is much more expensive than stabilising erosion directly and has other ecological impacts.

Monitoring techniques

Tree clearing for agriculture has been a primary driver of increased sediment loss. Monitoring tree clearing can therefore provide a potential indicator of further increases in anthropogenic sediment and particulate nutrient exports.

Vegetation cover within gullies and streambanks can be used as an indicator of erosion (Thorburn & Wilkinson, 2013; Wilkinson et al., 2018). However, monitoring cover within gullies and streambanks requires finer-resolution methods than the optical remote sensing used across landscapes. Lidar is a monitoring method which can potentially indicate total vegetation cover at fine resolution within gullies and streambanks within GBR catchments, but establishing this capability would require further testing.

Hillslope ground cover is an indicator of not only current yields but ongoing vegetation and soil degradation. However, other metrics are also important to hillslope erosion including biomass, basal area, the extent of bare patches particularly in close proximity to and within runoff pathways (Kinsey-Henderson et al., 2005), soil surface condition (Roth, 2004), and presence of gully networks (Wilkinson et al., 2018) and streams. Monitoring these attributes, including as conceptualised in land condition frameworks, is difficult even at site scale (Hassett, 2022). Regular and systematic assessment is required, but currently only extreme differences can be detected through remote sensing of cover (Beutel et al., 2021). Considering the large contributions of gully and streambank erosion (Question 3.3, Prosser & Wilkinson, this SCS), average land condition is likely to be a poor indicator of river basin sediment exports.

Global warming is exacerbating these drivers by increasing drought severity and runoff extremes (Question 3.3, Prosser & Wilkinson, this SCS), and the frequency of large rainfall events and drought severity could be monitored to assess this. Scenario analysis would be the most effective means to account for interactions between global warming and land use impacts on vegetation characteristics and erosion.

Knowledge gaps

Very few studies have addressed the effect of ground cover or vegetation composition on gully erosion, yet vegetation degradation is the most significant driver of gully erosion, and gully erosion is the largest source. Very few studies have been able to isolate the effects of surface disturbance and vegetation hydrologic change associated with tree clearing. There has been relatively little research into the drivers of gully and streambank erosion and on the ability to reverse the effect of vegetation degradation and tree clearing on those processes. Relatively few studies have considered the drivers of particulate nutrient export independent from the drivers of sediment export. Particulate nutrient adsorption and desorption in large dams has not been studied in GBR catchments, although their net effect is likely to be relatively minor. Knowledge gaps are considered in more detail in Section 4.5 (Knowledge gaps).

4.1.5 Uncertainties and/or limitations of the evidence

Few studies have set out to identify the biophysical drivers of anthropogenic sediment and nutrient export to the GBR, and this analysis has involved extracting the relevant information from studies focused elsewhere. With only one quarter of the evidence items involving experiments, and some observational studies including either drivers or exports but not both in their scope, there was a substantial number of studies in which the drivers had to be identified or the size of their effects assessed through triangulation against other studies based on spatial location or time of occurrence. Some of the observational studies have been based on short load monitoring records considering the variable climate, which contributes some uncertainty in the relative importance of different drivers being established. These limitations reduce the precision of the conclusions, although not their findings. There have been few studies of gully and streambank erosion rates in any region to refine the significance of each driver on sediment and particulate nutrient yield today. Some responses to the biophysical drivers appear to display non-linear responses which could not be quantified in many cases. The ability to define the relationship of land condition with sediment and particulate nutrient export is limited as no studies of comprehensive land condition assessment also measured sediment yield at any scale. While soil degradation is likely to be a small contributor to sediment and particulate export, there has been no consistent study of soil degradation across GBR catchments.

Relative to drivers related to land use change, the effect of global warming is poorly understood, with both drivers affecting vegetation, runoff, erosion and deposition in complex and interrelated ways. However, the effects of global warming are less apparent than the large effects of drivers associated with land use.

The biophysical drivers causing anthropogenic sediment exports to the GBR represent a degradation pathway. The historical changes in exports resulting from those drivers may provide some general indication of the types of reductions in exports which would result from those drivers being reversed but time-lags and some hysteretic behaviour may be expected, and these are poorly understood.

4.2 Contextual variables influencing outcomes

Table 8. Summary of contextual variables for Question 3.4.

Contextual variables	Influence on question outcome or relationships
Climate change (or climate variability)	Long term variations in climate have confounded attribution to drivers in a small number of studies (e.g., Lough et al., 2015), but almost all studies were not materially affected. If there is a future increase in flood variability it would be expected to lead to increased exports (Question 3.3, Prosser & Wilkinson, this SCS).
Land use	In a small number of studies (e.g., Bartley et al., 2018), multiple land use changes occurred within the study timeframe, which complicated identifying the combination of drivers occurring.

4.3 Evidence appraisal

Relevance

The relevance of the overall body of evidence to the question was rated as Moderate. Of the 135 eligible studies used in the Evidence Summary, 36% were observational, 28% were experimental, 22% were review studies, and 14% were modelling studies. The scope of most observational field studies included covered either sediment concentrations or yields at various scales but not drivers, and so the identification of drivers relied on being able to triangulate changes in drivers and exports that were coincident in time or space. The small proportion of experimental studies also reduces the overall relevance. A number of the review studies identified associations between drivers and exports but did not conclusively demonstrate that they caused increases in exports.

The spatial coverage of GBR catchments was focused on the Fitzroy and Burdekin regions, few in the Wet Tropics and Cape York regions, and very limited in the Burnett Mary and Mackay Whitsunday regions. Within the Fitzroy and Burdekin regions the experimental studies predominantly occurred at a small number of locations. Individual studies each covered small areas of the overall GBR catchment area and were relevant to those areas but used methods which indicated broader relevance. However, there is little reason why studies are not equally relevant in comparable climate and soil zones in adjacent regions. Further, one of the strengths of the conclusions is the consistency between the biophysical drivers identified in GBR studies with those identified in other regions of the world. For example, ground cover is a strong driver that has been identified empirically across the world and the empirical studies are consistent with our understanding of the physics of erosion so there is a strong consistency in the evidence. So even if the influence of ground cover has not been investigated in some catchments, the strong consistency in evidence across many landscapes mean that it is reasonable to expect ground cover to have the same influence in those locations as in other catchments. Temporal relevance was Moderate because sediment and coral tracing and dating studies gave good spatial and temporal coverage including of the pre-development period. However, these comprised a small proportion of the evidence, while experimental and observational studies focused on the most recent decades.

While the qualitative influence of drivers is very well established, the precise quantitative influences in specific GBR situations is moderately understood. Drivers of anthropogenic sediment and particulate nutrient yields from hillslope erosion are very well understood, from gully erosion they are moderately well understood and from bank erosion they are understood in principle but not well quantified. The evidence on the primary biophysical drivers is sufficient for management practices and erosion control approaches to identify and address them, but further research would improve understanding of the quantitative influences of each driver in given settings.

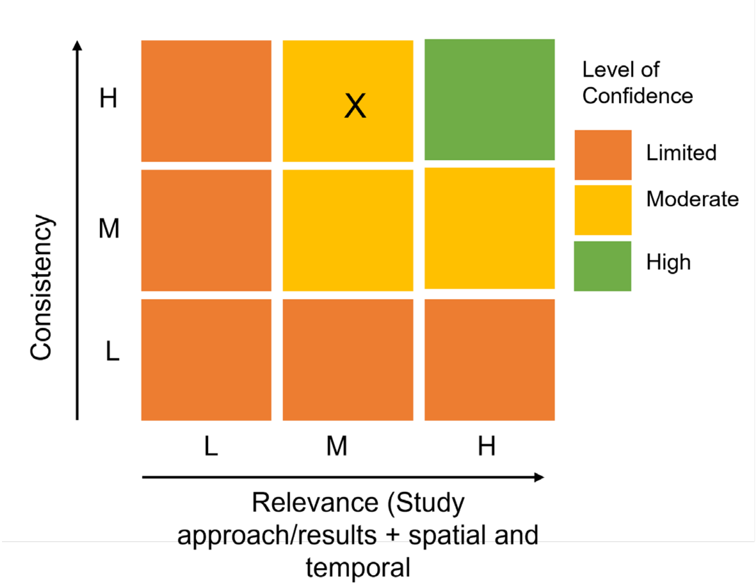
Consistency, Quantity and Diversity

In the authors experience and knowledge of the total potential available pool of evidence relating to the question, the quantity of evidence items eligible for inclusion was High for drivers of sediment export (>130), but Moderate for particulate nutrient export (32 studies, some of which made assumptions about the relationship). There was sufficient evidence to identify each of the drivers listed, and the primary drivers with the largest effects had a good quantity of evidence (Table 7). Those drivers with a small number of references were less conclusively identified as primary drivers and consistency was difficult to assess in those areas. The mix of study types was diverse across observational, experimental, modelling and review methods. The studies used a diverse range of measures and indicated a high degree of consistency in identifying the drivers and their significance.

Confidence

Based on the above analysis, the overall confidence in the body of evidence was Moderate, resulting from Moderate relevance, High consistency, Moderate quantity and High diversity (Table 9). Considering this confidence, claimed exceptions to the body of evidence would need to be supported by strong evidence.

Table 9. Summary of results for the evidence appraisal of the whole body of evidence in addressing the question. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency).

Indicator	Rating	Overall measure of Confidence
Relevance (overall)	Moderate	
-To the Question	High	
-Spatial	Moderate	
-Temporal	Moderate	
Consistency	High	
Quantity	Moderate (135 studies in total)	
Diversity	High (36% observational, 28% experimental, 22% reviews, and 14% modelling)	

4.4 Indigenous engagement/participation within the body of evidence

There was no Indigenous engagement or direct participation evident within the body of evidence.

4.5 Knowledge gaps

Table 10. Summary of knowledge gaps for Question 3.4.

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
Gully and streambank erosion rates to refine how each driver affects sediment and particulate nutrient yields today.	How do gully and streambank erosion rates vary based on current vegetation cover and composition, soil characteristics and upslope runoff?	Improved targeting and cost-effectiveness of erosion control programs; noting treatment cost and effectiveness also influence priorities.
Apparent inconsistency between sediment tracing indicating efficient delivery of fine-textured soils through river networks and low sediment delivery ratios in some catchments in the SedNet model.	What is the sediment delivery ratio of different soil particle sizes and does the SedNet model appropriately represent the net effect on delivery of sediment <20 µm particle sizes and particulate nutrients, through river systems and reservoirs?	Improved targeting and cost-effectiveness of erosion control programs.

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
Effect of ongoing tree clearing on sediment and particulate nutrient exports.	What is the annual extent of tree clearing and regrowth in catchments contributing to sediment and nutrient exports, including in areas vulnerable to gully and streambank erosion and in soil types with high nutrient content?	Assessment of need for approaches to reduce or mitigate the effect of tree clearing on erosion processes.
Understanding the reversibility of the effect of vegetation degradation on exports has been very rarely addressed but it is known to be partial or delayed.	Effect of removing or reducing grazing pressure from gullies and streambanks on erosion rates? Effect of removing or reducing grazing pressure on ground cover and land condition? Effect of revegetating gullies and streambanks on erosion rates?	Due diligence about the outcomes which can be expected from water quality improvement programs.
Extent of soil degradation and effect on sediment exports, particularly in the catchments contributing most to sediment and nutrient exports.	What is the extent of soil degradation affecting surface runoff and erosion rates in catchments contributing most to sediment and nutrient exports?	Increased priority for improved soil condition in target areas.
Impact of global warming on sediment and nutrient exports, including interactions with adaptations of land use.	What are the changes in drought and flood severity to date and projected, and what are their effects on vegetation, erosion and sediment transport?	Identifying changes in the erosion resilience and agricultural potential of GBR catchments and the adaptations required. New ability to assess the overall change in water quality considering both water quality improvement measures and global warming.
Understanding of the drivers of site and reach-scale variations in bank erosion.	What are the relative contributions of channel gradient and geometry, soil erodibility and riparian vegetation on variation in bank erosion rates?	Improved targeting and cost-effectiveness of erosion control programs; noting treatment cost and effectiveness also influence priorities.

5. Evidence Statement

The synthesis of the evidence for **Question 3.4** was based on 135 studies undertaken in the Great Barrier Reef and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (36% observational, 28% experimental, 22% review studies, and 14% modelling studies), and has a *Moderate* confidence rating (based on *High* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

The most important biophysical drivers of anthropogenic sediment and particulate nutrient export to the Great Barrier Reef are vegetation degradation and soil surface disturbance. Rainfall is a natural driver which determines the timing of exports. Vegetation degradation is caused by tree clearing (or more generally, land clearing) associated mainly with grazing and cropping land uses, low ground cover primarily from overgrazing and drought, and changes in the structure and function of vegetation including a shift to non-native grass species. Streambank erosion rates are several times higher where riparian tree cover has been removed. Gully and streambank erosion have been greatly accelerated by vegetation degradation and collectively deliver 77% of the sediment and 40–50% of the particulate nutrient export, from a very small proportion of the catchment area. Hillslope erosion rates increase sharply as cover declines below 30–50% because low ground cover exposes soil to erosion by rain splash and scour and increases the efficiency of sediment transport from hillslopes to streams. Vegetation degradation within stream channels, floodplains and wetlands also reduces sediment deposition in those areas. Surface disturbance, including trampling by cattle, tillage in cropping areas, unsealed roads and construction earthworks, is an important biophysical driver especially where it occurs around gullies and streambanks and in areas of erodible soils. Actions that reverse vegetation degradation and prevent surface disturbance can reduce export through reducing erosive forces and increasing erosion resistance, especially when actions are targeted within gully networks and riparian zones. Soil degradation, increases in runoff volumes, runoff concentration by roads, tracks, fence lines and drainage systems are less significant at the Great Barrier Reef scale, but are important drivers in some areas. The construction of large dams that detain some runoff has reduced anthropogenic exports of sediments and particulate nutrients to the Great Barrier Reef in some river basins. Climate change is projected to increase the magnitude of large floods and the severity of droughts, both of which are likely to exacerbate vegetation degradation, surface disturbance and soil degradation.

Supporting points

- The erosion rate of gully walls is inversely related to vegetation cover so it can be expected that gully wall revegetation will reduce sediment export. Revegetation of rapidly eroding gullies, or those in erodible soil, requires physical treatments to support establishment of vegetation.
- Surface disturbance such as tillage, trampling by cattle or feral pigs is a contributor to anthropogenic export of sediment and particulate nutrients especially around gullies and streambanks.
- Reversing vegetation degradation without active intervention is a challenging prospect, so targeting efforts to the most actively eroding features within catchments is likely to be important to efficiently reduce exports, however, assessment of cost-effectiveness of different options is also required.
- Overgrazing during droughts is a primary cause of vegetation degradation and can be avoided by maintaining forage consumption within limits of biomass availability during droughts, including by destocking.
- Soil degradation can include soil compaction, decline in soil fauna and carbon rundown, particularly in more erodible soil types including soils that have depth profiles with texture contrasts. It can increase exports by reducing the capacity for water to infiltrate the surface and be available to support plant survival, and by increasing the rates of surface runoff.
- An increase in runoff detention in large reservoirs is the only driver studied which has substantially decreased anthropogenic sediment and particulate nutrient exports to the Great

Barrier Reef. For example, construction of the Burdekin Falls Dam in 1987 decreased sediment export from the Burdekin River basin by 35%. This driver is less effective at capturing the fine particulates that have most impact in the marine environment, has negative impacts on freshwater ecology, and is much more costly than interventions that stabilise erosion directly.

- Land condition is a measure of forage productivity based on forage composition, ground cover, and soil surface characteristics. While land condition can indicate differences in erosional status between the extremes of very low and very high ground cover, it has not been consistently related to hillslope soil loss and it is difficult to measure.
- Changes in the biophysical drivers over time are best documented in the Burdekin and Fitzroy River basins. Significant events have included: surface disturbance associated initially with the introduction of livestock and subsequently with alluvial mining in the Upper Burdekin catchment, vegetation degradation associated with expansion and intensification of grazing which increased Burdekin basin sediment export to record levels by the 1950s, historical and ongoing land/tree clearing including but not limited to the Brigalow bioregion which resulted in Fitzroy River basin sediment export increasing around the 1950s, expansion of cropping, dam construction and road and urban earthworks. More recent construction of large dams has had a smaller effect on exports than the cumulative effect of the other drivers. Ongoing vegetation degradation including land/tree clearing, and surface disturbance, appear to be contributing to expansion in coastal water quality impacts in recent decades, especially where they occur in areas prone to or experiencing gully and streambank erosion.
- Climate change is projected to increase the magnitude of large floods, the severity of droughts and alter fire regimes, all of which may exacerbate vegetation degradation and gully and stream bank erosion processes to increase future export volumes and concentrations. Therefore, the need for vegetation protection in areas of sediment supply will become increasingly important. The overall effect of climate change on sediment and particulate nutrient yields has received limited attention to date and remains poorly understood due to complex interactions with vegetation and land use.

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 3.4

Theme 3: Sediments and particulate nutrients – catchment to reef

Primary Question 3.4 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?

Secondary Question 3.4.1 What evidence is there to link low ground cover, vegetation and tree clearing with poor water quality and runoff?

Secondary Question 3.4.2 What is the relationship between land condition and sediment and particulate nutrient runoff for management of Great Barrier Reef catchments?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Scott N Wilkinson	CSIRO	Catchment sediment and nutrients	Lead Author	All Sections, screening, data extraction, data appraisal, drafting, revision
2. Bruce Murray	CSIRO	Vegetation ecologist	Contributor	Online searches, screening, data extraction, review and editing
3. Ian P Prosser	CSIRO	Catchment sediment and nutrients	Contributor	Conceptual model, review and editing