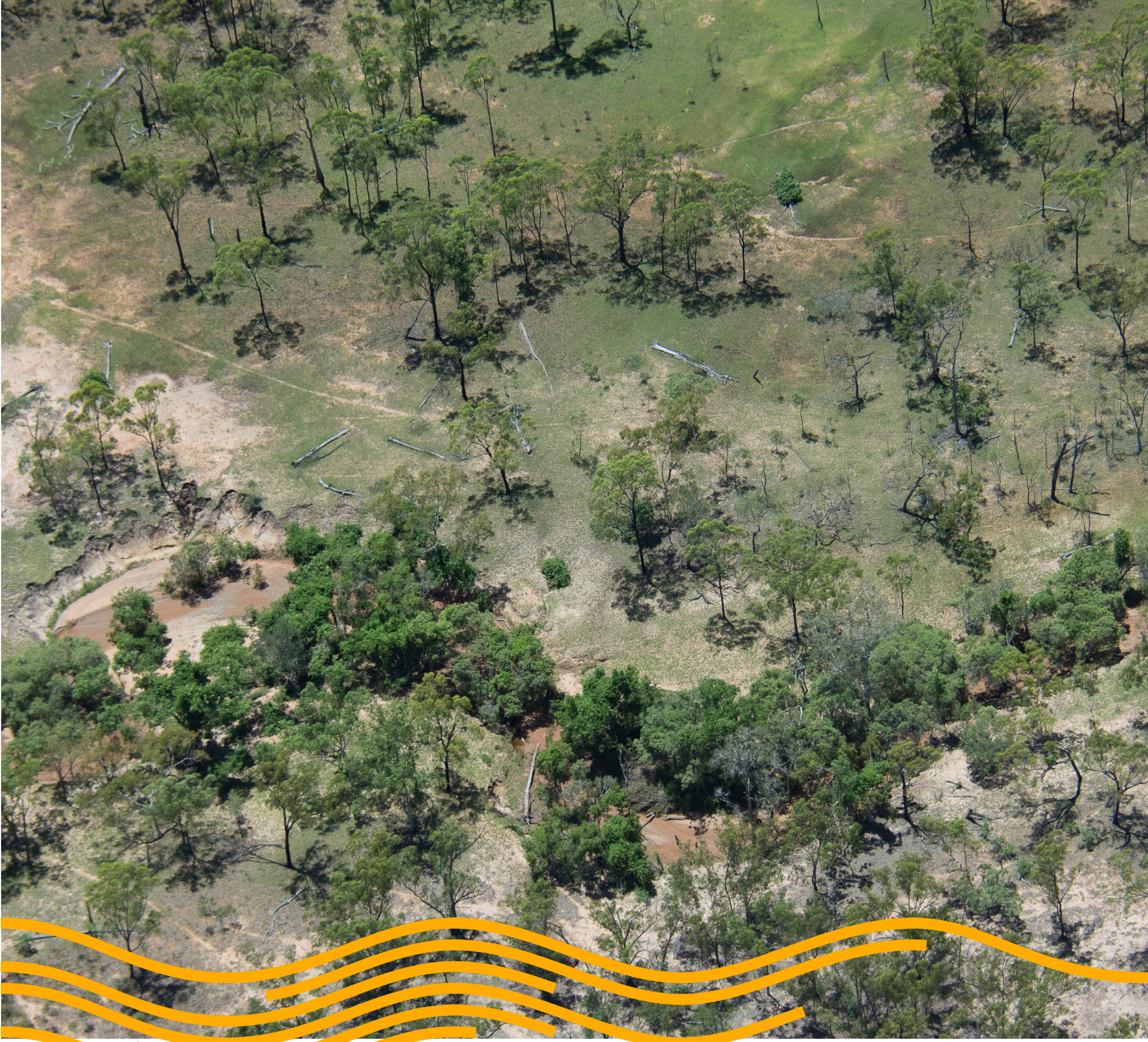

2022 Scientific Consensus Statement

Question 3.3 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?

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Citation

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The 2022 Scientific Consensus Statement was led and coordinated by C_2O 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.

Cover image credit: Matt Curnock

Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

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

What is the Scientific Consensus Statement?

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

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

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

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

Method used to address the 2022 SCS Questions

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

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

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

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

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

Two methods were developed for the 2022 SCS:

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

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

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

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

[2] Collins A, Coughlin D, Miller J, & Kirk S (2015) The production of quick scoping reviews and rapid evidence assessments: A how to guide. UK Government. https://www.gov.uk/government/publications/the-production-of-quick-scoping-reviews-and-rapid-evidence-assessments
[3] Richards R, Pineda MC, Sambrook K, Waterhouse J (2023) 2022 Scientific Consensus Statement: Methods for the synthesis of evidence. C_2O Consulting, Townsville, pp. 59.
[4] https://libguides.jcu.edu.au/systematic-review/define

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

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

Guidance for using the synthesis of evidence

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

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

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

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

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

Peer Review and Quality Assurance

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

Contents

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Executive Summary

Question

Question 3.3 How much anthropogenic sediment and particulate nutrients are exported from Great Barrier Reef catchments (including the spatial and temporal variation in export), what are the most important characteristics of anthropogenic sediments and particulate nutrients, and what are the primary sources?

Background

Rivers are a link between catchment land uses and marine impacts in the Great Barrier Reef (GBR). This question addresses the degree to which increased erosion and nutrient loss from catchment land use (Question 3.4, Wilkinson et al., this Scientific Consensus Statement (SCS)) results in higher than pre-development exports of sediment and particulate nutrients. The current exported load of sediment minus the pre-development load gives the anthropogenic export. Some express the multiplier of current load over pre-development load as an acceleration of suspended sediment export.

It is important to understand catchment exports to help understand their influence on the distributions of sediments in the marine environment (Question 3.1, Lewis et al., this SCS), the most relevant characteristics of sediment with a focus on fine sediment which is transported furthest in the GBR, and the impacts of sediment and particulate nutrients on GBR ecosystems (Question 3.2, Collier et al., this SCS). Question 4.4 (Prosser and Wilkinson, this SCS) covers the parallel and related topic of the exports of dissolved nitrogen (N) and phosphorus (P). Other questions also provide additional discussion of the transport and delivery processes for sediments and particulate nutrients from source to the end of catchment (Question 3.4, Wilkinson et al., this SCS) and for dissolved nutrients (Question 4.5, Burford et al., this SCS). Related topics are combined in the overall SCS Summary and Conclusions documents as part of the 2022 SCS Consensus Process.

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 were Web of Science, Scopus, and Google Scholar.
- Main source of evidence: GBR, as evidence from outside the GBR has very limited relevance to this question.
- From the initial keyword search more than 400 studies were identified through online searches for peer reviewed and published literature. 19 studies were added manually from citations in online search publications and personal collections, which represented 12% of the total evidence. 119 studies were found eligible for inclusion in the synthesis of evidence. All studies were obtainable.

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 two academic databases were searched.

[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

- Only GBR derived studies were included.
- The review was restricted to peer reviewed journal publications as well as peer reviewed publications of the major government programs.
- Only studies published post 1990 were included.

In the authors' professional opinion the review included the vast majority of research findings on the topic.

Key Findings

Summary of evidence to 2022

Overall there is a strong body of evidence on GBR catchment exports, covering multiple lines of evidence, a wide range of GBR catchments, and addressing each element of the question. Of the 119 GBR publications used, the majority of the papers (76) included observations or measurements pertinent to exports; 26 were modelling studies, of which 9 were statistical models of measured exports; 11 combined observations with models; and 6 were review studies containing some new data. There were 43 studies which had a GBR wide scope. The two biggest catchments by far, the Burdekin and Fitzroy River, had 30 and 14 studies respectively. The Tully-Murray (10), Johnstone (7), and Normanby (5) Rivers were also well studied. The spatial patterns of exports were informed by 61 studies; 46 addressed aspects of sources of material; 26 described the characteristics of sediment or particulate nutrients; and 47 contained information on the temporal patterns of exports, including the differences between pre-development and current exports.

Key conclusions from the body of evidence are that:

- Current exports of fine sediments are well above pre-development rates and overall are 1.4 to 3 times higher than pre-development estimates, and in the largest basins are 2 to 5 times above pre-development rates. Rates of increase[6] of fine sediment exports over pre-development rates are lower in the Cape York and Wet Tropics Natural Resource Management (NRM) regions than in other regions.
- Monitoring and modelling confirm that the Burdekin and Fitzroy basins are by far the largest exporters of total fine sediment and particulate nutrients to the GBR, each exporting an annual average load of over 1,300 kilotonnes of fine sediment per year and more than 3,000 tonnes of particulate nitrogen per year.
- Following the Burdekin and Fitzroy basins, the Mary, Herbert and Burnett River basins are the next largest exporters of fine sediment to the GBR (up to 600 kilotonnes per year). Other basins in the GBR catchment that export notable fine sediment loads (over 150 kilotonnes per year) include the Don, O'Connell, Johnstone and Normanby basins. All of these basins have a high proportion of anthropogenic exports.
- It is estimated that 54% of the total export of fine sediment to the GBR comes from gully erosion, with almost equal contributions from streambank erosion (24%) and hillslope erosion (22%). Each process can dominate in particular basins. In the wet tropical climatic areas, hillslope erosion tends to be the dominant source. In the dry tropical areas, gully erosion is by far the biggest source. Intensity of erosion is influenced by soil properties, rainfall and other attributes.
- The estimated proportion of total fine sediment loads exported to the GBR from each land use is well established through modelling, supported by monitoring data. It is estimated that grazing lands contribute 60% of the total fine sediment load from 73% of the GBR catchment area, sugarcane contributes 10% from 1.2% of the area, irrigated and dryland cropping contribute 4% from 2.8% of the area, urban contributes 2% from 0.7% of the area, and bananas and horticulture contribute 1% from 0.2% of the area. Other land uses such as nature conservation and forestry collectively contribute 23% of the total fine sediment load from approximately

[6] The rate of increase between the current and pre-development loads is formally referred to as the 'rate of acceleration' and is calculated by the division of the current load by the pre-development load.

22.1% of the GBR catchment area, but this is natural, not anthropogenic export. Anthropogenic load contributions of agricultural and urban land uses are much higher than those of conservation areas.
- The land use contributing the largest export of fine sediment varies among NRM regions. For example, grazing contributes significantly to exports in the Burdekin and Fitzroy regions, sugarcane contributes significantly to exports in the Wet Tropics and Mackay Whitsunday regions, and dryland cropping in the Fitzroy region. Urban land use contributes <5% of fine sediment export in all Regions.
- Fine sediment and particulate nutrient export occurs mainly during floods and the larger the flood event in a particular basin, the greater the export. However, the intermittent frequency of large floods means that annual exports can vary by up to three orders of magnitude in the large dry basins such as the Burdekin and Fitzroy.
- The Reef Water Quality Report Card 2020 estimates that ’Moderate’ overall progress has been made towards meeting the fine sediment load reduction target and ‘Very Good’ progress for the particulate nutrient load reduction targets. In some basins, targets have been exceeded while in others which were not given management priority, there has been little progress. For some management actions it may be several years until the benefits of management are fully realised, and it may take decades to detect reduced exports in the monitoring program because of the high annual variability of exports controlled by river discharge.
- Significant improvements have been made to the Paddock to Reef Program SedNet model (referred to as Source Catchments) in the last few years and it now better matches observed patterns of fine sediment and particulate nutrients. It provides the best available estimates of fine sediment and particulate nutrient exports as a result of the consistency in approach across all 35 basins and the wealth of information that can be extracted from the results.

Recent findings 2016-2022

Approximately 30 of the 119 papers reviewed (25%) have been published since the 2017 SCS. The strongest themes in the recent publications are:

- Better understanding of particulate N, its sources, and bioavailability, showing that more becomes bioavailable than was previously understood and much of that comes from intense land use and is not well represented just by looking at patterns of all particulate N.
- Better understanding of pre-development erosion rates and therefore pre-development sediment exports which strengthen the lines of evidence that current suspended sediment exports are well above pre-development rates, especially in those basins identified to be of high priority for management.
- Improved modelling whether that be statistical modelling of exports or improvements to SedNet and its full documentation in the peer reviewed literature. There is now closer agreement between modelling and observations which strengthens the confidence about sources, priorities, and export patterns that were reported in the 2017 SCS.

In addition, since 2017 there has been an expansion in the export monitoring program, including more sites and longer records of consistent measurement providing a better primary dataset to inform models and increase understanding.

Significance for policy, practice, and research

There is now even stronger evidence than in earlier Scientific Consensus Statements that current exports of sediment and particulate nutrients are well above pre-development rates of export. The marine chapters of this SCS and previous iterations show that these accelerated exports are having impacts on GBR ecosystems.

The spatial patterns of exports are reasonably well understood from the continuing Queensland Government river monitoring and modelling programs (GBR Catchment Monitoring and Modelling Programs within the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program), both of which provide a detailed picture of export patterns which can be used to explore marine impacts (see Questions 3.1, Lewis et al., and 3.2, Collier et al., this SCS).

Gully, streambank erosion, and hillslope erosion are all significant sources of exported material. All erosion processes should continue to be the focus of management with the priority determined by more detailed local assessments of sources and land uses.

Grazing is the biggest contributing land use to export because of its combination of huge areal extent and acceleration of erosion in degraded parts of the landscape. Sugarcane and dryland cropping are important contributors as well as they cover large areas and have accelerated erosion. Any land use which has accelerated erosion and where sediment is delivered efficiently to the coast will be a hotspot contributor and is worth considering for management, for example urban land use.

Particulate N transport is of increasing concern. Much of it can become bioavailable and it is emerging that its sources and export rates can be different enough from sediment or from dissolved nitrogen (Question 4.4, Prosser and Wilkinson, this SCS) to be worth considering and managing separately. There is quite a range of bioavailable particulate N concentrations among contributing land uses and erosion processes.

Catchment management programs are steadily working towards meeting the target reductions in exports, showing that management is working, but future progress will need to be at least as great as that to 2020 to meet all targets.

Both the export monitoring program and modelling programs, which are linked to policy and management, have been improved in recent years. Continued focus on both of these and continued improvements are needed to increase confidence in the patterns of exports; to confidently assess management progress; and to monitor a wider range of conditions and provide warnings of any unforeseen patterns in exports.

Key uncertainties and/or limitations

It is emerging that some particulate N is bioavailable but this needs more investigation and the sources of that material are quite uncertain but appear to be distinct from patterns of suspended sediment sources.

Monitoring of exports needs to continue to cover the full range of flood magnitudes and for long enough to detect trends in exports as short-term monitoring leaves much uncertainty about patterns of exports.

Annual reports on the monitoring program are published and there are some analyses over multiple years of data but full analysis of the record would help better understand particulate exports.

The SedNet model should continue to be improved through use of higher quality regional data. Some key uncertainties include source patterns in the Fitzroy basin, details of nutrient sources, patterns of riverbank erosion and details of river sediment delivery through some large catchments.

Monitoring and modelling of exports have been largely independent endeavours with monitoring results used to calibrate and test the SedNet model. Pioneering studies have shown there is much potential to formally combine a suite of measurements with modelling to better use all sources of information and formally represent uncertainties in ways that could be incorporated into GBR decision making.

Evidence appraisal

The overall confidence in the body of evidence was rated as High. The export of sediments and particulate nutrients has been the topic of many studies of GBR rivers for a long time. Individual studies have focused on the large intensively used catchments and those with the most intensive land use. Catchments not specifically studied by measurements are covered by several GBR-wide assessments and modelling studies of exports and monitoring covers the vast majority of total export so there is a high level of spatial coverage to the studies. Key concepts or theories from catchment exports in other regions of the world have been tested and adopted in GBR export research so there was no need to consider less directly relevant research. Many studies examine current exports but several also address pre-development exports, acceleration of exports over pre-development rates, variability with flood intensity, and changes with land use over time. There are now over 20 years of published catchment export monitoring data.

There was a High diversity of approaches including: direct measurements of discharge and constituent concentrations, annual export calculations from these, modelling of exports from all GBR catchments, modelling and geochemical tracing of the sources of exported material, and proxy records of exports over time in coral cores. There is now a High degree of consistency between independent types of studies. Earlier differences between observational studies of sources and their modelling have now largely been resolved as a result of model improvements. In addition to the internal consistency of findings within the export studies, they are consistent with upstream work on the drivers of erosion (Question 3.4, Wilkinson et al., this SCS) and downstream work on marine distributions of sediment (Question 3.1, Lewis et al., this SCS).

1. Background

Rivers are a link between catchment land uses and marine impacts in the Great Barrier Reef (GBR). Question 3.4 (Wilkinson et al., this Scientific Consensus Statement (SCS)) reviews the evidence for how much erosion has increased as a result of replacing natural vegetation with various land uses and how particular land use practices increase erosion. This question addresses the degree to which that increased erosion results in higher than pre-development exports of sediment and particulate nutrients to the marine environment. Knowledge about catchment exports helps to inform understanding about their influence on the distributions of sediments in the marine environment (Question 3.1, Lewis et al., this SCS) and the impacts of sediment and particulate nutrients on GBR ecosystems (Question 3.2, Collier et al., this SCS).

As described in Chapter 2 of the 2017 SCS[7], suspended sediments and nutrients play an important role supporting freshwater and marine ecosystems and they are naturally exported from catchments. However, there is general agreement that excessive amounts of sediments and nutrients under current conditions are impacting on the ecological health of the GBR. The evidence for impacts is described in detail in Question 3.2 (Collier et al., this SCS) but in summary it is through light attenuation, smothering and increased nutrient supply all of which reduce the diversity of corals and abundance of seagrass communities, and favour macroalgae and other heterotrophic and turbidity-tolerant species.

Priority basins for management have been identified, export reduction targets set, land management programs implemented to reduce erosion and nutrient loss at source, and progress is reported on how well export targets are being met. Catchment exports are thus an integral part of GBR management.

To support GBR water quality management the following knowledge about catchment sediment and nutrient exports is needed:

- Estimates of total exports coming from the land to the GBR to assess if the land is a significant source compared to marine sources.
- Which rivers have the greatest influence on GBR ecosystems through the size of their flood plumes and concentrations of sediment and nutrients.
- The seasonal and year-to-year variability of exports and flood plume concentrations to understand their marine impacts and how much smaller exports would need to be to remove impacts (target setting).
- The characteristics of the sediment and particulate nutrients that cause problems in the marine environment (Question 3.2, Collier et al., this SCS), including the bioavailability of particulate nutrients.
- Temporal trends of exports with past changes to land use and climate and thus how they might change in future.
- Which major subcatchments, erosion processes, and land uses contribute to anthropogenic exports so that they can be prioritised for management.
- How effective land management to date has been at reducing exports and meeting targets.

Sometimes the research focus has been on how accurately mean annual load of sediment and nutrient in each catchment is able to be calculated, but the point of outlining the needs above is that the absolute value of the mean annual load has little bearing on these questions. More often it is only necessary to know relativities: which basins pose the worst problems, at what times, which types of material, in which approximate concentrations, and from which major parts of large complex basins. Another point to emerge from the questions above is that there is no single measure of exports that can answer all the questions. It is not just the total load exported, the concentrations, the size of catchment, how many times greater than pre-development the export is, or the bioavailability of nutrients. It is a

[7] Bartley, R., et al., (2017). Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 2: Sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef. State of Queensland, 2017

combination of all these factors that matter to marine impacts, and it is only by understanding the marine impacts that appropriate export targets and management can be put in place.

1.1 Question

Primary question	**Q3.3** How much anthropogenic sediment and particulate nutrients are exported from Great Barrier Reef catchments (including the spatial and temporal variation in export), what are the most important characteristics of anthropogenic sediments and particulate nutrients, and what are the primary sources?

The question is interpreted in the following context. This section is not referenced but further explanation is included in the Key Findings and in addressing other SCS Questions (particularly Questions 2.3, 3.1, 3.2, 3.4 and to a lesser extent, 4.1 and 4.2).

Exports are often measured or calculated as loads carried by rivers at their downstream end as they discharge into the sea. In this question, loads and exports are used interchangeably as only the loads at the end of catchments/basins are considered.

Anthropogenic export is the difference between current loads and those under pre-development conditions and is the component that potentially causes problems, attributable to current land use or other changes in catchments. Anthropogenic load cannot be measured directly; it is calculated from the difference between pre-development and current loads, so this question considers evidence for these two components. The loads of sediment were not measured prior to European settlement so these are either estimated from models or measured using surrogates such as from sediment deposits or change in coral chemistry or measurements of long-term erosion rates of the catchments.

There are 35 river basins (also called catchments) that drain to the GBR ecosystems (Figure 1). These span from the Jacky Jacky River at the northern end of Cape York to the Mary River north of Brisbane. The defined river basins may be individual large rivers (such as the Burdekin River) or may include several small separate rivers. Measurements of sediments and nutrient concentrations are made in some but not all catchments using *in situ* monitoring at various time intervals. Calculations are made to scale the sampled concentrations up over time to the total load carried by individual floods, years, or sequence of years. This can be done because discharge volume of the river is monitored more continuously. Those measurements can also be used to extrapolate to unmonitored catchments using various catchment modelling techniques. The different types of measurements and models are reviewed as multiple lines of evidence as they all have strengths and weaknesses. The review looks at the calculated pattern of exports among the 35 river basins.

Much of the sediment exported is suspended in river water. Suspended sediment is the smaller sediment particles of clay, silt and fine sand. It can contain organic matter as well and have nutrients of phosphorus (P) and nitrogen (N) attached to the particles. The lighter the sediment particles, the easier they are to suspend and the further they travel. Most sediment transport occurs during floods and the finest particles can be transported as flood plumes well beyond the river mouth and well into the marine ecosystems of the GBR (see Question 3.1, Lewis et al., this SCS). This review considers the composition of particles (mineralogy and organic matter) that are exported from the river basins. The review considers sediment characteristics that have been identified as being important for GBR ecosystems, with a focus on the fine sediment (<20 µm) exports. While the focus of research has been on suspended sediment and its impacts, passing note is made of bedload sediment and its possible impacts for completeness.

There is a parallel question on the export of dissolved nutrients (Question 4.4, Prosser & Wilkinson, this SCS). In some ways the distinction between particulate and dissolved nutrients is artificial as during transport nutrients may move between dissolved and particulate phases. The most significant of these transformations are noted in this section of this question on nutrient characteristics but transformations in rivers are described in more detail in Question 4.5 (Burford et al., this SCS and for the marine environment in Question 3.2 (Collier et al., this SCS).

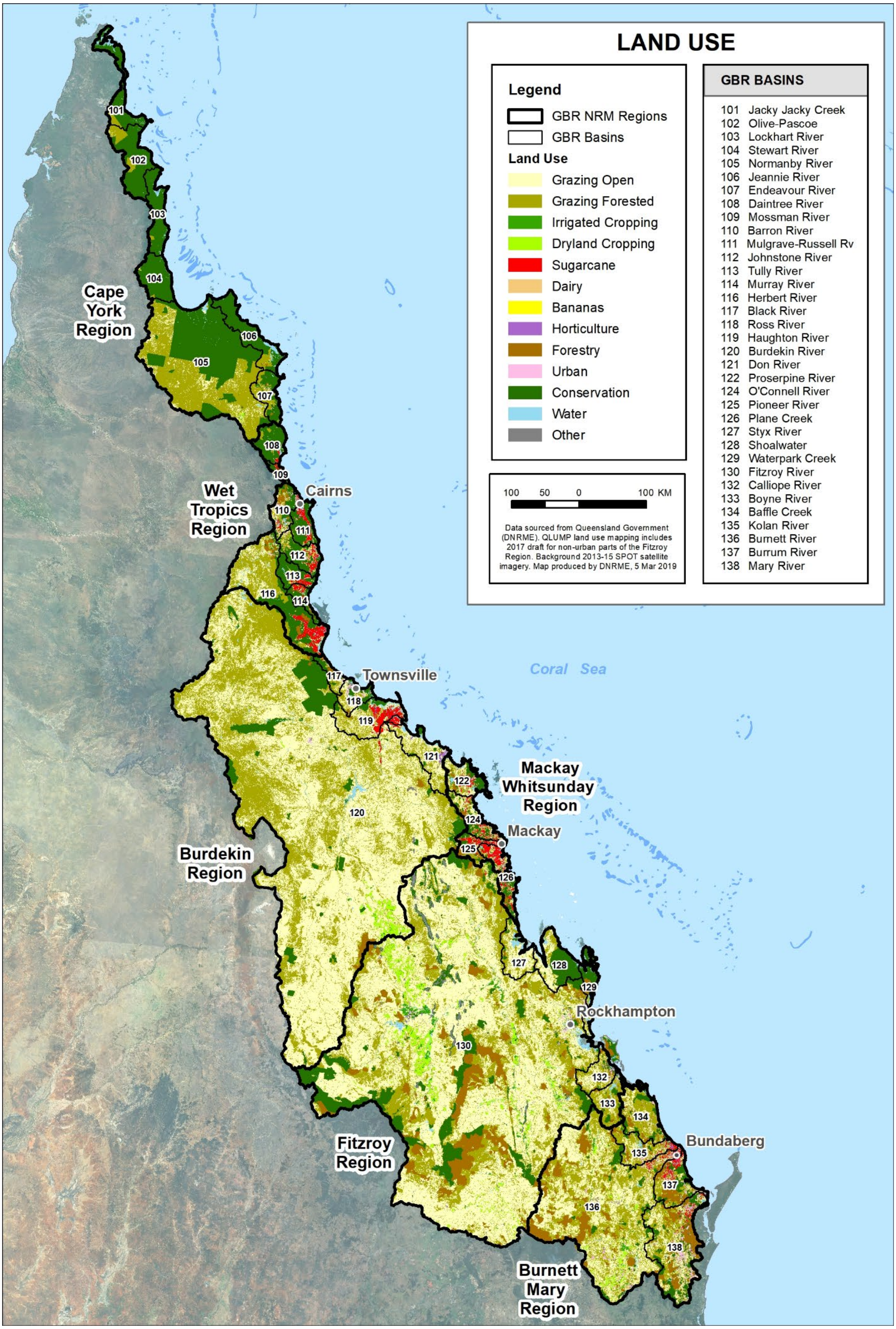


Figure 1. Natural Resource Management regions, river basins and land uses of the GBR (map provided by G. McCloskey from McCloskey et al., 2021).

River monitoring usually occurs somewhere in the last purely freshwater reaches before the estuary, where tides and increasing salinity start to influence flow and material loads. In the estuary and when river waters reach marine conditions sediment can flocculate and be deposited, and nutrients can transform to other forms often through biological mediation (see Question 3.1, Lewis et al., this SCS). Thus, river export may not be quantitatively the same as marine input.

As described in the 2017 SCS (Bartley et al., 2017), the anthropogenic exports of sediment and particulate nutrient can be attributed to different land uses. The contribution of a particular land use to export is a function of the area of land use, the intensity of erosion or nutrient loss within that land use, and how much of that material gets delivered to the mouth of the river. Some eroded material is deposited in river channels, on floodplains and in reservoirs for hundreds to thousands of years and does not contribute to sediment export. Thus, where catchment deposition is a significant moderator between erosion and export that is noted in this review.

Suspended sediment export can also be attributed to different erosion processes. The three main types of erosion in GBR catchments are hillslope erosion (broadscale erosion of landscapes including flat lands); erosion gullies; and erosion of riverbanks. It is important to distinguish the relative importance of these three types of erosion as sources because they are managed in quite different ways. Question 3.4 (Wilkinson et al., this SCS) considers the drivers of these erosion processes, here their relative importance in each catchment is examined. Traditionally it was only hillslope erosion of agricultural lands that was considered, neglecting gully and riverbank erosion, but it is now understood that the latter process are just as important.

The export of sediment and particulate nutrient is highly variable over time. The vast majority of sediment is transported during floods when rainfall, overland flow and fast river flows erode sediment and transport it downstream. Concentrations of material may also change during a flood and with the progress of the wet season. The evidence for these patterns will be reviewed. At longer timescales exports may vary with climate induced changes to discharge or land use and other changes in the catchments. The sensitivity of exports to these changes will also be reviewed to help understand how exports might change in future and how progress toward meeting export reduction targets might be assessed.

1.2 Conceptual diagram

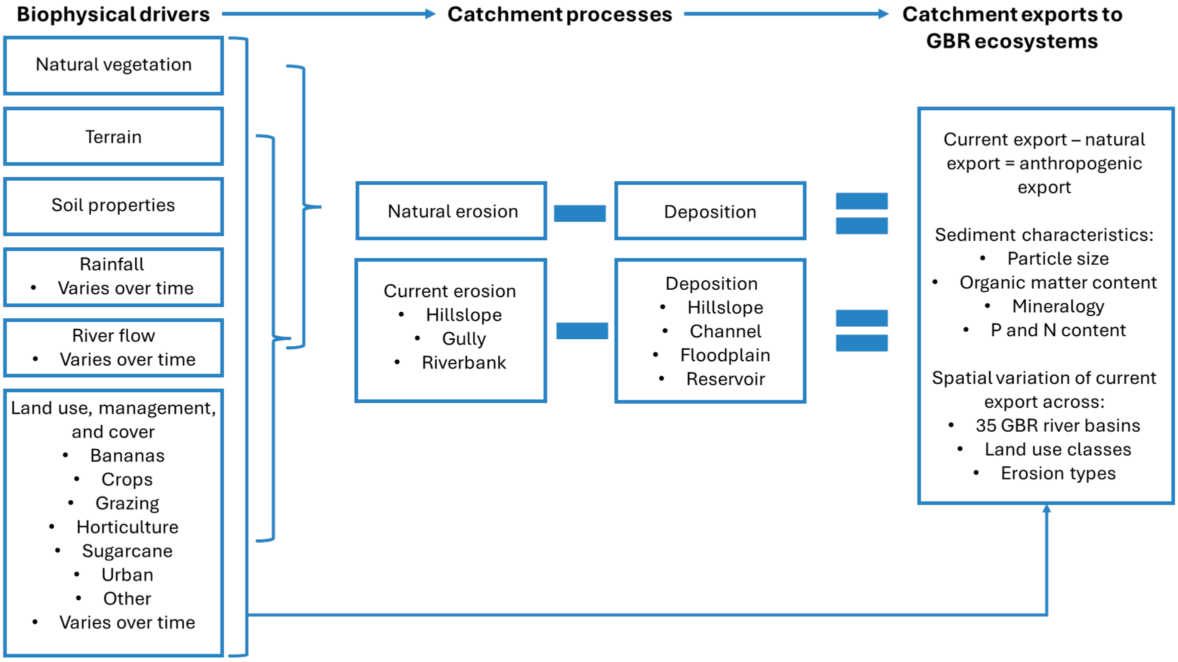


Figure 2. Conceptual diagram of catchment suspended sediment and particulate nutrient exports showing from left to right: the drivers for differences in export intensity across catchments and over time; that anthropogenic exports are the difference between pre-development and current exports; and the reported characteristics and spatial variations in exports.

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	**Q2.3** What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef? (Provides a review of evidence of changes in suspended sediment exports to the GBR over time.) **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? (Covers the drivers of GBR catchment processes that influence sediment and particulate nutrient export in detail.) Q3.1 and Q3.2 deal with how the exported sediment is distributed in the GBR marine environment and the impacts of that. They also identify characteristics of sediment and particulate nutrients that are important for GBR ecosystems and thus need considering when looking at catchment exports.) **Q3.1** What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef? **Q3.2** What are the measured impacts of increased sediment and particulate nutrient loads on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef? **Q4.1** What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef? **Q4.2** What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef? **Q4.4** How much anthropogenic dissolved nutrient (nitrogen and phosphorus species) is exported from Great Barrier Reef catchments (including the spatial and temporal variation in delivery), what are the most important characteristics of anthropogenic dissolved nutrients, and what are the primary sources? (Covers export of dissolved nutrients from GBR catchments. Particulate nutrients may transform to dissolved nutrients under certain conditions.)

2. Method

A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[8]. 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: ***How much anthropogenic sediment and particulate nutrients are exported from GBR catchments (including the spatial and temporal variation in export), what are the most important characteristics of anthropogenic sediments and particulate nutrients, and what are the primary sources?***

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[9] 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?

[8] 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

[9] 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 3.3.

Question S/PICO elements	Question term	Description
Subject/Population	Sediment and particulate nutrients in GBR catchments	Suspended sediment and sediment attached nutrients of nitrogen and phosphorus in GBR catchments.
Intervention, exposure & qualifiers	Anthropogenic	The concern is over anthropogenic increases to catchment loads. These are the amount by which current loads are greater than the pre-development loads of the catchments prior to European settlement of Australia and thus may cause problems of marine pollution.
Comparator (if relevant)	Spatial and temporal variation in export	Compare loads among the 35 river basins that drain to GBR ecosystems. Are loads likely to change with future climate and with changes to land use over time?
Outcome & outcome qualifiers	Exported from the GBR catchment area Characteristics of anthropogenic sediments and particulate nutrients Primary sources	Loads at the mouth of the rivers, where they discharge to the sea. The characteristics of the sediment loads may be important for GBR ecological impacts. Characteristics of interest include sediment particle size, mineralogy, organic matter content, and nutrient content. To help reduce the anthropogenic loads there is a need to understand which land uses contribute most to loads and which sediment sources in terms of gully, riverbank and hillslope erosion sources.

Table 2. Definitions for any relevant terms used in Question 3.3.

Definitions	
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.
Suspended sediment load	Sediment, generally fine sand, silt, and clay, that is carried in the water column of rivers as they flow downstream.
Anthropogenic load	The additional load of sediment or nutrients carried by rivers in current and historical times compared to the load carried prior to European settlement.
Particulate nutrient	Nitrogen and phosphorus nutrients carried in suspended sediment predominantly in the form of organic matter that is part of that sediment.
Land uses	Includes grazing, sugarcane, horticulture, banana, cropping and urban.
Sediment sources	Three types of sediment source are recognised as being important contributors to loads: hillslopes, erosion gullies and riverbanks. Hillslope sources include erosion by rainfall, surface wash and rill erosion on catchment land, including flat lands such as floodplains.

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. The first set of search terms will pick most studies of catchment exports and the characteristics of the exported material.

The aim of the second set of search terms is to identify research on the pre-development sediment loads of GBR catchments because that is required to compare to current sediment loads in order to identify how much of the current load is anthropogenic and increased above pre-development rates. Several of the papers identified from the primary question will consider this but a second element is included to expand the search to a wider range of evidence on pre-development erosion rates. This is required as the pre-development sediment loads cannot be measured directly but there are measures of long-term erosion rates of the catchments which can be converted into pre-development sediment loads.

The third set of search terms considers changes to loads of sediment and particulate nutrients over time as a result of land use change or climate change. This will be a small subset of the overall scientific literature on sediment or particulate nutrient loads. That subset will be identified by adding search terms of climate change and land use change to the strings used for the first search.

Table 3. Search terms for S/PICO elements of Question 3.3.

Primary question element	Search terms
Subject/Population	Catchment sediment load, catchment particulate nutrients, sediment particle size, sediment mineralogy, sediment nutrient content, sediment organic matter
Exposure or Intervention	Great Barrier Reef, Queensland
Comparator	Anthropogenic sediment loads, anthropogenic particulate nutrients, historical sediment loads
Outcome	Land use, sediment sources
Primary question element (2nd set)	Search terms
Subject/Population	Great Barrier Reef, eastern highlands of Australia
Exposure or Intervention	Natural, pre-development, Pre-European, long-term
Outcome	sediment yield, sediment export, sediment load, erosion rate, denudation rate

Primary question element	Search terms
Primary question element (3rd set)	Search terms
Subject/Population	Great Barrier Reef, Queensland
Exposure or Intervention	Climate change, land use change
Outcome	Catchment, drainage basin, river basin, sediment export, sediment load, particulate nutrients

c) Search strings

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

Table 4. Search strings used for electronic searches for Question 3.3.

Search strings
TS=("Great Barrier Reef" AND (catchment OR river OR basin) AND (sediment*) AND (load* OR suspended OR source* OR "land use*" OR anthropogenic OR historical))
TS=("Great Barrier Reef" AND (catchment OR river OR basin) AND (nitrogen OR phosphor* OR nutrient*) AND (particulate OR attached) AND (load* OR "land use*" OR anthropogenic OR historical))
2nd set: TS=(("Great Barrier Reef" OR ("eastern highlands" AND Australia OR "Great Dividing Range")) AND (natural OR pre-development OR Pre-European OR geolog*) AND ("sediment yield" OR "sediment load" OR "erosion rate" OR "denudation rate"))
3rd set: TS=("Great Barrier Reef" AND (catchment OR river OR basin) AND (sediment* OR nutrient) AND (load* OR suspended OR source* OR "land use*" OR anthropogenic OR historical) AND ("climate change" OR "land use change"))

d) Inclusion and exclusion criteria

Table 5 shows a list of the inclusion and exclusion criteria used for accepting or rejecting evidence items.

Table 5. Inclusion and exclusion criteria for Question 3.3 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/ Population	Suspended sediment and particulate nutrients of nitrogen and phosphorus.	Bedload, coarse sediment, dissolved nutrients, pesticides, solutes or other pollutants.
Exposure or Intervention	Anthropogenic loads, current loads, pre-development loads and pre-development erosion rates.	Loads and geological history prior to the Holocene (see Question 2.3. Lewis et al., this SCS).
Comparator	Patterns among GBR catchments. Changes to exports over historical times, changes with climate and land use.	Non GBR catchments. Land use and erosion management to reduce exports (considered in other questions).
Outcome	Exports from GBR catchments. The particulate nutrient content and other characteristics of the sediment that have been shown to be important for GBR ecosystems. The attribution of sources and land uses for the exported sediment.	Small subcatchment or single land use studies at source. Research on drivers within catchments and on marine processes (considered in other questions). Sediment and nutrient characteristics not identified as relevant for GBR ecosystems.
Language	English	Other languages
Study type	Published 1990 and after, peer reviewed journal papers with original data, calculations, methods or findings.	Conference papers, technical reports, and fact sheets. Any other publications not presenting new data, calculations, methods, or comprehensive reviews of data.

3. Search Results

More than 400 studies were identified through online searches for peer reviewed and published literature. 19 studies were added manually from citations in online search publications and personal collections, which represented 12% of the total evidence. 119 studies were eligible for inclusion in the synthesis of evidence (Table 6; Figure 3). All studies were accessible.

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

Date (d/m/y)	Search strings	Sources	
A) Academic databases		Scopus	Web of Science
14/12/2022	*“Great Barrier Reef” AND (catchment OR river OR basin) AND (sediment*) AND (load* OR suspended OR source* OR "land use*" OR anthropogenic OR historical)*	*67 of 270*	*36 (31) of 438*
14/12/2022	*“Great Barrier Reef” AND (catchment OR river OR basin) AND (nitrogen OR phosphor* OR nutrient*) AND (particulate OR attached) AND (load* OR “land use*” OR anthropogenic OR historical)*	*7(7) of 31*	*1(6) of 35*
14/12/2022	*“Great Barrier Reef” OR ("eastern highlands" AND Australia OR "Great Dividing Range")) AND (natural OR pre-development OR Pre-European OR geolog*) AND ("sediment yield" OR "sediment load" OR "erosion rate" OR "denudation rate")*	*3(6) of 43*	*1(4) of 13*
14/12/2022	*“Great Barrier Reef” AND (catchment OR river OR basin) AND (sediment* OR nutrient) AND (load* OR suspended OR source* OR "land use*" OR anthropogenic OR historical) AND ("climate change" OR "land use change")*	*2(19) of 47*	*2(8) of 58*
B) Google Scholar			
17/01/2023	*“Great Barrier Reef” AND (catchment OR river OR basin) AND (sediment* OR nitrogen OR phosphor* OR nutrient*) AND (load* OR suspended OR source* OR "land use*" OR anthropogenic OR historical)*	*20 of 13,900 (first 250)*	
	Total items online searches		***139 (88%)***
C) Manual search			
Date	Source	Number of items added	
23/02/2023	*Author personal knowledge and citations in papers from database search*	*17*	
	Total items manual searches		***19 (12%)***

All of the academic database search results retained to answer the question met the inclusion criteria shown in Table 5, notably that they were peer reviewed scientific journal papers on GBR catchments. This strict inclusion criteria still resulted in 139 potential papers on the topic and 119 of these were retained after screening of the full text, showing the depth of peer reviewed published research on the topic.

Of the 19 manual items that were added, four were additional international scientific journal articles that were identified as relevant from citations in the search result papers but which had not been identified by the search terms themselves. A further 15 publications were added as exceptions to the rule of only including scientific journal papers, because of their importance to the body of evidence. Six of these publications were technical reports on the primary export data from the Queensland Government's river monitoring program (GBR Catchment Monitoring Program within the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program) which are widely used as primary data for modelling and interpretative studies on patterns of loads. Three were widely cited reports of early modelling attempts to determine the pattern of exports among all 35 river basins. These were the only calculations of exports at their time of publication so they too are important primary sources of data on how knowledge has changed since 1990. Two Queensland Government reports were added which addressed climate change assessment and knowledge gaps in estimating sediment and particulate nutrient exports. These were added because they directly addressed parts of the question that are not addressed by journal papers so were added for completeness. Finally, Chapter 2 of the 2017 SCS (Bartley et al., 2017) was included for continuity with prior assessments.

Most of the papers excluded during primary screening of the academic database results were excluded because they addressed topics other than catchment exports but referred to concern over exports as context for their study such as in studies of marine impacts or management of land uses. These topics are considered by other questions.

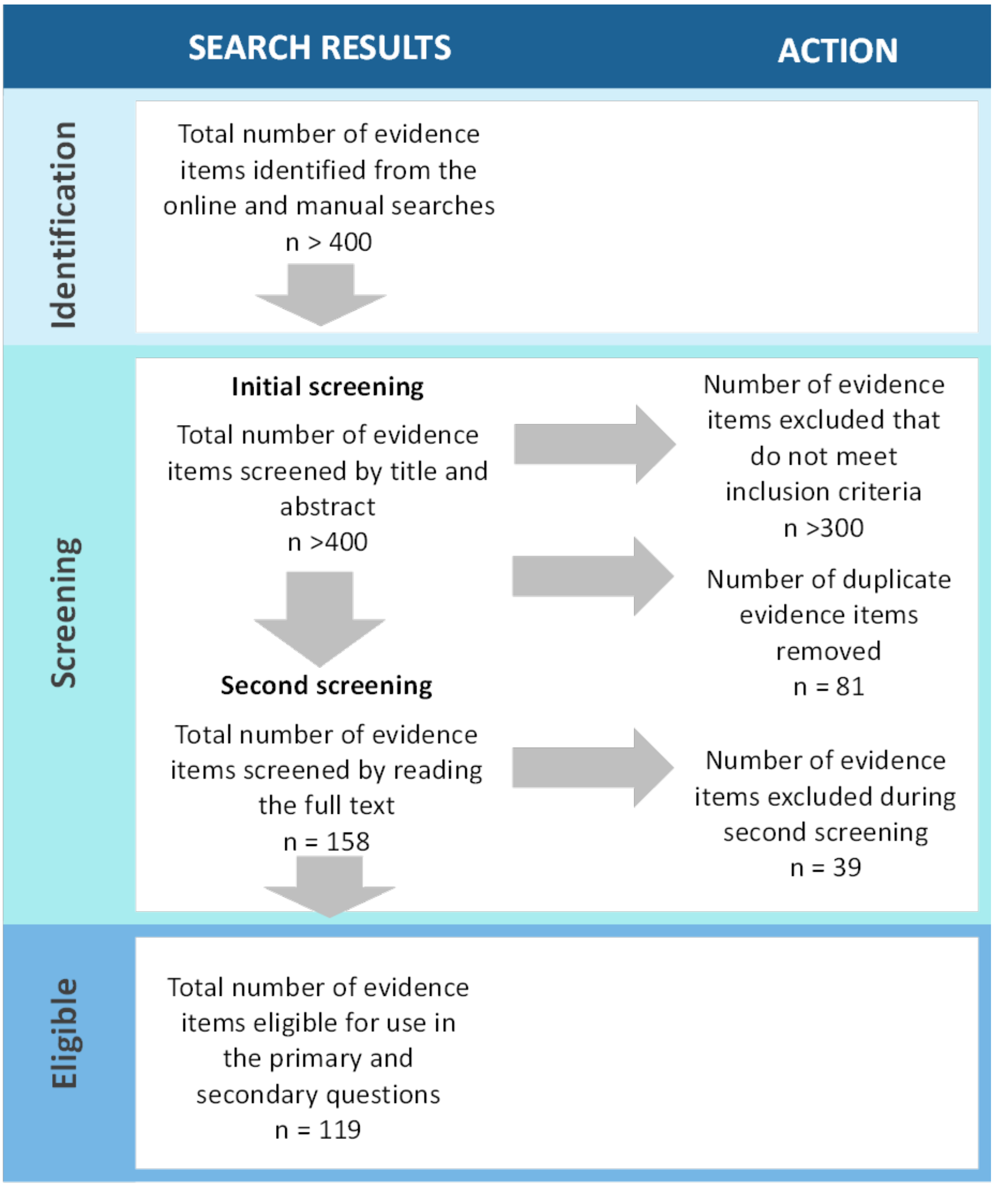


Figure 3. Flow chart of results of screening and assessing all search results for Question 3.3.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

Overall, 119 studies were used to answer elements of the primary question. All of these studies included GBR basins and the vast majority were exclusively about one or more GBR basins. Given the large number of studies on exports from GBR basins, only directly relevant high-quality studies were included, as reflected in the relevance rating for the body of evidence. The vast majority of papers were peer reviewed international journal papers published since 1990. Excluded papers included conference papers, reviews which did not contain original data or findings, and most technical reports, and books. Some of the excluded conference papers and technical reports were superseded by later journal publications. They were excluded because of uncertain independent peer review and time constraints of a rapid review. None of them contain substantiated findings that contradict the body of evidence.

The majority of papers (76) included observations or measurements pertinent to understanding exports; 26 were modelling studies, of which 9 were statistical models of measured exports; 11 combined observations with models; and 6 were review studies containing some new data. The distinction between observational studies and modelling studies is slightly arbitrary as exports are never measured directly. There is always some form of statistical interpolation to calculate export loads from time-specific samples, or there is a conceptual model to relate proxy observations to loads. Similarly, all the modelling studies have quite extensive observed data inputs on which to make the calculations. The classification here was whether the primary contribution of a study was new observations or new modelling.

The geographical spread of studies among GBR basins reflects the size and management priority of the catchments. There were 43 studies which had a GBR-wide scope. These were largely the Queensland Government's monitoring studies and modelling studies where observations were extrapolated across catchments and/or basins. The two biggest basins by far, the Burdekin and Fitzroy Rivers, had 30 and 14 studies respectively. The Tully-Murray (10), Johnstone (7), and Normanby (5) Rivers were also well studied. The most under-represented basins were the Burnett and Mary Rivers where no peer reviewed studies were recorded. These and other basins are covered by the GBR-wide studies including monitoring of exports.

Regarding elements of the question, 61 studies helped inform the spatial patterns of exports; 46 addressed aspects of sources of material; 26 described the characteristics of sediment or particulate nutrients; and 47 contained information on the temporal patterns of exports, including the differences between pre-development and current exports.

Overall, there is a strong body of evidence on GBR sediment exports, covering multiple lines of evidence, a wide range of individual GBR catchments and basins, and addressing each element of the question.

4.1.1 Summary of evidence to 2022

Is there anthropogenic acceleration of exports?

The first consideration is whether there is evidence that current exports are significantly higher than pre-development exports, with the difference being the anthropogenic export. In some cases this is referred to as accelerated exports (the multiplier of current exports over pre-development exports). There are large differences in area (Figure 1), climate and terrain among GBR basins so a large range in pre-development export rates between basins is expected. Thus large current exports from particular basins do not necessarily reflect large accelerations of loads or land management problems for GBR ecosystems. This has long been recognised (Brodie & Mitchell, 2005; Furnas, 2003; Hunter & Walton, 2008; Neil & Yu, 1996) so one research focus has been to examine if there is evidence for acceleration of exports over pre-development levels (discussed below). This framework is better than assuming all exports are a problem but it raises the additional challenge of estimating pre-development exports, which of course were not measured directly at the time.

The search found 21 papers that present evidence relevant to estimating pre-development exports or the acceleration between pre-development and current exports. These cover several independent lines of evidence. They are corroborated by evidence for historical acceleration of erosion within basins (Question 3.4, Wilkinson et al., this SCS) and increased sediment in marine environments (Questions 3.1, Lewis et al., and 3.2, Collier et al., this SCS). There is thus strong evidence that current sediment and particulate nutrients exports are higher than pre-development exports as summarised below.

Pre-development loads are not measured but they can be inferred from long-term rates of erosion. Pre-development rates of denudation have been measured by ^{10}Be isotopes and compared to current monitored loads (Bartley et al., 2015; Croke et al., 2015; Mariotti et al., 2021; Nichols et al., 2014). Of the 17 catchments assessed, 9 show accelerated erosion, and 7 suggest erosion in current times is less than pre-development rates (Mariotti et al., 2021). Acceleration values range from 0.2 to 3.8 with an overall acceleration of 1.4 (i.e., current erosion overall is assessed to be 40% greater than pre-development).

Acceleration values of below 1.0 imply either that current sediment yields in some places have declined since pre-development settlement times, or there is some uncertainty in the calculations. For example, one catchment with largely undisturbed rainforest has an acceleration factor of 0.7 (Mariotti et al., 2021). Not all natural denudation results in sediment exports (some is dissolved load) and there is evidence that sediment storage in the catchments is affecting the ^{10}Be calculations of denudation (Codilean et al., 2021), which may lead to overestimates of pre-development sediment exports. Furthermore, the monitored sediment export data may underestimate the longer-term average export (see below) and the very high annual variability in loads means there is uncertainty over the mean annual rate. For example, Nichols et al. (2014) estimated no acceleration of current erosion above pre-development rates in the Barron River using monitored loads available at the time but subsequent more comprehensive monitoring of loads means acceleration would now be recalculated as in excess of two times. No explanations other than these methodological limitations are given for the catchments where current erosion appears to have declined relative to pre-development levels (Bartley et al., 2015; Croke et al., 2015; Mariotti et al., 2021). The natural denudation rates are broadly consistent with expected control of denudation by chemical weathering, are typical of passive continental margins, and vary predictably with rainfall and terrain (Codilean et al., 2021). Thus despite the methodological problems of interpreting denudation rates as pre-development sediment yields they provide a minimum estimate of acceleration of current exports.

Hunter and Walton (2008) calculate an acceleration of 1.4 for suspended sediment and similar for P in the Johnstone River based on monitoring current water quality from various land uses including natural rainforest. They find in the Wet Tropics that pastures produce similar sediment loads to rainforests in contrast to the situation in drier catchments (see Question 3.4, Wilkinson et al., this SCS). Cropping land uses have elevated sediment and particulate nutrient loads of three to four times the natural rainforest. They note reasons based on land use and climate to explain why the Johnstone River basin would have a lower acceleration value than many other GBR basins.

The observational evidence for accelerated sediment exports is consistent with evidence for accelerated erosion at source of agricultural land, and for acceleration of gully and riverbank erosion in post-European times (Question 3.4, Wilkinson et al., this SCS). In addition, since European settlement, floodplain deposition in the Fitzroy basin has increased four times (Hughes et al., 2010); coastal deposition off the mouth of the Burdekin River has increased 8 to 10 times (Lewis et al., 2014); sedimentation in Burdekin delta floodplain wetlands has increased by an order of magnitude (Tibby et al., 2019); and coastal floodplain and estuary deposition in the Fitzroy has increased by at least 40% (Bostock et al., 2007). These are all estimates from dated sediment deposits from before and after European settlement.

Observed current sediment concentrations of exports and increases in sediment loss from different land uses have been used to estimate acceleration of sediment exports for all GBR basins (Neil et al., 2002; Neil & Yu, 1996). These show acceleration rates ranging from 1.6 to 4.1 with an overall acceleration rate of 3.8. Sediment budget models have also been used to make the same calculations. The latest version of the Dynamic SedNet model (McCloskey et al., 2021) calculates an acceleration of 1.6 to 5.2 in GBR basins with an average of 3, lower values than earlier iterations of the model (Kroon et al., 2012; McKergow et al., 2005b; NLWRA, 2001). The modelling of pre-development loads removes all gully and riverbank erosion which is a harsh assumption so these could be interpreted as maximum estimates of acceleration.

Particulate nutrient loads have similar acceleration values to those for suspended sediment (Hunter & Walton, 2008; McCloskey et al., 2021). This is to be expected because the majority of sediment comes from unfertilised land so particulate nutrient concentrations would be similar now to what they were naturally (McCloskey et al., 2021).

A record of Barium (Ba) inclusions in coral cores (McCulloch et al., 2003) has been frequently cited as evidence for an eight-fold historical acceleration of fine sediment reaching corals from the Burdekin River. However, several studies have shown that Ba is not a good surrogate for sediment discharge or other factors can be used to explain the record (Leonard et al., 2019; Lewis et al., 2018; Lough et al., 2015; Orpin & Ridd, 2012). Most recently, D'Olivo and McCulloch (2022) in more detailed Ba/Calcium (Ca) analysis claim sediment concentrations reaching inshore corals have doubled and expanded the conclusions about increased sediment exposure to inshore reefs from Cairns to near the mouth of the Fitzroy River. Rare earth elements are proposed as better surrogate indicators of sediment exports, but they have not been used yet to examine anthropogenic acceleration (Leonard et al., 2019). The marine evidence for increased sediment exports is covered more fully in Question 2.3 (Lewis et al., this SCS).

In conclusion, there is high confidence from multiple lines of evidence that overall current suspended sediment and particulate nutrient exports are at least 40% higher overall than pre-development exports and perhaps as much as 3 times higher. In the largest individual basins of the Burdekin and Fitzroy Rivers, they are two to five times higher than pre-development exports (Mariotti et al., 2021; McCloskey et al., 2021; Neil et al., 2002). Most of the more recent estimates of acceleration are lower than earlier estimates as a result of methodological improvements.

What are current exports of sediment and particulate nutrients?

There is good knowledge of catchment exports and it is adequate for most uses of export rates (see Section 1 Background for uses of export information). There is huge variability in exports between years because of very high year to year variability of flow in the rivers, especially for the wet-dry tropics (Waterhouse et al., 2016) and because the highest loads of sediment occur in the largest events which are quite infrequent and the hardest to monitor accurately (Wallace et al., 2012). Thus the precise mean annual loads exported from catchments are uncertain and estimates vary among studies (Darnell et al., 2012; Wang et al., 2015). For most applications, all that is needed are relative differences between catchments and approximate concentrations and there is strong agreement about these. The Burdekin and Fitzroy basins are by far the largest contributors, making up 85% of the GBR catchment area, with the largest freshwater discharges and export loads, and having significantly accelerated exports above pre-development rates (Bartley et al., 2017).

The Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef Program), part of the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP), includes ongoing monitoring of exports of sediments, nutrients and pesticides. This provides much of the primary data used in research on exports. There are now 26 sediment and nutrient export monitoring sites and 61 sites in total across the GBR catchment area. These cover all but one of the 17 priority basins for action under the Reef 2050 WQIP (https://www.reefplan.qld.gov.au/tracking-progress/paddock-to-reef/modelling-and-monitoring). The largest basins now have 14-15 years of data. The program samples sediments and nutrients during flow events and statistical interpolation is used to scale these point of time measurements up to annual loads by using more continuous records of river water level and discharge. Annual reports were published on loads (Huggins et al., 2017; Joo et al., 2012; Turner et al., 2012; 2013; Wallace et al., 2014; 2015). Further annual reporting and data have since been published on the Paddock to Reef Program website[10].

[10] https://www.reefplan.qld.gov.au/tracking-progress/paddock-to-reef/modelling-and-monitoring

The monitoring data have been analysed to calculate mean annual loads of suspended sediment (Bartley et al., 2017; Joo et al., 2014) (Figure 4). These mean loads have not been updated since with more recent monitoring data. Wallace et al. (2008, 2009, 2012) show that the monitoring results may underestimate overbank flows because these are poorly gauged. They show which rivers this is likely to be a problem for and suggest this is a problem that leads to underestimation of total N and P loads but perhaps not for suspended sediment because of lower concentrations at the highest flows.

Leigh et al. (2019) show there are advantages of complementing laboratory analyses of river samples with *in situ* monitoring of turbidity, conductivity and river level. The *in situ* measurements are correlated to the sampled concentrations. A single statistical model of the *in situ* data worked well across three diverse catchments for suspended sediment. It shows promise for using cheaper, more continuous *in situ* monitoring to complement a manual sampling program.

There are different statistical approaches that can be used to estimate annual loads from point-in-time monitoring. Wang et al. (2011) and Kuhnert et al. (2012) developed a loads regression estimator for this purpose which also expresses uncertainty in loads. When applied to estimate annual loads of suspended sediment over 24 years from 1986 to 2010 in the Burdekin River (Kroon et al., 2012) it produced a mean load of 3.9 Mt per year. There was very high variability from one year to another with annual loads of 0.004 to 14.8 Mt each year. This shows how hard it is to estimate an average and why monitoring needs to continue for many years to capture the full temporal variability. The Kuhnert et al. (2012) mean is 20% lower than the Bartley et al., (2017) mean but this does not change the ranking of the Burdekin as the highest exporting river. There are at least two orders of magnitude difference between mean export loads of priority catchments, partly reflecting catchment area, so high precision in export load estimates is not required for most management purposes. Similarly, Khan et al. (2020) describe the eReefs model which when used in hindcast mode can calculate pollutant loads for events or years based on various flow metrics and the monitoring of concentrations. The calculations work well but have not been used to calculate exports across all areas.

There were earlier river monitoring programs. Furnas (2003) provide summary data and export calculations from an Australian Institute of Marine Science (AIMS) program. Part of that program is also presented for the Tully River, Mackay Whitsunday rivers and other catchments with similar climate and land use (Mitchell & Furnas, 2001; Mitchell et al., 2005). There has been independent monitoring of loads from the Johnstone, Burdekin, Normanby and Fitzroy Rivers (Bainbridge et al., 2014; Howley et al., 2018; 2021; Hunter & Walton, 2008; Packett et al., 2009; Yu et al., 2013). These all show similar temporal and spatial patterns of loads and concentrations to the current program. The GBR Catchment Monitoring Program is probably the best data, providing a consistent approach across many sites and growing number of years, and covering the most recent period of land uses and pressures on the GBR.

Modelling is used to extend from monitored rivers to calculations of total sediment and nutrient export to the marine environment of the GBR and extend to longer term or unmonitored conditions. The analysis of monitoring data in Bartley et al. (2017) show that the measured loads are from 12 of the 35 basins but that these basins cover 85% of the GBR catchment area. Much of the remaining area is small catchments, or relatively undisturbed catchments on Cape York, both of which are likely to have lower than typical impacts on GBR ecosystems because of small flood plumes and low intensity land use. Modelled catchment exports are used in the eReefs marine model (Steven et al., 2019) to examine whether flood plumes are impacting marine environments, and the results are used to set the targets for reductions to loads (Brodie et al., 2009; Brodie et al., 2017).

Early estimates of sediment export combined measured concentrations of sediment and/or nutrients with estimates of catchment/basin discharge (Furnas, 2003; Furnas & Mitchell, 2000; Neil et al., 2002; Neil & Yu, 1996). The approach is used because there is far better data and predictability of river discharge than exports of material. The approach assumes that any differences in concentrations between catchments are small compared to the major differences in discharge. Given there are order of magnitudes differences in discharge between basins (Bartley et al., 2017) these assumptions can work reasonably well to estimate relative loads between basins and total export to the GBR.

The most widely used model of sediment exports is SedNet and its subsequent developments in the Source Catchments platform under the Paddock to Reef Program (McCloskey et al., 2021). It takes a sediment budget approach, estimating catchment sediment exports from modelled spatial patterns of erosion and deposition within the catchments. The sister model ANNEX (McKergow et al., 2005a) predicts nutrient exports (dissolved and particulate) using the same budget approach and including transformations during catchment transport. SedNet was developed for the National Land and Water Resources Audit (NLWRA, 2001) and was subsequently used for a GBR wide updated application (McKergow et al., 2005b). It was further developed to a daily time stepping model, Dynamic SedNet (Wilkinson et al., 2014) and converted to professional software standards as a component model in the Source Catchments platform (McCloskey et al., 2021). There are now over 20 years of development, use and improvement to the model in the GBR.

McCloskey et al. (2021) provide the latest reported basin exports from the model (Figure 4). They are from the baseline period of 1986 to 2014 so do not conform with the monitoring period described above and do not necessarily represent long term means. Thus, we would expect differences between the models and the monitoring results given that both are sensitive to the highly variable discharge conditions assessed. The modelled exports have been compared to monitoring over the baseline period (Joo et al., 2014; McCloskey et al., 2021; Figure 4). The majority of the modelled exports are within 15% of the monitored exports and the model performs similarly well for particulate nutrients as for suspended sediment. Catchment area is a strong control on exports so it is possible that the measurements and model are both just showing that big catchments export more material than small catchments. This is not the case though as both show more than an order of magnitude variation of export per unit area and there is strong correlation of export intensity between model and measurement, so both are showing which catchments are the most intense contributors. The modelled exports have been calibrated against some measured exports and are now lower and more accurate overall than earlier model implementations (NLWRA, 2001; McKergow et al, 2005a; 2005b). They probably represent the best overall estimate of exports, with the added advantage that the model also estimates source land uses, erosion processes and source subcatchments for these loads (see below). Priority basins were identified based upon assessed marine impacts (Brodie et al., 2017) but these are also the catchments with large export loads and large accelerations of current loads over pre-development loads (Figure 4). There have been several basin or catchment specific applications of the SedNet model (e.g., Armour et al., 2009) in addition to the GBR-wide modelling program. These provide opportunities to use more local data to inform the model and they have been used to explore management priorities.

Sources of sediment – a) erosion processes

One role the SedNet model has played in the GBR is in knowledge transfer from elsewhere and hypothesis raising. Prior to SedNet, research on water quality in the GBR catchments focused on land use, implying that anthropogenic sediment and particulate nutrient came from erosion of agricultural and grazing land – from surface runoff erosion in paddocks. Research in southeast Australia had shown that subsoil erosion of gullies and streambanks were larger sources of sediment than surface erosion of land (termed hillslope erosion in the SedNet model). SedNet applied this knowledge by modelling and comparing streambank, gully and hillslope erosion in catchments across Australia raising the hypothesis that gully and streambank erosion were important processes in GBR catchments as well (NLWRA 2001; McKergow et al., 2005a; 2005b). Several geochemical tracing studies of GBR catchments have since shown that gully and riverbank erosion are the predominant sediment sources (see below). Reflecting that, these erosion processes have been a priority for catchment management since. Early GBR SedNet applications did not get the proportion of each erosion process correct, mainly due to overestimating hillslope erosion (see below), but subsequent versions of the model better matched the new observational evidence, showing the importance of obtaining independent measurements to the model. The published evidence of which erosion process predominates is reviewed here.

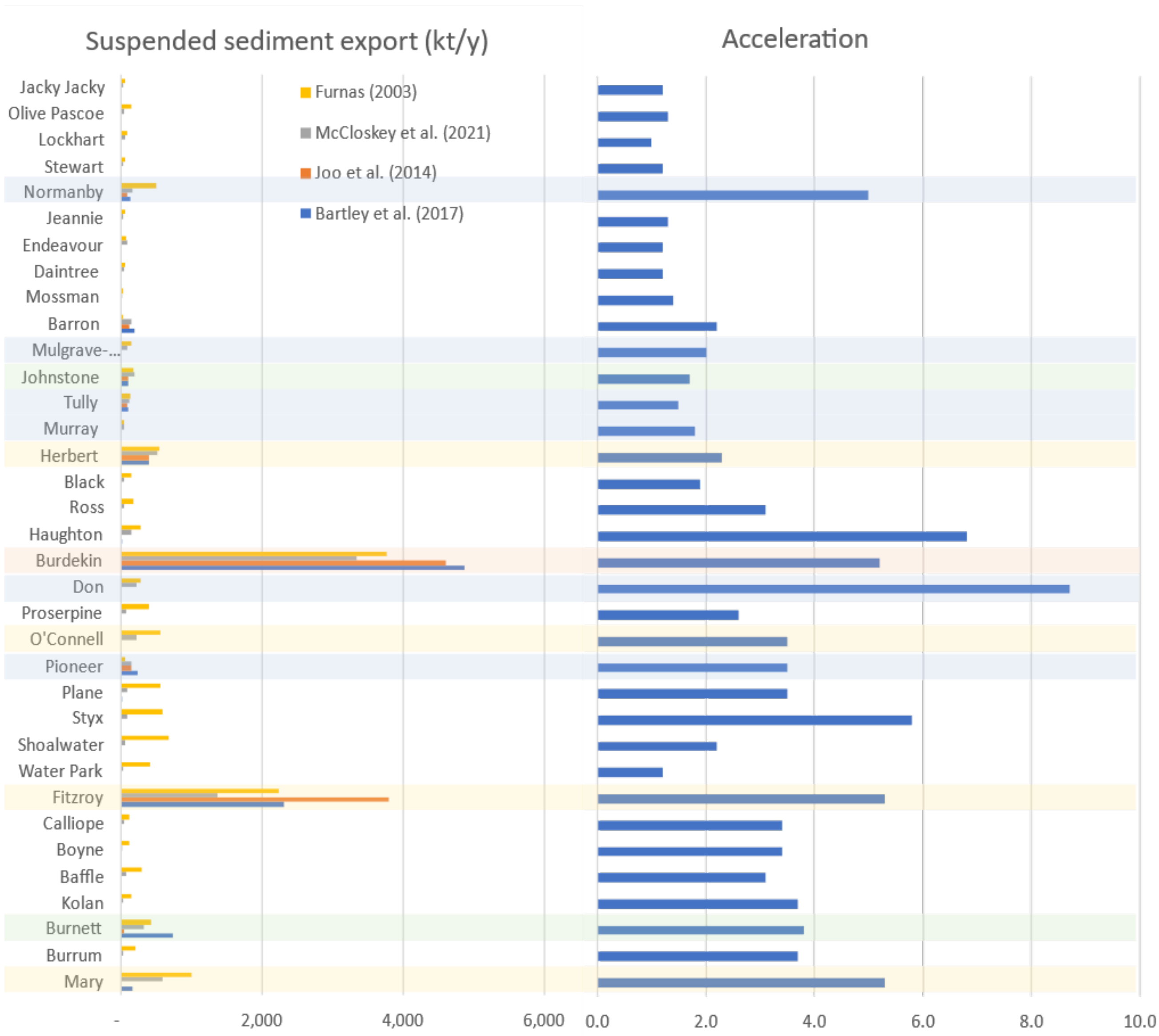


Figure 4. Observed (Furnas, 2003; Joo et al., 2014; Bartley et al., 2017) and modelled suspended sediment exports and acceleration of current loads over pre-development loads (McCloskey et al., 2021). Management priority of catchments for sediment shown in colour bands (blue = low; green = medium; yellow = high; orange = very high).

Radioisotope tracing has shown that the Burdekin, Herbert, and Normanby Rivers and subcatchments of the Fitzroy and Burdekin Rivers are dominated by subsoil erosion from gullies and riverbanks (Hughes et al., 2009; Olley et al., 2013; Tims et al., 2010; Wilkinson et al., 2013; 2015). The proportion of gully and riverbank erosion relative to hillslope erosion can be overestimated by isotope measurements, as heavily eroded scalds and hillslopes can have an isotope signal between hillslope and gully or riverbank end members (Hancock et al., 2014; Wilkinson et al., 2015) however these differences are not enough to overturn the conclusion that in many GBR basins, gully and riverbank erosion dominate.

The radioisotope studies noted that the SedNet model generally underpredicted the dominance of gully or riverbank erosion over hillslope erosion. Brooks et al. (2014) also noted in the Normanby River the model overestimated hillslope erosion compared to their measurements, although the measurements were for a short period with no major runoff events. Early versions of SedNet were found to overestimate hillslope erosion because of problems of predicting seasonal ground cover from remote sensing imagery. Cover values from runoff plot observations are now used, or for low intensity land uses a mean event concentration approach is used, which has corrected the problem (McCloskey et al., 2021). There was only limited gully erosion mapping available for early model implementations. Much more gully mapping has now been completed, increasing the amount of gully erosion in the model

(McCloskey et al., 2021) The bank erosion source term in SedNet has been found to be the least accurate because of a lack of supporting data at a large scale (Prosser, 2018). It is probably only good enough to give a rough estimate of bank erosion potential within GBR basins. Appropriately, in regional water quality plans reach-scale bank erosion is assessed using field and aerial photograph evidence, and not the model.

The most recent published SedNet predictions (McCloskey et al., 2021) suggest that across the GBR basins, 54% of suspended sediment comes from gullies, 23% from riverbanks and 22% from hillslope erosion. Each process can dominate in particular basins. The model results now agree well with the radioisotope evidence that hillslope erosion is a minority source in the Normanby, Herbert, Burdekin and Fitzroy basins. All three processes are also important as sources of particulate P and N but hillslope erosion is a bit more dominant for particulate P and much more dominant for particulate N. This reflects differences in nutrient concentrations between contributing materials and for intensive land use to preferentially occur on high nutrient content soils (McCloskey et al., 2021). There is quite high uncertainty about nutrient concentration of some materials as there has been limited soil property mapping of these (McCloskey et al., 2021; Sherman & Read, 2008).

The last question to consider for erosion sources is whether there are other significant processes not included in the model or management priorities. Packett (2020) showed that 50% of the modelled streambank erosion may be attributable to cattle track erosion of the banks even though that is not explicitly modelled. Most erosion was in smaller streams. Bigger rivers were observed to have such high and steep banks as to discourage cattle tracks. As noted above, riverbank erosion is not accurately modelled at present but cattle tracks may be a component of that source process. In-channel benches or inset floodplains in the Normanby River can be more important as a catchment store of fine sediment than the broad higher floodplains (Pietsch et al., 2015). Much of this sediment comes from post-European times but some is from older periods, and much is from the early years of land use (Lewis et al., 2021). In-channel erosion and deposition is now represented in the model but it is predicted to be a minor source of current exports (McCloskey et al., 2021). There has been episodic floodplain stripping on confined sections of the Daintree River, a sediment source that is not modelled (Leonard & Nott, 2015). Floodplain stripping is highly episodic, occurring once every hundred to thousands of years and has not been recorded in historical times. It is thus unlikely to be a significant source for anthropogenic sediment or a major contributor to chronic sediment impacts.

In conclusion, gully erosion, hillslope erosion and riverbank erosion are all significant erosion processes in GBR basins as shown by measurements and modelling. The SedNet model provides a starting point for assessment in each basin and from there local evidence for high erosion by particular processes should continue to be assessed from remote sensing and field investigations.

Sources of sediment – b) land uses

Statistical analysis of the sediment export monitoring data has been used to find explanatory variables in catchment characteristics. Event mean concentrations can be explained by land use differences between catchments, which has often been assumed if not demonstrated (Liu et al., 2018). Further work looked at a wide range of environmental variables and multiple statistical models (Liu et al., 2021b). They found that natural environmental characteristics such as climate and lithology had a strong influence on spatial patterns, reinforcing the need to look at natural variation between catchments and not just assume that high loads equals accelerated pollution. These natural features were observed to be cross correlated with anthropogenic loads – such as erodible soils, so correlation of current loads with natural features does not mean there is no anthropogenic signal.

Concentrations of sediment and particulate nutrients have been measured in subcatchments dominated by particular land uses. In the Wet Tropics cropped land (bananas and sugarcane) and urban areas produce higher concentrations than grazing or rainforest (Bainbridge et al., 2009; Hunter & Walton, 2008). Pastures were found to have similar concentrations to rainforest. The same results were found using geochemical tracing techniques (Bahadori et al., 2019; 2020). Mitchell et al. (2009) show in the Tully River that sediment and particulate nutrients could not be explained by land use alone.

Packett et al. (2009) found a strong correlation in the Fitzroy River between the concentration of suspended sediment and the proportion of cropland in the contributing catchment suggesting that cropland is the more significant sediment source. They observed other differences too. The Connors River has low concentrations, and it has high cover being higher rainfall and has limited cropping. Grazing still dominates overall as the contributor of sediment to export as far more of the catchment is used for grazing but highest concentrations come from smaller areas of cropland.

A review of event mean concentration data derived from water quality measurements taken in the GBR basins as well as other parts of Australia suggest that the highest median suspended sediment concentrations are generally from mining (~50,000 mg L^{-1}), horticulture (~3000 mg L^{-1}), dryland cropping (~2000 mg L^{-1}), cotton (~600 mg L^{-1}) and grazing on native pastures (~300 mg L^{-1}) (Bartley et al., 2012).

Mining is often not represented in water quality studies but Saint-Amand et al. (2022) in an extreme case of a proposed coal mine close to the coast found that significant sediment from that mine could reach critical marine ecosystems. In the Fitzroy River, mines make up a very small proportion of the basin and are much further inland.

The observational studies show that the intense land uses (such as urban areas) can be locally large sources of sediment but to understand exports the erosion intensity needs to be considered together with the area of land covered. Intensity of erosion is also influenced by soil properties, rainfall and other attributes. The SedNet model considers all these factors across all GBR basins, essentially adding up contributions in detail across each catchment and subtracting deposition. SedNet predicts that >10% of exported suspended sediment from each region comes from the following land uses (Figure 5; Bartley et al., 2017):

- Grazing in all GBR regions
- Sugarcane in the Wet Tropics and Mackay Whitsunday regions
- Dryland cropping in the Fitzroy region

Subsequent SedNet modelling (McCloskey et al., 2021) has not reported contributions by land use by region so Bartley et al. (2017) remain as the best peer reviewed estimates. The estimated proportion of total fine sediment loads exported to the Great Barrier Reef from each land use are grazing (60%), sugarcane (10%), irrigated and dryland cropping (4%) bananas and horticulture (1%), urban (2%). Other land uses such as nature conservation, forestry, roads and dairy collectively contribute 23% of the total fine sediment load.

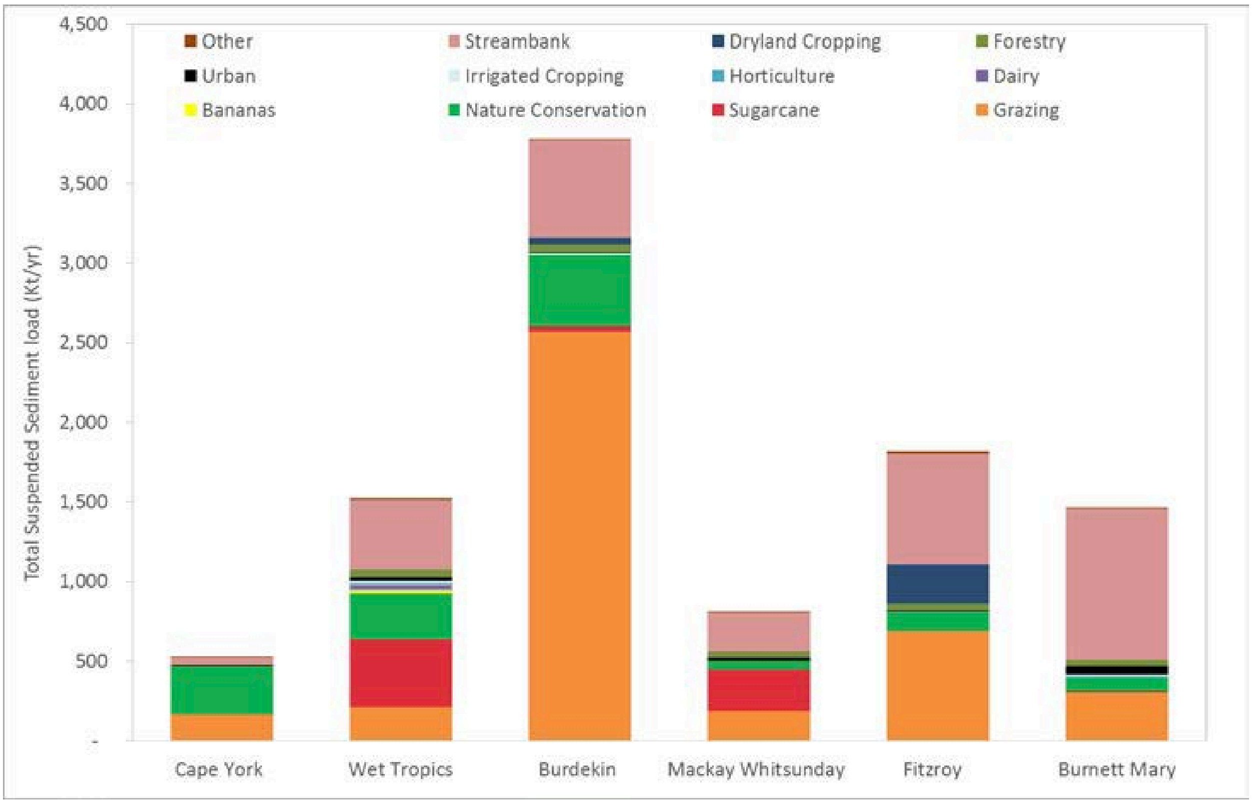


Figure 5. Contribution of land uses to suspended sediment export for each region. Reproduced from Bartley et al. (2017).

Sources of sediment – c) subcatchments

In the large basins it is important to distinguish which subcatchments are contributing the most to export. The patterns will be determined by the intensity of erosion in each subcatchment and how effectively that eroded sediment is delivered to the mouth. Dams such as the Burdekin Falls Dam can trap a large proportion of the suspended sediment carried (Lewis et al., 2013) as can extensive floodplains.

In the Burdekin River, geochemical tracers and clay chemistry show that almost three quarters of the exported sediment comes from subcatchments below the Burdekin Falls Dam and that much of the rest comes from the Upper Burdekin River (Bainbridge et al., 2014; 2016; Furuichi et al., 2016). River monitoring and SedNet modelling results shows similar patterns (Bartley et al., 2014; 2017; McCloskey et al., 2021) all concluding that the Suttor, Belyando and Cape River subcatchments contribute little sediment and that the Burdekin Falls Dam buffers exports from the upper catchments. These results all provide support for focus of catchment management on subcatchments below the dam.

In the Fitzroy basin, assessment of subcatchment contributions is made difficult by a large number of subcatchments with diverse climate, land use, geology and opportunities for storage of sediment before export. The SedNet model and monitored subcatchment sediment loads agree well (McCloskey et al., 2021) pointing to eastern subcatchments being the largest contributors to export, partly because of ineffective sediment delivery from catchments to the west. Sediment tracing studies and analysis of sediment concentration data point to fine sediment from basalt soils being overrepresented in exports (Douglas et al., 2006a; 2010; Packett et al., 2009; Smith et al., 2008) and these soils are used mainly for dryland cropping. The model also shows that dryland cropping is two to three times overrepresented in exports than one would expect from the area of land use, although Hughes and Croke (2011) note that an early version of SedNet underrepresented the amount of sediment coming from cropland erosion on basalt soils. There is thus likely to be several places in the Fitzroy basin that need to be the focus for reducing suspended sediment exports, and some observational data appear to contrast the SedNet model predictions in terms of sediment connectivity.

Sediment characteristics

During large flood events particles from clay up to coarse sand can be carried in suspension (Amos et al., 2004). However the coarser silt and sand sized particles drop out very quickly wherever flow velocities reduce such as near the mouth of a river (Bartley et al., 2014; Bostock et al., 2007; Lewis et al., 2014). Only the very fine clay and silt fractions (<16 µm) are transported more than 3 km offshore in flood plumes so it is this sediment that has marine impacts (Bainbridge et al., 2012; 2014; 2016; Packett et al., 2009; Webster & Ford, 2010). Some of the silt and fine sand particles measured in freshwater river exports are actually larger flocs of fine silt and clay held together by bacteria (Bainbridge et al., 2012; 2021). These flocs probably form during river transport and thus do not represent the origin of the particles which preferentially come from clay rich soils.

Looking at the clay mineralogy of exported sediment, much of it is expandable clays which stay suspended easily and therefore preferentially continue into flood plumes rather than being deposited in floodplains and estuaries. These clays dominate in marine plumes from the Fitzroy and Burdekin Rivers (Bainbridge et al., 2016; Douglas et al., 2006b; Furuichi et al., 2016) and they preferentially come from basalt and similar lithologies which seem to have a stronger representation in exported sediment than expected from the area of catchment covered, although other lithologies also contribute sediment to export. The conclusion is that catchment management for marine protection should focus on the source areas of <20 µm sediment and sources of expandable clays (Bainbridge et al., 2018). The current SedNet model does this to some extent by only considering erosion of <20 µm material in the suspended sediment budget (McCloskey et al., 2021) and the modelled sources in the Burdekin basin correspond reasonably well to the sources of clay (Bainbridge et al., 2016).

The focus for GBR impacts has been on suspended sediment but changes to bedload exports from rivers can have important consequences along coasts. For example, Wolanski and Hopper (2022) show potential impacts to coastal wetlands of bedload transport change and sea level rise along the Burdekin delta.

Particulate nutrient characteristics

Particulate N is of more concern for the GBR than particulate P because there are bigger marine sources of P than river exports (Alongi & McKinnon, 2005; Furnas, 2003) and particulate N can quickly become bioavailable and contribute to primary production in flood plumes (Franklin et al., 2018; Garzon-Garcia et al., 2018; 2021). Particulate N makes up about one third to half of total N export and particulate P is the vast majority of total P export (Bartley et al., 2017). However, Judy et al. (2018) have shown that up to 45% of the N classified as dissolved is actually fine colloidal matter so particulate matter may make up a greater overall proportion than measured in the past.

The bioavailability of particulate N varies with both land use and soil material (Garzon-Garcia et al., 2021). In the Johnstone River organic matter from natural rainforest areas had the highest bioavailability along with dairy grazing lands followed by sugarcane and banana cropping. Surface soils were found to have much more bioavailable particulate N than subsoils, and fine sediments were enriched in bioavailable N compared to the source soils, but where there is a lot of gully erosion it can be a significant source of bioavailable N. Thus the most problematic bioavailable material may not have the same sources as indicated by measures of total particulate N.

P attached to sediments can go into solution and the reverse depending upon relative concentrations and buffering capacity (Pailles & Moody, 1992). Results from the Johnstone River suggest that desorption occurs during flood plume transport. Pailles et al. (1993) showed that extractable phosphate from sediments was much higher in agricultural catchments than rainforest catchments.

The Paddock to Reef Program export monitoring and modelling studies reported above for suspended sediment also report on particulate N and P transport (Figure 6). The first order patterns of particulate nutrients follow the patterns of suspended sediment. This is because there is a strong correlation between particulate nutrient concentrations and suspended sediment concentrations (Robson & Dourdet, 2015). GBR catchment soils, whether fertilised or not, naturally contain substantial stocks of nitrogen and phosphorus (Furnas, 2003) and overall erosion of unfertilised materials dominates sediment exports (McCloskey et al., 2021). Thus, the conclusions of studies reviewed above for suspended sediment probably apply in the first order to particulate nutrient transport, even though that may not have been studied explicitly. This section reports on some of the important differences between particulate nutrient export and that of suspended sediment.

There are no independent measures of pre-development particulate nutrient exports, unlike the estimates of pre-development catchment erosion rates. Evidence for acceleration of particulate nutrient exports comes from comparing concentrations coming from natural land covers to those from current land uses. This is easier in the Wet Tropics where there are more extensive natural and protected lands. There, particulate nitrogen (PN) and particulate phosphorus (PP) or total nitrogen (TN) and total phosphorus (TP) concentrations coming from cropland and urban areas are over ten times that from rainforest (Bainbridge et al., 2009; Bartley et al., 2012; Brodie & Mitchell, 2005) while grazing lands have less elevated values. Hunter and Walton (1998) found similar results for the Johnstone basin but with lower multipliers of concentration and close matching between suspended sediment and particulate nutrients. Adame and Reef (2020) use tracers to show that current land uses contribute the majority of nitrogen to coastal and nearshore wetlands further supporting the acceleration of nitrogen exports.

The SedNet model uses nutrient concentrations of eroded soil materials to estimate PN and PP budgets just as it does for sediment (McCloskey et al., 2021). Thus it can make similar predictions for PN and PP as it does for suspended sediment. Because of the source nutrient characteristics described above, the first order patterns for PN and PP are the same as for suspended sediment. Therefore the degree of acceleration over pre-development is similar but with some subtle differences. For example, the Herbert basin is predicted to have a greater increase in PN exports than either sediment or PP. Because nutrient contents are higher in surface soils than subsoils, hillslope erosion is predicted to be a much more important source of PN and PP than for suspended sediment and is the predominant source in most basins (McCloskey et al., 2021).

In both measured and modelled exports there is a slightly more even distribution of PN and PP between basins because many of the smaller river basins have naturally more fertile soils with higher nutrient concentrations (Bartley et al., 2017; McCloskey et al., 2021). This applies to Mackay Whitsunday and Wet Tropics basins where the soils are richer in organic matter and have a greater proportion of basalt lithologies with higher P concentration. The two largest basins, the Fitzroy and Burdekin have lower than average implied nutrient concentration from the exports, which matches their basin characteristics. The model appears to underestimate PN and PP loads but it should be noted that the modelled period and the measured period do not coincide, and the measured period is often for a short record (e.g., the Mary River was only two years). However, the relative patterns of export remain largely the same.

Modelled PN and PP exports are less certain than the suspended sediment exports because they are less constrained by independent measurements. The fluxes are also not conservative with transformations possible with dissolved forms of nutrient (Adame et al., 2021; Alongi & McKinnon, 2005). Modelling particulate nutrient fluxes from gully and streambank erosion is hampered by poor representation of these types of material in soil databases (Sherman & Read, 2008). Nevertheless, when comparing the model results for particulate nutrients with monitored exports over the same period (Joo et al., 2014; McCloskey et al., 2021) the model performs similarly well at estimating particulate nutrient loads as for suspended sediment.

Modelled land use sources of PN and PP are similar to that for suspended sediment but with one difference. The similarities are that grazing land use contributes >10% of exported particulate nutrient in all regions and sugarcane is the biggest contributor in the Wet Tropics and Mackay Whitsunday regions. The difference is that dryland cropping is not predicted to be a big contributor of particulate nutrients in the Fitzroy basin (Bartley et al., 2017). Instead grazed and conservation areas with forest cover make up a higher contribution of PN and PP than for suspended sediment. This is possibly because of surface erosion of particulate organic matter in forests but this discrepancy remains to be investigated.

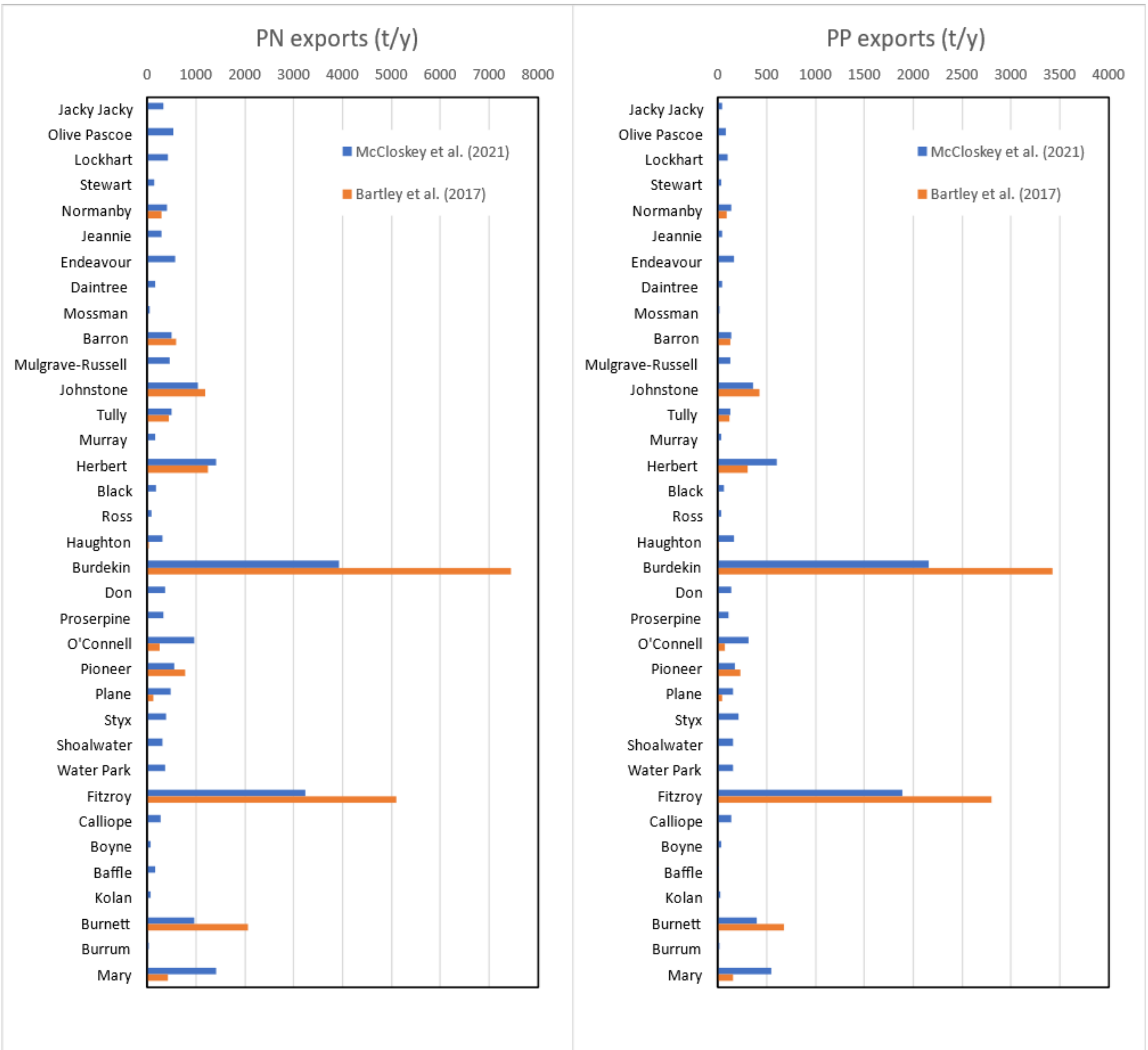


Figure 6. Measured loads (Bartley et al., 2017) and modelled baseline loads (McCloskey et al., 2021) for particulate N and P for the 35 GBR basins. The measured and modelled periods are both short and cover different times, partly explaining the differences. McCloskey et al. (2021) compare modelling with measurements for the same baseline period showing a better comparison but the Bartley et al. (2017) results are shown here because they are a larger and more current dataset.

Changes over time, including climate change

Land use has changed considerably in historical times and continues to do so, with consequences for sediment exports. Lewis et al. (2021) give a detailed history of land use across the GBR showing some important trends (see also Question 2.3, Lewis et al., this SCS). As with other regions of Australia, there was an initial phase of substantial erosion and sediment export in the early years of settlement resulting from major disturbance of fragile soils. Alluvial gold mining and the introduction of cattle were major drivers of change at this time along with a period of major floods (Bartley et al., 2018; Lewis et al., 2021; Lough et al., 2015).

The next period of major recorded change in sediment exports was after the 1950s. This was when much of the forest clearing for agriculture occurred and when cattle numbers greatly increased resulting in increased rates of sediment deposition in the Fitzroy and Burdekin Rivers (Bartley et al., 2018; Douglas et al., 2006a; 2010; Lewis et al., 2021).

Beyond these major changes recorded in sediment inventories there has been a gradual intensification of land use over recent decades, punctuated in places by temporary declines during droughts. The intensification is recorded in increased stock numbers, areas of cropping, and use of fertilisers (Bartley et al., 2018; Brodie et al., 2001; Lewis et al., 2021). This gradual intensification is also recorded in increased P/Ca ratios in corals off the mouth of the Tully-Murray catchment (Mallela et al., 2013). However such intensification or other changes in land use are hard to detect statistically in water quality monitoring because of the very high interannual variability of flow and the limited length of water quality records (Yu et al., 2013). It does show however that it is important to keep track of land use changes and incorporate their consequences in the SedNet model predictions of loads over time.

There has been little investigation of climate change as a temporal driver of exports beyond noting that exports are related to historical changes in the frequency of major floods (see above). This is partly because changes to land use and land management are likely to have a stronger influence because of significant past changes and potential for future changes. Climate change in the GBR catchment area could lead to greater variability in floods and increased frequency of very large floods even though mean annual rainfall may decline in future but these changes may be small compared to the interannual variability of floods which will still dominate (Alluvium, 2019). Most flood pulses have the potential for marine impacts not just the extreme floods (see Question 3.1, Lewis et al., this SCS). The statistical models of water quality and the SedNet model are both capable of exploring the direct consequences of changes to flood frequency and intensity on exports, however to predict changes in the catchment supply of sediments and particulate nutrients would be more speculative and probably within the error of predictions given the complex casual chains between aspects of climate and erosion (Alluvium, 2019; see Question 3.4, Wilkinson et al., this SCS).

There are year-to-year patterns in exports that have been explored statistically. These temporal correlations are useful to identify which catchment factors are controlling exports. Annual patterns of loads in the Burdekin River are related to catchment vegetation cover and flows through the Burdekin Falls Dam (Kuhnert et al., 2012), showing that the dam is able to explain lower than expected loads because of sediment trapping. Similarly, Chaiechi et al. (2016) show correlation with beef prices, cattle numbers and the impact of building the Burdekin Falls Dam. There is a lag of three years between beef indicators and sediment response which could be from lags of pasture condition adjusting to stock numbers. There was no lag between building of the Burdekin Falls Dam and lower suspended sediment loads. Other work on temporal patterns of concentrations across the GBR catchments confirm known variations with rainfall and discharge but also show relationships with the previous three months vegetation cover, again suggesting that water quality responses reflect the immediate preceding conditions with no major lags in response (Liu et al., 2021a). Robson and Dourdet (2015) found in the Fitzroy River that flow in tributaries (specifically, the Nogoa River, Comet River, Isaac and Connors Creek) substantially improved predictive capacity for different nutrient forms and sediment. Thus, the spatial patterns of sources modelled in the dynamic version of SedNet may matter for predicting exports.

All four above studies of statistical temporal patterns suggest short lag times between events in the catchment and export response. These are in contrast to others (Hairsine, 2017; Nichols et al., 2014; Waterhouse et al., 2012) who cite research from GBR catchments and elsewhere of substantial sediment stores within catchments which they claim is evidence of long lags in catchment export response to land management of decades or more. However this argument overlooks the probabilistic nature of sediment transport in catchments. While some sediment is stored for tens, hundreds, or thousands of years, a proportion is exported during events or wet seasons. The smaller particles which matter most (see sediment and nutrient characteristics section above) tend to have higher probabilities of quick export. Thus the presence of sediment stores in a catchment is not at odds with quick response times of some proportion of the load. The SedNet model accounts for deposition of a proportion of sediment within catchments.

It has often been shown that the highest concentrations of exported material is in wet season breaking floods, especially after long dry periods, although this phenomenon is stronger in the seasonal rivers of the dry tropics than wet tropics rivers (Davis et al., 2017; Mitchell & Furnas, 2001; Saha et al., 2018; Wallace et al., 2008). At the finest temporal scale, sediment and particulate nutrient concentrations are often higher on the rising limb of the hydrograph than the peak or falling limb (Davis et al., 2017;

Howley et al., 2018; Mitchell & Furnas, 2001; Wallace et al., 2008). It is not clear whether these finest scale patterns matter for marine or other impacts.

One of the main uses of the SedNet model is to predict the reductions in loads expected from the GBR catchment management programs (McCloskey et al., 2021). This is important annual progress reporting toward the sediment and nutrient end-of-catchment reduction targets (Figure 7). The full benefits of those actions are modelled immediately even though they may take time to reduce sediment exports because of the time it may take for erosion to reduce (e.g., gully erosion reduction responding to grazing management). Thus the maximum benefit is modelled, not the actual expected reductions in loads, and the difference can be large especially in early years for actions that have long response times (Roberts & Ellis, 2019). The modelling is required though as it will take decades to statistically prove reductions in exports from export monitoring because of the high variability between years (Darnell et al., 2012; Wang et al., 2015).

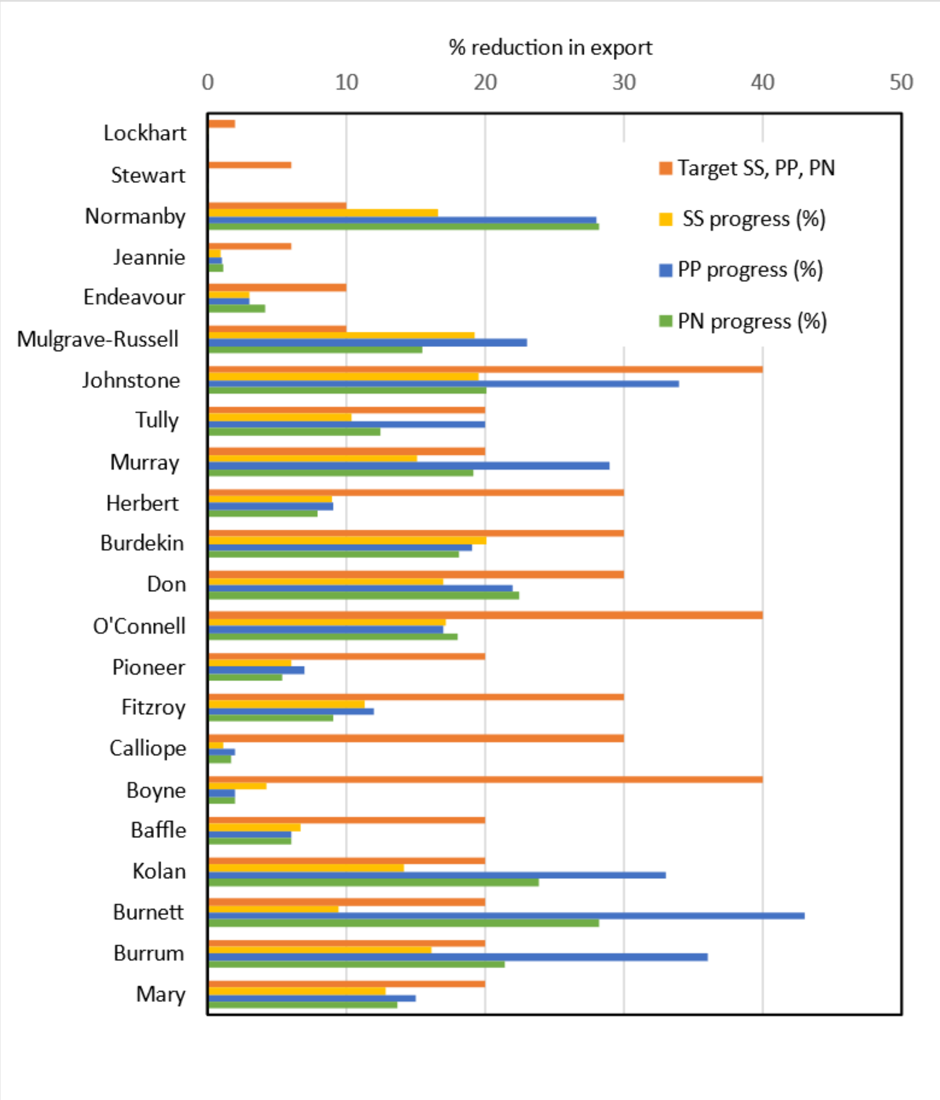


Figure 7. Reef 2050 Water Quality Improvement Plan 2025 fine sediment and particulate nutrient targets for the 35 GBR basins, and progress toward meeting them (2016-2020). Sourced from *https://www.reefplan.qld.gov.au/tracking-progress/paddock-to-reef*

The targets shown in Figure 7 were set for each basin based upon ecological impacts (Brodie et al., 2017). They are equivalent to a 25% reduction in anthropogenic fine sediment export to the GBR and 20% reduction in particulate nutrient exports. Overall, there has been a 15% reduction in fine sediment exports, 17% reduction in PP and 14% reduction in PN to 2020[11]. In some basins, targets have been

[11] https://www.reefplan.qld.gov.au/tracking-progress/paddock-to-reef

exceeded while in others which were not given management priority there has been little progress. The modelling shows good overall progress but that continued effort is required to meet the targets by 2025.

In all basins, meeting sediment reduction targets would still result in higher than pre-development suspended sediment exports with the possible exception of the Johnstone basin. There the current loads are 1.4 to 1.7 times pre-development (see anthropogenic acceleration section above). A 40% reduction of the lower of those acceleration estimates would result in a load 0.84 of the pre-development load. Perhaps this reflects uncertainty in the ability to estimate natural loads but it may also be cause to examine the ecological basis for the target more closely.

SedNet model performance

Much use is made of the SedNet model in catchment management for sediment and particulate nutrient exports because of its explicit modelling of land uses, erosion processes, deposition and variable catchment environments. The model is subsequently quite data intensive which can be a problem in data sparse environments but has the advantage of being able to accommodate much of the independent findings from research projects and observational programs. As explained by McCloskey et al. (2021) the model is being continually improved in response to new findings and data and many of the problems of the initial model implementations (e.g., McKergow et al., 2005a; 2005b; NLWRA, 2001) have now been resolved. Table 7 shows the major improvements over time and how they relate to observations and research findings. In addition, there have been significant software development and improvements turning what was once a single application research model into accessible professional standard software. Hopefully there will continue to be improved understanding of catchment material transport and incorporation of that into modelling. Prosser (2018) worked with GBR catchment researchers to reach a consensus on future priorities for research and model improvement.

Table 7. Improvements to the SedNet model since its first development.

Model improvement	Related to need or observation
Time varying exports (Wilkinson et al., 2014)	Better link with marine models and export monitoring. Better represent dynamics of different subcatchments (Packett et al., 2009).
Improved hillslope erosion prediction to lower predicted rates	Overestimation of hillslope erosion (Brooks et al., 2014; Tims et al., 2010; Wilkinson et al., 2013).
Mapping of gully erosion	Poor representation of gullies in several catchments (Wilkinson et al., 2013).
Representation of improvements to catchment condition	Enables the model to be used for Reef 2050 WQIP annual progress reporting.
Calibration against a wider range of measured river loads	Increased number of monitored sites and longer records from existing sites.
Introduction of in-stream deposition and re-entrainment	Observed in-stream benches (Bartley et al., 2018; Pietsch et al., 2015).
Use of local data in key catchments	Local data better constrains the model (Hughes & Croke, 2011; Wilkinson et al., 2013).
Better estimation of deposition in dams	Observed deposition in Burdekin Falls Dam (Lewis et al., 2013).
Use of finer particle size in suspended sediment budget to better represent marine impacts	Only <20 µm material has marine impact (Bainbridge et al., 2012; 2016; 2018; Bartley et al., 2013).
Lower acceleration of anthropogenic loads resulting from some of the above improvements	Independent estimates of anthropogenic acceleration (Bartley et al., 2015; Croke et al., 2015; Hunter & Walton, 2008).

Some alternative modelling approaches have been trialled. Perhaps the most novel of these is essentially a probabilistic data assimilation model that formally combines load monitoring observations with the spatiotemporal patterns of SedNet (Gladish et al., 2016; Kuhnert et al., 2018). The model addresses statistical uncertainties in both the export monitoring and the SedNet model to provide probabilities of exceeding target conditions in time and space. This addresses the need to express uncertainty in the SedNet predictions which has been identified as a need (but not addressed to date; Prosser, 2018). It provides a more advanced and formal way of incorporating the monitoring results into mass balance modelling. It could be applied anywhere with a reasonable monitoring record but is yet to be tested beyond part of the Burdekin basin or evaluated for its usefulness for management.

The SWAT modelling software has been trialled in the Johnstone basin (Rafiei et al., 2020) and a Bayesian belief model trialled in the Mackay Whitsunday region (Lynam et al., 2010). In both cases it was not clear if the models offer significant advantages over SedNet.

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

Approximately 30 of the 119 papers reviewed above (25%) have been published since the 2017 SCS. The strongest themes in the recent publications are:

1. Better understanding of particulate N, its sources, and bioavailability, showing that a lot of it becomes bioavailable and much of that comes from intense land use and is not well represented just by looking at patterns of all particulate N.
2. Better understanding of pre-development catchment erosion rates and therefore pre-development catchment sediment exports which strengthen the lines of evidence that current suspended sediment exports are well above pre-development rates especially in those catchments identified to be high priority for management.
3. Improved modelling whether that be statistical modelling of exports or improvements to SedNet and its full documentation in the peer reviewed literature. There is now closer agreement between modelling and observations which strengthens the confidence about sources, priorities, and export patterns that were reported in the 2017 SCS.

In addition, since 2017 there has been an expansion in the Paddock to Reef Program sediment and particulate nutrient export monitoring program, including more sites and longer records of consistent measurement providing a better primary dataset to inform models and increase understanding.

4.1.3 Key conclusions

- Overall there is a strong body of evidence on GBR catchment exports, covering multiple lines of evidence, a wide range of GBR basins, and addressing each element of the question.
- Current exports of fine sediments from the Great Barrier Reef catchment to the Great Barrier Reef are well above pre-development rates. Overall, exports of anthropogenic fine sediment are 1.4 to 3 times higher than pre-development estimates, and in the largest basins 2 to 5 times above pre-development rates. Rates of increase[12] of fine sediment exports over pre-development rates are lower in the Cape York and Wet Tropics Natural Resource Management Regions than in other Regions.
- There is good agreement between measured and modelled exports where there is a reasonable length of monitoring record. Monitoring and modelling confirm that the Burdekin and Fitzroy basins are by far the largest exporters of total fine sediment and particulate nutrients to the Great Barrier Reef, each exporting an annual average load of over 1,300 kilotonnes of fine sediment per year and more than 3,000 tonnes of particulate nitrogen per year. Following the Burdekin and Fitzroy basins, the Mary, Herbert and Burnett River basins are the next largest exporters of fine sediment to the Great Barrier Reef (up to 600 kilotonnes per year). Other basins in the Great Barrier Reef catchment that export notable fine sediment loads (over 150 kilotonnes per year)

[12] The rate of increase between the current and pre-development loads is formally referred to as the 'rate of acceleration' and is calculated by the division of the current load by the pre-development load.

include the Don, O'Connell, Johnstone and Normanby basins. All of these basins have a high proportion of anthropogenic exports.

- It is estimated that 54% of the total export of fine sediment to the Great Barrier Reef comes from gully erosion, with almost equal contributions from streambank erosion (24%) and hillslope erosion (22%). Each process can dominate in particular basins. In the wet tropical climatic areas, hillslope erosion tends to be the dominant source. In the dry tropical areas, gully erosion is by far the biggest source. Intensity of erosion is influenced by soil properties, rainfall and other attributes.
- The estimated proportion of total fine sediment loads exported to the Great Barrier Reef from each land use is well established through modelling, supported by monitoring data. It is estimated that grazing lands contribute 60% of the total fine sediment load from 73% of the Great Barrier Reef catchment area, sugarcane contributes 10% from 1.2% of the area, irrigated and dryland cropping contribute 4% from 2.8% of the area, urban contributes 2% from 0.7% of the area, and bananas and horticulture contribute 1% from 0.2% of the area. Other land uses such as nature conservation and forestry collectively contribute 23% of the total fine sediment load from approximately 22.1% of the Great Barrier Reef catchment area, but this is natural, not anthropogenic export. Anthropogenic load contributions of agricultural and urban land uses are much higher than those of conservation areas.
- In the Burdekin basin there is strong evidence that the subcatchments below the Burdekin Falls Dam are the biggest contributors to export. In the similarly large Fitzroy basin, areas with basaltic soils are big contributors of sediment but the subcatchments which contribute most are more equivocal.
- Fine sediment and particulate nutrient export occurs mainly during floods and the larger the flood event in a particular basin, the greater the export. However, the intermittent frequency of large floods means that annual exports can vary by up to three orders of magnitude in the large dry basins such as the Burdekin and Fitzroy. This extreme variability means trends in exports over time could take decades to detect to statstically significant levels. Land use has intensified over time and this has probably lead to increased exports, and changes to flood intensity have occurred over the last 150 years as well but it is the year-to-year variability that dominates the temporal patterns. Statistical analysis shows that major changes such as the construction of the Burdekin Falls Dam or rainfall induced changes to land cover lead to almost immediate changes to sediment exports although it still takes a long record to detect that statistically.
- The Reef Water Quality Report Card 2020 estimates that 'Moderate' overall progress has been made towards meeting the fine sediment load reduction target and 'Very Good' progress for the particulate nutrient load reduction targets. In some basins, targets have been exceeded while in others which were not given management priority, there has been little progress. For some management actions it may be several years until the benefits of management are fully realised, and it will take decades to detect reduced exports in the monitoring program because of the high annual variability of exports controlled by river discharge.
- Significant improvements have been made to the Paddock to Reef Program SedNet model (referred to as Source Catchments) in the last few years and it now better matches observed patterns of fine sediment and particulate nutrients. It provides the best available estimates of fine sediment and particulate nutrient exports as a result of the consistency in approach across all 35 basins and the wealth of information that can be extracted from the results.

4.1.4 Significance of findings for policy, management and practice

There is now even stronger evidence than in previous iterations of the SCS that current exports of sediment and particulate nutrients are well above pre-development rates of export. The marine questions addressed in this SCS show that accelerated exports are having impacts on GBR ecosystems.

The spatial patterns of exports are reasonably well understood from the continuing Paddock to Reef Program monitoring and modelling programs, both of which provide a detailed picture of export patterns which can be used to explore marine impacts (Questions 3.1, Lewis et al., and 3.2, Collier et al., this SCS).

Gully, streambank erosion, and hillslope erosion are all significant sources of exported material. All erosion processes should continue to be the focus of management with the priority determined by more detailed local assessments of sources and land uses. Alongside the evidence on sources described here, considering the connectivity of sources to the GBR lagoon, and the effectiveness of treatments and practices to reduce sediment exports (Question 3.5, Bartley & Murray, this SCS) will be critical to the cost-effectiveness of water quality improvement programs.

Grazing is the biggest contributing land use to export because of its combination of huge areal extent and acceleration of erosion in degraded parts of the landscape. Sugarcane and dryland cropping are important contributors as well as they cover large areas and have accelerated erosion. Any land use which has accelerated erosion and where sediment is delivered efficiently to the coast will be a hotspot contributor and is worth considering for management, for example urban land use.

Particulate N transport is of increasing concern. Much of it can become bioavailable and it is emerging that its sources and export rates can be different enough from sediment or from dissolved nitrogen (Question 4.4, Prosser & Wilkinson, this SCS) to be worth considering and managing separately. There is quite a range of bioavailable particulate N concentrations among contributing land uses and erosion processes.

Catchment management programs are steadily working toward meeting the target reductions in exports, showing that management is working, but future progress will need to be at least as great as that to 2020 to meet all targets.

Both the export monitoring program and modelling programs, which are linked to policy and management, have been improved in recent years. Continued focus on both of these and continued improvements are needed to increase confidence in the patterns of exports, to confidently assess management progress, and to monitor a wider range of conditions and provide warnings of any unforeseen patterns in exports.

4.1.5 Uncertainties and/or limitations of the evidence

It is emerging that some particulate N is bioavailable but this needs more investigation and the sources of that material are quite uncertain but appear to be distinct from patterns of suspended sediment sources.

Monitoring of exports needs to continue to cover the full range of flood magnitudes and for long enough to detect trends in exports as short-term monitoring leaves much uncertainty about patterns of exports.

Annual reports on the monitoring program are published and there are some analyses over multiple years of data but full analysis of the record would help better understand particulate exports.

The SedNet model should continue to be improved through use of higher quality regional data. Some key uncertainties include source patterns in the Fitzroy basin, details of nutrient sources, patterns of riverbank erosion and details of river sediment delivery through some large catchments.

Monitoring and modelling of exports have been largely independent endeavours with monitoring results used to calibrate and test the SedNet model. Pioneering studies have shown there is much potential to formally combine a suite of measurements with modelling to better use all sources of information and formally represent uncertainties in ways that could be incorporated into GBR decision making.

4.2 Contextual variables influencing outcomes

Table 8 summarises contextual influences on material exports, as explained more fully in the summary of evidence.

Table 8. Summary of contextual variables for suspended sediment and attached nutrients.

Contextual variables	Influence on question outcome or relationships
Flood variability	Very high year-to-year flood variability has a very strong control on annual exports. Big floods export far more than small floods (Darnell et al., 2012; Wallace et al., 2012; Wang et al., 2015).
Seasonality	The first flood of the wet season usually has higher concentrations than later wet season floods, especially in dry tropics catchments (Davis et al., 2017; Mitchell & Furnas, 2001; Saha et al., 2018; Wallace et al., 2008).
Land use	Catchments with large areas of intensive land use export more sediment per unit area than others. Changes to land use over time are likely to be the primary driver of changes to export (Bainbridge et al., 2009; Bartley et al., 2017; Hunter & Walton, 2008; Lewis et al., 2021; McCloskey et al., 2021; Packett et al., 2009).
Climate	Wet Tropic catchments tend to have less accelerated current sediment yields, greater particulate N export, less gully erosion and more hillslope erosion than dry tropics catchments (Hunter & Walton, 2008; Mariotti et al., 2021; McCloskey et al., 2021).
Climate change	Changes to rainfall to 2050 are projected to be small compared to the current high annual variability of rainfall thus exports will continue to be dominated by climate and flood variability. If there is a future increase in flood variability it would be expected to lead to increased exports (Alluvium, 2019).
Catchment area	There is a huge range in area of catchments exporting to the GBR. Large catchments export more than small catchments, but the export rate per unit area varies by two orders of magnitude and is dependent upon climate and land use (Bartley et al., 2017; McCloskey et al., 2021).
Lithology and soil type	There is evidence that basaltic lithologies and other areas with soils dominated by expandable clays contribute disproportionately to export and these clays travel the furthest in the marine environment (Bainbridge et al., 2016; 2018; Douglas et al., 2006b; Furuichi et al., 2016).
Erosion processes	Gully erosion, streambank erosion and hillslope erosion are all significant sources of exported sediment and particulate nutrient and each can dominate in particular catchments. Hillslope erosion is likely to be the predominant source for particulate N (Bartley et al., 2017; Hancock et al., 2014; Hughes et al., 2009; McCloskey et al., 2021; Olley et al., 2013; Tims et al., 2010; Wilkinson et al., 2013; 2015).

4.3 Evidence appraisal

Relevance

The overall relevance of the body of evidence was rated as High. The export of sediments and particulate nutrients has been the topic of many studies of GBR rivers for a long time. Individual studies have focused on the large intensively used catchments and those with the most intensive land use. These are the basins most likely to produce marine impacts. Basins that are not specifically studied by measurements are covered by several GBR-wide assessments, and modelling studies of exports and monitoring covers the vast majority of total export resulting in high spatial coverage to the studies. Key concepts or theories from catchment exports in other regions of the world have been tested and adopted in GBR sediment export research so there was no need to consider less directly relevant research.

Temporal relevance is High with many studies examining current exports but several also addressing pre-development exports, acceleration of exports over pre-development rates, variability with flood intensity, and changes with land use over time. There are now over 20 years of published catchment export monitoring data and there are longer term proxy records of exports over the full historical period. The influence of climate change has not been investigated in detail but the understanding of the controls on catchment exports suggests that until at least 2050 land use change and flood variability will continue be stronger drivers of exports. Land use change includes future improvements to catchment management to reach target export reductions and risks from changes to types and intensity of land use practice which have changed considerably in past decades.

Because of the large body of directly relevant papers only highly relevant peer reviewed papers on the GBR catchments were reviewed.

Consistency, Quantity and Diversity

There were over 100 peer reviewed journal papers that directly address the primary question in one or more GBR basins. Two academic databases were searched as well as Google Scholar capturing the vast majority of peer reviewed published work. All aspects of the question were covered. There is a strong diversity of approaches taken to examine exports including: direct measurements of discharge and constituent concentrations, annual export calculations from these, modelling of exports from all GBR basins, modelling and geochemical tracing of the sources of exported material, proxy records of exports over time in coral cores. There is now a High degree of consistency between independent types of studies on the patterns and sources of export. There were early differences between observational studies of sources and their modelling but these have now largely been resolved as a result of model improvements and this is demonstrated in the recent literature (see Summary of Findings above). The overall patterns of export are well supported by multiple lines of evidence. Details of sources within particular subcatchments are investigated by local field and remote sensing evidence and this is more appropriate than using export modelling, measuring or proxy records at a finer temporal or spatial scale than they are designed for. A few other potential sources and erosion processes have been identified by field studies but their significance for annual exports has not been demonstrated (see Summary of Findings above).

In addition to the internal consistency of findings within the export studies they are consistent with upstream work on the drivers of erosion (Question 3.4, Prosser & Wilkinson, this SCS) and downstream work on marine distributions of sediment (Question 3.1, Lewis et al., this SCS).

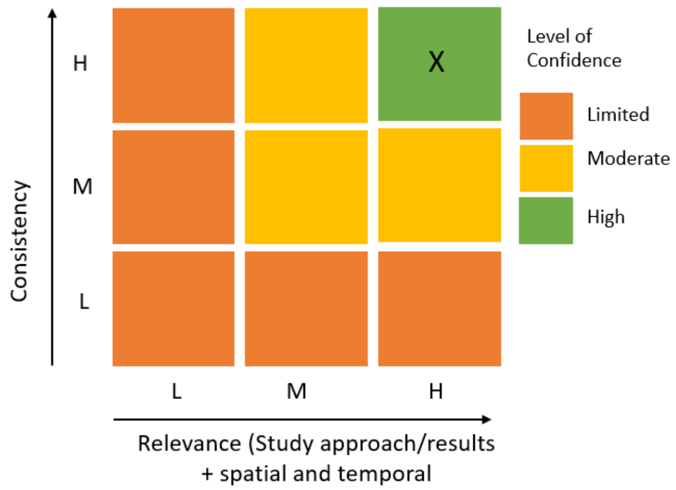
Particulate N is not as well understood as suspended sediment and may be important for marine impacts as much of it may be bioavailable but not equally in each catchment. It is worthy of extra studies on its own as the sources are not as well constrained, nor are the characteristics that make it bioavailable.

The large annual variability in exports makes it hard to be certain about mean annual rates or to track changes in rates over time. This will improve as more years of monitoring data are collected and more large floods are included in the monitoring data. The largest floods are also the hardest from which to estimate exports but it should be noted that marine impacts are chronic (Question 3.1, Lewis et al., this SCS) and not restricted to occasional big floods so it is not just big floods that are of concern.

Confidence

The confidence rating for the question is High as a result of the High consistency and spatial and temporal relevance of a large number of studies. Overall, there is High confidence on the main exporting rivers, the land uses, erosion processes, and characteristics of the exported material. There are some areas of moderate uncertainty over subcatchment sources in the Fitzroy basin and over bioavailable particulate N but these are small elements of the overall concerns over exports. The knowledge base on exports has contributed strongly to GBR management programs for nearly two decades now with some major improvements in understanding over that time and it is well placed to continue to support management if the monitoring and modelling programs are maintained and well targeted future research is supported.

Table 9. Summary of results for the evidence appraisal of the whole body of evidence in addressing Question 3.3. 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)	High	
-To the Question	High	
-Spatial	High	
-Temporal	High	
Consistency	High	
Quantity	High (119 GBR studies)	
Diversity	High (76 observational, 26 modelling, 11 combined, 6 secondary)	

4.4 Indigenous engagement/participation within the body of evidence

There was no Indigenous engagement or participation described in the body of evidence. The topic of quantifying exports of particular sediment and nutrient constituents is probably more reductive than the overall systems conceptualisations of Indigenous knowledge.

4.5 Knowledge gaps

Overall, there is a very good body of knowledge to support management of exports and knowledge has continued to improve. Continued improvement would help reduce uncertainties and give more confidence to management. There are some gaps in understanding which if filled would help reduce future pollution. These are outlined in Table 10.

Table 10. Summary of knowledge gaps.

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
Characterisation of the bioavailable portion of particulate N.	Studies into which components of particulate N are bioavailable, the sources of that material, and how to manage it.	Better targeting of N pollution of marine environments beyond the current focus on dissolved N.
Monitoring of a full range of exporting flows and for long enough to detect trends.	Continue export monitoring program and adapt it to meet evolving needs.	Increased confidence on exports and how they are changing.
Analysis of the full monitoring record.	Complement annual reports on monitoring with a full analysis of statistical patterns in space and time.	Increased confidence on exports and their patterns in space and time.
Aspects of the SedNet export modelling program.	Continue to improve components of the model and its evaluation against independent data. See Prosser (2018) for researcher	Increased confidence on exports, their sources, and management priorities.

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
	consensus statement on possible improvements.	
Understanding of sources in particular priority basins.	Better data and modelling on subcatchment sources in the Fitzroy basin. Independent studies of sources in the Burnett basin. Consideration of other basins.	Improved ability to target catchment management in large complex basins.
Indigenous knowledge of export patterns.	Engage with Indigenous communities to understand their knowledge of catchment sources and changes to rivers over time.	Improved understanding of historical changes and patterns. Improved community engagement.
Formal integration of monitoring and modelling studies.	Test approaches to more formally combine monitoring and modelling results and explicitly represent uncertainty in ways that can be incorporated into GBR decision making.	Better use of existing knowledge to explicitly represent uncertainty and inform risk-based management approaches.

5. Evidence Statement

The synthesis of the evidence for **Question 3.3** was based on 119 studies undertaken mostly in the Great Barrier Reef and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (64% observational, 22% modelling, 9% combined and 5% reviews), and has a *High* confidence rating (based on *High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management action

There is a strong body of evidence showing that current exports of fine sediments from the Great Barrier Reef catchment to the Great Barrier Reef are well above pre-development rates. Overall, exports of anthropogenic[13] fine sediment are 1.4 to 3 times higher than pre-development estimates, and in the largest basins 2 to 5 times above pre-development rates. Monitoring and modelling confirm that the Burdekin and Fitzroy basins are by far the largest exporters of total fine sediment and particulate nutrients to the Great Barrier Reef, each exporting an annual average load of over 1,300 kilotonnes of fine sediment per year and more than 3,000 tonnes of particulate nitrogen per year. These basins also have the highest anthropogenic exports. Grazing land use is the largest contributor of fine sediment export to the Great Barrier Reef, estimated to be 60% of the total load, with all other land uses each contributing much smaller amounts (linked to total land area). Hillslope, gully and streambank erosion are each important sources of fine sediment in particular regions. These findings are supported by multiple lines of evidence including monitoring, modelling and radioisotope tracing studies.

Supporting points

- Rates of increase[14] of fine sediment exports over pre-development rates are lower in the Cape York and Wet Tropics Natural Resource Management regions than in other regions.
- Following the Burdekin and Fitzroy basins, the Mary, Herbert and Burnett River basins are the next largest exporters of fine sediment to the Great Barrier Reef (up to 600 kilotonnes per year). Other basins in the Great Barrier Reef catchment that export notable fine sediment loads (over 150 kilotonnes per year) include the Don, O'Connell, Johnstone and Normanby basins. All of these basins have a high proportion of anthropogenic exports.
- It is estimated that 54% of the total export of fine sediment to the Great Barrier Reef comes from gully erosion, with almost equal contributions from streambank erosion (24%) and hillslope erosion (22%). Each process can dominate in particular basins. In the wet tropical climatic areas, hillslope erosion tends to be the dominant source. In the dry tropical areas, gully erosion is by far the biggest source. Intensity of erosion is influenced by soil properties, rainfall and other attributes.
- The estimated proportion of total fine sediment loads exported to the Great Barrier Reef from each land use is well established through modelling, supported by monitoring data. It is estimated that grazing lands contribute 60% of the total fine sediment load from 73% of the Great Barrier Reef catchment area, sugarcane contributes 10% from 1.2% of the area, irrigated and dryland cropping contribute 4% from 2.8% of the area, urban contributes 2% from 0.7% of the area, and bananas and horticulture contribute 1% from 0.2% of the area. Other land uses such as nature conservation and forestry collectively contribute 23% of the total fine sediment load from approximately 22.1% of the Great Barrier Reef catchment area, but this is natural, not anthropogenic export. Anthropogenic load contributions of agricultural and urban land uses are much higher than those of conservation areas.
- The land use contributing the largest export of fine sediment varies between regions. For example, grazing contributes significantly to exports in the Burdekin and Fitzroy regions,

[13] The end-of-catchment anthropogenic load of fine sediment or particulate nutrients is calculated as the current end-of-catchment load minus the predicted end-of-catchment pre-development load.
[14] The rate of increase between the current and pre-development loads is formally referred to as the 'rate of acceleration' and is calculated by the division of the current load by the pre-development load.

sugarcane contributes significantly to exports in the Wet Tropics and Mackay Whitsunday regions, and dryland cropping in the Fitzroy region. Urban land use contributes <5% of fine sediment export in all regions.

- Observational studies show that intense land uses such as mining and urban areas can generate large sources of fine sediment locally but cover a relatively small proportion of the Great Barrier Reef catchment area and overall exports are relatively low.
- The Burdekin, Fitzroy, Mary and Herbert River basins are also the largest exporters of particulate nutrients (nitrogen and phosphorus) to the Great Barrier Reef. There are no independent measures of pre-development particulate nutrient exports.
- Particulate nutrient export from the Great Barrier Reef catchment generally follows similar patterns to fine sediment due to the strong correlation between particulate nutrient and fine sediment. For both particulate nitrogen and phosphorus, however, there is a more even distribution across the basins in terms of relative contributions, than there is for fine sediment; this is partly linked to soil types.
- In most basins, hillslope erosion is estimated to be the most important source of particulate nutrients due to higher nutrient content in surface soils.
- Fine sediment and particulate nutrient export occurs mainly during floods and the larger the flood event in a particular basin, the greater the export. However, the intermittent frequency of large floods means that annual exports can vary by up to three orders of magnitude in the large dry basins such as the Burdekin and Fitzroy.
- The Reef Water Quality Report Card 2020 estimates that ’Moderate’ overall progress has been made towards meeting the fine sediment load reduction target and ‘Very Good’ progress for the particulate nutrient load reduction targets. In some basins, targets have been exceeded while in others which were not given management priority, there has been little progress. For some management actions it may be several years until the benefits of management are fully realised, and it will take decades to detect reduced exports in the monitoring program because of the high annual variability of exports controlled by river discharge.
- Significant improvements have been made to the Paddock to Reef Program SedNet model (referred to as Source Catchments) in the last few years and it now better matches observed patterns of fine sediment and particulate nutrients. It provides the best available estimates of fine sediment and particulate nutrient exports as a result of the consistency in approach across all 35 basins and the wealth of information that can be extracted from the results.

6. References

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

Body of Evidence

Adame, M. F., & Reef, R. (2020). Potential pollution sources from agricultural activities on tropical forested floodplain wetlands revealed by soil eDNA. *Forests*, *11*(8), 892. https://doi.org/10.3390/f11080892

Adame, M. F., Vilas, M. P., Franklin, H. M., Garzon-Garcia, A., Hamilton, D. P., Ronan, M., & Griffiths, M. (2021). A conceptual model of nitrogen dynamics for the Great Barrier Reef catchments. *Marine Pollution Bulletin*, *173*, 112909. https://doi.org/10.1016/j.marpolbul.2021.112909

Alluvium (2019). Critical review of climate change and water modelling in Queensland – Final Report. *Queensland Government*. https://science.des.qld.gov.au/__data/assets/pdf_file/0034/98863/critical-review-climate-change-water-modelling-qld.pdf

Alongi, D. M., & McKinnon, A. D. (2005). The cycling and fate of terrestrially-derived sediments and nutrients in the coastal zone of the Great Barrier Reef shelf. *Marine Pollution Bulletin*, *51*(1–4), 239–252. https://doi.org/10.1016/j.marpolbul.2004.10.033

Amos, K. J., Alexander, J., Horn, A., Pocock, G. D., & Fielding, C. R. (2004). Supply limited sediment transport in a high-discharge event of the tropical Burdekin River, North Queensland, Australia. *Sedimentology*, *51*(1), 145–162. https://doi.org/10.1111/j.1365-3091.2004.00616.x

Armour, J. D., Hateley, L. R., & Pitt, G. L. (2009). Catchment modelling of sediment, nitrogen and phosphorus nutrient loads with SedNet/ANNEX in the Tully - Murray basin. *Marine and Freshwater Research*, *60*(11), 1091-1096. https://doi.org/10.1071/MF08345

Bahadori, M., Chen, C. R., Lewis, S. E., Rashti, M. R., Cook, F. J., Parnell, A., Esfandbod, M., & Stevens, T. (2020). Tracing the sources of sediment and associated particulate nitrogen from different land uses in the Johnstone River catchment, Wet Tropics, north-eastern Australia. *Marine Pollution Bulletin*, *157*, 111344. https://doi.org/10.1016/j.marpolbul.2020.111344

Bahadori, M., Chen, C. R., Lewis, S. E., Rezaei Rashti, M., Cook, F. J., Parnell, A., Esfandbod, M., & Boyd, S. (2019). A novel approach of combining isotopic and geochemical signatures to differentiate the sources of sediments and particulate nutrients from different land uses. *Science of The Total Environment*, *655*, 129–140. https://doi.org/10.1016/j.scitotenv.2018.11.084

Bainbridge, Z. T., Brodie, J. E., Faithful, J. W., Sydes, D. A., & Lewis, S. E. (2009). Identifying the land-based sources of suspended sediments, nutrients and pesticides discharged to the Great Barrier Reef from the Tully - Murray Basin, Queensland, Australia. *Marine and Freshwater Research*, *60*(11), 1081–1090. https://doi.org/10.1071/MF08333

Bainbridge, Z. T., Lewis, S. E., Smithers, S. G., Kuhnert, P. M., Henderson, B. L., & Brodie, J. E. (2014). Fine-suspended sediment and water budgets for a large, seasonally dry tropical catchment: Burdekin River catchment, Queensland, Australia. *Water Resources Research*, *50*(11), 9067–9087. https://doi.org/10.1002/2013WR014386

Bainbridge, Z. T., Lewis, S. E., Smithers, S. G., Wilkinson, S. N., Douglas, G. B., Hillier, S., & Brodie, J. E. (2016). Clay mineral source tracing and characterisation of Burdekin River (NE Australia) and flood plume fine sediment. *Journal of Soils and Sediments*, *16*(2), 687–706. https://doi.org/10.1007/s11368-015-1282-4

Bainbridge, Z. T., Lewis, S. E., Stevens, T., Petus, C., Lazarus, E., Gorman, J., & Smithers, S. G. (2021). Measuring sediment grain size across the catchment to reef continuum: Improved methods and environmental insights. *Marine Pollution Bulletin*, *168*, 112339. https://doi.org/10.1016/j.marpolbul.2021.112339

Bainbridge, Z. T., Wolanski, E. C., Álvarez-Romero, J. G., Lewis, S. E., & Brodie, J. E. (2012). Fine sediment and nutrient dynamics related to particle size and floc formation in a Burdekin River flood plume, Australia. *Marine Pollution Bulletin*, *65*(4–9), 236–248. https://doi.org/10.1016/j.marpolbul.2012.01.043

Bartley, R., Bainbridge, Z. T., Lewis, S. E., Kroon, F. J., Wilkinson, S. N., Brodie, J. E., & Silburn, D. M. (2014). Relating sediment impacts on coral reefs to watershed sources, processes and management: A review. *Science of The Total Environment*, *468–469*, 1138–1153. https://doi.org/10.1016/j.scitotenv.2013.09.030

Bartley, R., Croke, J. C., Bainbridge, Z. T., Austin, J. M., & Kuhnert, P. M. (2015). Combining contemporary and long-term erosion rates to target erosion hot-spots in the Great Barrier Reef, Australia. *Anthropocene*, *10*, 1–12. https://doi.org/10.1016/j.ancene.2015.08.002

Bartley, R., Olley, J. M., & Henderson, A. E. (2004). A sediment budget for the Herbert River catchment, North Queensland, Australia. *IAHS-AISH Publication*, *2004*(288), 147–154.

Bartley, R., Speirs, W. J., Ellis, T. W., & Waters, D. K. (2012). A review of sediment and nutrient concentration data from Australia for use in catchment water quality models. *Marine Pollution Bulletin*, *65*(4–9), 101–116. https://doi.org/10.1016/j.marpolbul.2011.08.009

Bartley, R., Thompson, C., Croke, J. C., Pietsch, T. J., Baker, B., Hughes, K., & Kinsey-Henderson, A. E. (2018). Insights into the history and timing of post-European land use disturbance on sedimentation rates in catchments draining to the Great Barrier Reef. *Marine Pollution Bulletin*, *131*, 530–546. https://doi.org/10.1016/j.marpolbul.2018.04.070

Bartley, R., Waters, D. K., Turner, R., Kroon, F. J., Wilkinson, S. N., Garzon-Garcia, A., Kuhnert, P. M., Lewis, S. E., Smith, R., Bainbridge, Z. T., Olley, J. M., Brooks, A. P., Burton, J. M., Brodie, J. E., & Waterhouse, J. (2017). Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 2: Sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef. *State of Queensland*.

Bostock, H. C., Brooke, B. P., Ryan, D. A. J., Hancock, G. J., Pietsch, T. J., Packett, R., & Harle, K. (2007). Holocene and modern sediment storage in the subtropical macrotidal Fitzroy River estuary, Southeast Queensland, Australia. *Sedimentary Geology*, *201*(3–4), 321–340. https://doi.org/10.1016/j.sedgeo.2007.07.001

Brodie, J. E., Christie, C. A., Devlin, M. J., Haynes, D., Morris, S., Ramsay, M., Waterhouse, J., & Yorkston, H. (2001). Catchment management and the Great Barrier Reef. *Water Science and Technology*, *43*(9), 203–211. https://doi.org/10.2166/wst.2001.0540

Brodie, J. E., Kroon, F. J., Schaffelke, B., Wolanski, E. C., Lewis, S. E., Devlin, M. J., Bohnet, I. C., Bainbridge, Z. T., Waterhouse, J., & Davis, A. M. (2012). Terrestrial pollutant runoff to the Great Barrier Reef: An update of issues, priorities and management responses. *Marine Pollution Bulletin*, *65*(4–9), 81–100. https://doi.org/10.1016/j.marpolbul.2011.12.012

Brodie, J. E., Lewis, S. E., Bainbridge, Z. T., Mitchell, A. W., Waterhouse, J., & Kroon, F. J. (2009). Target setting for pollutant discharge management of rivers in the Great Barrier Reef catchment area. *Marine and Freshwater Research*, *60*(11), 1141-1149. https://doi.org/10.1071/MF08339

Brodie, J. E., Lewis, S. E., Collier, C. J., Wooldridge, S. A., Bainbridge, Z. T., Waterhouse, J., Rasheed, M. A., Honchin, C., Holmes, G., & Fabricius, K. E. (2017). Setting ecologically relevant targets for river pollutant loads to meet marine water quality requirements for the Great Barrier Reef, Australia: A preliminary methodology and analysis. *Ocean & Coastal Management*, *143*, 136–147. https://doi.org/10.1016/j.ocecoaman.2016.09.028

Brodie, J. E., & Mitchell, A. W. (2005). Nutrients in Australian tropical rivers: changes with agricultural development and implications for receiving environments. *Marine and Freshwater Research*, *56*(3), 279–302. https://doi.org/10.1071/MF04081

Brooks, A. P., Spencer, J. R., Borombovits, D., Pietsch, T. J., & Olley, J. M. (2014). Measured hillslope erosion rates in the wet-dry tropics of Cape York, northern Australia: Part 2, RUSLE-based modeling significantly over-predicts hillslope sediment production. *Catena*, *122*, 1–17. https://doi.org/10.1016/j.catena.2014.06.002

Chaiechi, T., Stoeckl, N., Jarvis, D., Lewis, S. E., & Brodie, J. E. (2016). Assessing the impact of price changes and extreme climatic events on sediment loads in a large river catchment near the Great Barrier Reef. *Australian Journal of Agricultural and Resource Economics*, *60*(3), 386–405. https://doi.org/10.1111/1467-8489.12140

Codilean, A. T., Fülöp, R.-H., Munack, H., Wilcken, K. M., Cohen, T. J., Rood, D. H., Fink, D., Bartley, R., Croke, J. C., & Fifield, L. K. (2021). Controls on denudation along the East Australian continental margin. *Earth-Science Reviews*, *214*(10354), 103543. https://doi.org/10.1016/j.earscirev.2021.103543

Croke, J. C., Bartley, R., Chappell, J., Austin, J. M., Fifield, K., Tims, S. G., Thompson, C. J., & Furuichi, T. (2015). ^{10}Be-derived denudation rates from the Burdekin catchment: The largest contributor of sediment to the Great Barrier Reef. *Geomorphology*, *241*, 122–134. https://doi.org/10.1016/j.geomorph.2015.04.003

D'Olivo, J. P., & McCulloch, M. T. (2022). Impact of European settlement and land use changes on Great Barrier Reef river catchments reconstructed from long-term coral Ba/Ca records. *Science of The Total Environment*, *830*, 154461. https://doi.org/10.1016/j.scitotenv.2022.154461

Darnell, R., Henderson, B. L., Kroon, F. J., & Kuhnert, P. M. (2012). Statistical power of detecting trends in total suspended sediment loads to the Great Barrier Reef. *Marine Pollution Bulletin*, *65*(4–9), 203–209. https://doi.org/10.1016/j.marpolbul.2012.04.002

Davis, A. M., Pearson, R. G., Brodie, J. E., & Butler, B. B. (2017). Review and conceptual models of agricultural impacts and water quality in waterways of the Great Barrier Reef catchment area. *Marine and Freshwater Research*, *68*(1), 1–19. https://doi.org/10.1071/MF15301

Douglas, G. B., Ford, P. W., Palmer, M., Noble, R. M., & Packett, R. (2006a). Fitzroy River Basin, Queensland, Australia. I. Identification of Sediment Sources in Impoundments and Flood Events. *Environmental Chemistry*, *3*(5), 364-376. https://doi.org/10.1071/EN06009

Douglas, G. B., Ford, P. W., Palmer, M., Noble, R. M., & Packett, R. (2006b). Fitzroy River, Queensland, Australia. II. Identification of Sources of Estuary Bottom Sediments. *Environmental Chemistry*, *3*(5), 377-385. https://doi.org/10.1071/EN06010

Douglas, G. B., Kuhnen, M., Radke, L. C., Hancock, G. J., Brooke, B. P., Palmer, M. J., Pietsch, T. J., Ford, P. W., Trefry, M. G., & Packett, R. (2010). Delineation of sediment sources to a coastal wetland in the Great Barrier Reef catchment: influence of climate variability and land clearing since European arrival. *Environmental Chemistry*, *7*(2), 190–206. https://doi.org/10.1071/EN09089

Franklin, H. M., Garzon-Garcia, A., Burton, J. M., Moody, P. W., De Hayr, R. W., & Burford, M. A. (2018). A novel bioassay to assess phytoplankton responses to soil-derived particulate nutrients. *Science of The Total Environment*, *636*, 1470–1479. https://doi.org/10.1016/j.scitotenv.2018.04.195

Furnas, M. J. (2003). Catchments and corals: terrestrial runoff to the Great Barrier Reef. *Australian Institute of Marine Science*. https://www.aims.gov.au/sites/default/files/catchments-and-corals.pdf

Furnas, M. J., & Mitchell, A. (2000). Runoff of terrestrial sediment and nutrients into the Great Barrier Reef World Heritage Area. In *Oceanographic Processes of Coral Reefs* (pp. 57–72). *CRC Press*. https://doi.org/10.1201/9781420041675-9

Furuichi, T., Olley, J. M., Wilkinson, S. N., Lewis, S. E., Bainbridge, Z. T., & Burton, J. M. (2016). Paired geochemical tracing and load monitoring analysis for identifying sediment sources in a large catchment draining into the Great Barrier Reef Lagoon. *Geomorphology*, *266*, 41–52. https://doi.org/10.1016/j.geomorph.2016.05.008

Garzon-Garcia, A., Burton, J. M., Franklin, H. M., Moody, P. W., De Hayr, R. W., & Burford, M. A. (2018). Indicators of phytoplankton response to particulate nutrient bioavailability in fresh and marine waters of the Great Barrier Reef. *Science of The Total Environment*, *636*, 1416–1427. https://doi.org/10.1016/j.scitotenv.2018.04.334

Garzon-Garcia, A., Burton, J. M., Lewis, S. E., Bainbridge, Z. T., De Hayr, R. W., Moody, P. W., & Brodie, J. E. (2021). The bioavailability of nitrogen associated with sediment in riverine plumes of the Great Barrier Reef. *Marine Pollution Bulletin*, *173*, 112910. https://doi.org/10.1016/j.marpolbul.2021.112910

Garzon-Garcia, A., Olley, J. M., & Bunn, S. E. (2015). Controls on carbon and nitrogen export in an eroding catchment of south-eastern Queensland, Australia. *Hydrological Processes*, *29*(5), 739–751. https://doi.org/10.1002/hyp.10192

Gladish, D. W., Lewis, S. E., Bainbridge, Z. T., Brodie, J. E., Kuhnert, P. M., Pagendam, D. E., Wikle, C. K., Bartley, R., Searle, R. D., Ellis, R. J., Dougall, C., & Turner, R. D. R. (2016). Spatio-temporal assimilation of modelled catchment loads with monitoring data in the Great Barrier Reef. *The Annals of Applied Statistics*, *10*(3), 1590–1618. https://doi.org/10.1214/16-AOAS950

Hairsine, P. B. (2017). Review: Sediment-related controls on the health of the Great Barrier Reef. *Vadose Zone Journal*, *16*(12), 1–15. https://doi.org/10.2136/vzj2017.05.0115

Hancock, G. J., Wilkinson, S. N., Hawdon, A. A., & Keen, R. J. (2014). Use of fallout tracers ^{7}Be, ^{210}Pb and ^{137}Cs to distinguish the form of sub-surface soil erosion delivering sediment to rivers in large catchments. *Hydrological Processes*, *28*(12), 3855–3874. https://doi.org/10.1002/hyp.9926

Howley, C., Devlin, M. J., & Burford, M. A. (2018). Assessment of water quality from the Normanby River catchment to coastal flood plumes on the northern Great Barrier Reef, Australia. *Marine and Freshwater Research*, *69*(6), 859–873. https://doi.org/10.1071/MF17009

Howley, C., Shellberg, J. G., Olley, J. M., Brooks, A., Spencer, J., & Burford, M. A. (2021). Sediment and nutrient sources and sinks in a wet-dry tropical catchment draining to the Great Barrier Reef. *Marine Pollution Bulletin*, *165*, 112080. https://doi.org/10.1016/j.marpolbul.2021.112080

Huggins, R. L., Wallace, R. M., Orr, D. N., Smith, R. A., Taylor, O., King, O. C., Gardiner, R., Wallace, S., Ferguson, B., Preston, S., Simpson, S., Shanks, J., Warne, M. S. J., Turner, R. D. R., & Mann, R. M. (2017). Total suspended solids, nutrient and pesticide loads (2015-2016) for rivers that discharge to the Great Barrier Reef - Great Barrier Reef Catchment Loads Monitoring Program. *Department of Environment and Science*. https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0028/45991/2015-2016-gbr-catchment-loads-technical-report.pdf

Hughes, A. O., & Croke, J. C. (2011). Validation of a spatially distributed erosion and sediment yield model (SedNet) with empirically derived data from a catchment adjacent to the Great Barrier Reef Lagoon. *Marine and Freshwater Research*, *62*(8), 962-973. https://doi.org/10.1071/MF11030

Hughes, A. O., Croke, J. C., Pietsch, T. J., & Olley, J. M. (2010). Changes in the rates of floodplain and in-channel bench accretion in response to catchment disturbance, Central Queensland, Australia. *Geomorphology*, *114*(3), 338–347. https://doi.org/10.1016/j.geomorph.2009.07.016

Hughes, A. O., Olley, J. M., Croke, J. C., & McKergow, L. A. (2009). Sediment source changes over the last 250 years in a dry-tropical catchment, Central Queensland, Australia. *Geomorphology*, *104*(3–4), 262–275. https://doi.org/10.1016/j.geomorph.2008.09.003

Hunter, H. M., & Walton, R. S. (2008). Land-use effects on fluxes of suspended sediment, nitrogen and phosphorus from a river catchment of the Great Barrier Reef, Australia. *Journal of Hydrology*, *356*(1–2), 131–146. https://doi.org/10.1016/j.jhydrol.2008.04.003

Joo, M., McNeil, V. H., Carroll, C., Waters, D. K., & Choy, S. C. (2014). Sediment and nutrient load estimates for major Great Barrier Reef catchments (1987-2009) for Source Catchment Model validation. *Department of Science, Information Technology, Innovation, and Arts, Queensland Government*. https://www.researchgate.net/profile/Marianna-Joo/publication/274007590_Joo_ReefScience_report_APPROVED_corrected/data/551223ca0cf268a4aae9ab0e/Joo-ReefScience-report-APPROVED-corrected.pdf

Joo, M., Raymond, M. A. A., McNeil, V. H., Huggins, R. L., Turner, R. D. R., & Choy, S. C. (2012). Estimates of sediment and nutrient loads in 10 major catchments draining to the Great Barrier Reef during 2006–2009. *Marine Pollution Bulletin*, *65*(4–9), 150–166. https://doi.org/10.1016/j.marpolbul.2012.01.002

Judy, J. D., Kirby, J. K., Farrell, M., McLaughlin, M. J., Wilkinson, S. N., Bartley, R., & Bertsch, P. M. (2018). Colloidal nitrogen is an important and highly-mobile form of nitrogen discharging into the Great Barrier Reef lagoon. *Scientific Reports*, *8*(1), 12854. https://doi.org/10.1038/s41598-018-31115-z

Khan, U., Cook, F. J., Laugesen, R., Hasan, M. M., Plastow, K., Amirthanathan, G. E., Bari, M. A., & Tuteja, N. K. (2020). Development of catchment water quality models within a realtime status and forecast system for the Great Barrier Reef. *Environmental Modelling & Software*, *132*, 104790. https://doi.org/10.1016/j.envsoft.2020.104790

Kroon, F. J., Kuhnert, P. M., Henderson, B. L., Wilkinson, S. N., Kinsey-Henderson, A. E., Abbott, B. N., Brodie, J. E., & Turner, R. D. R. (2012). River loads of suspended solids, nitrogen, phosphorus and herbicides delivered to the Great Barrier Reef lagoon. *Marine Pollution Bulletin*, *65*(4–9), 167–181. https://doi.org/10.1016/j.marpolbul.2011.10.018

Kuhnert, P. M., Henderson, B. L., Lewis, S. E., Bainbridge, Z. T., Wilkinson, S. N., & Brodie, J. E. (2012). Quantifying total suspended sediment export from the Burdekin River catchment using the loads regression estimator tool. *Water Resources Research*, *48*(4). https://doi.org/10.1029/2011WR011080

Kuhnert, P. M., Pagendam, D. E., Bartley, R., Gladish, D. W., Lewis, S. E., & Bainbridge, Z. T. (2018). Making management decisions in the face of uncertainty: a case study using the Burdekin catchment in the Great Barrier Reef. *Marine and Freshwater Research*, *69*(8), 1187-1200. https://doi.org/10.1071/MF17237

Leigh, C., Kandanaarachchi, S., McGree, J. M., Hyndman, R. J., Alsibai, O., Mengersen, K., & Peterson, E. E. (2019). Predicting sediment and nutrient concentrations from high-frequency water-quality data. *PLOS ONE*, *14*(8), e0215503. https://doi.org/10.1371/journal.pone.0215503

Leonard, N. D., Welsh, K. J., Nguyen, A. D., Sadler, J., Pandolfi, J. M., Clark, T. R., Zhao, J., Feng, Y. X., & Webb, G. E. (2019). High resolution geochemical analysis of massive *Porites spp.* corals from the Wet Tropics, Great Barrier Reef: rare earth elements, yttrium and barium as indicators of terrigenous input. *Marine Pollution Bulletin*, *149*, 110634. https://doi.org/10.1016/j.marpolbul.2019.110634

Leonard, S., & Nott, J. (2015). Rapid cycles of episodic adjustment: Understanding the Holocene fluvial archive of the Daintree River of Northeastern Australia. *The Holocene*, *25*(8), 1208–1219. https://doi.org/10.1177/0959683615580860

Lewis, S. E., Bainbridge, Z. T., Kuhnert, P. M., Sherman, B. S., Henderson, B. L., Dougall, C., Cooper, M., & Brodie, J. E. (2013). Calculating sediment trapping efficiencies for reservoirs in tropical settings: A case study from the Burdekin Falls Dam, NE Australia. *Water Resources Research*, *49*(2), 1017–1029. https://doi.org/10.1002/wrcr.20117

Lewis, S. E., Bartley, R., Wilkinson, S. N., Bainbridge, Z. T., Henderson, A. E., James, C. S., Irvine, S. A., & Brodie, J. E. (2021). Land use change in the river basins of the Great Barrier Reef, 1860 to 2019: A foundation for understanding environmental history across the catchment to reef continuum. *Marine Pollution Bulletin*, *166*, 112193. https://doi.org/10.1016/j.marpolbul.2021.112193

Lewis, S. E., Lough, J. M., Cantin, N. E., Matson, E. G., Kinsley, L., Bainbridge, Z. T., & Brodie, J. E. (2018). A critical evaluation of coral Ba/Ca, Mn/Ca and Y/Ca ratios as indicators of terrestrial input: New data from the Great Barrier Reef, Australia. *Geochimica et Cosmochimica Acta*, *237*, 131–154. https://doi.org/10.1016/j.gca.2018.06.017

Lewis, S. E., Olley, J. M., Furuichi, T., Sharma, A. K., & Burton, J. M. (2014). Complex sediment deposition history on a wide continental shelf: Implications for the calculation of accumulation rates on the Great Barrier Reef. *Earth and Planetary Science Letters*, *393*, 146–158. https://doi.org/10.1016/j.epsl.2014.02.038

Liu, S., Ryu, D., Webb, J. A., Lintern, A., Waters, D. K., Guo, D., & Western, A. W. (2018). Characterisation of spatial variability in water quality in the Great Barrier Reef catchments using multivariate statistical analysis. *Marine Pollution Bulletin*, *137*, 137–151. https://doi.org/10.1016/j.marpolbul.2018.10.019

Liu, S., Ryu, D., Webb, J. A., Lintern, A., Guo, D., Waters, D. K., & Western, A. W. (2021a). A Bayesian approach to understanding the key factors influencing temporal variability in stream water quality – a case study in the Great Barrier Reef catchments. *Hydrology and Earth System Sciences*, *25*(5), 2663–2683. https://doi.org/10.5194/hess-25-2663-2021

Liu, S., Ryu, D., Webb, J. A., Lintern, A., Guo, D., Waters, D. K., & Western, A. W. (2021b). A multi-model approach to assessing the impacts of catchment characteristics on spatial water quality in the Great Barrier Reef catchments. *Environmental Pollution*, *288*, 117337. https://doi.org/10.1016/j.envpol.2021.117337

Lough, J. M., Lewis, S. E., & Cantin, N. E. (2015). Freshwater impacts in the central Great Barrier Reef: 1648–2011. *Coral Reefs*, *34*(3), 739–751. https://doi.org/10.1007/s00338-015-1297-8

Lynam, T., Drewry, J. E., Higham, W. A., & Mitchell, C. (2010). Adaptive modelling for adaptive water quality management in the Great Barrier Reef region, Australia. *Environmental Modelling & Software*, *25*(11), 1291–1301. https://doi.org/10.1016/j.envsoft.2009.09.013

Mallela, J., Lewis, S. E., & Croke, B. (2013). Coral skeletons provide historical evidence of phosphorus runoff on the Great Barrier Reef. *PLOS ONE*, *8*(9), e75663. https://doi.org/10.1371/journal.pone.0075663

Mariotti, A., Croke, J. C., Bartley, R., Kelley, S. E., Ward, J., Fülöp, R.-H., Rood, A. H., Rood, D. H., Codilean, A. T., Wilcken, K. M., & Fifield, K. (2021). Pre-development denudation rates for the Great Barrier Reef catchments derived using ^{10}Be. *Marine Pollution Bulletin*, *172*. https://doi.org/10.1016/j.marpolbul.2021.112731

McCloskey, G. L., Baheerathan, R., Dougall, C., Ellis, R. J., Bennett, F. R., Waters, D. K., Darr, S., Fentie, B., Hateley, L. R., & Askildsen, M. (2021). Modelled estimates of fine sediment and particulate nutrients delivered from the Great Barrier Reef catchments. *Marine Pollution Bulletin*, *165*, 112163. https://doi.org/10.1016/j.marpolbul.2021.112163

McCulloch, M. T., Pailles, C., Moody, P. W., & Martin, C. E. (2003). Tracing the source of sediment and phosphorus into the Great Barrier Reef lagoon. *Earth and Planetary Science Letters*, *210*(1–2), 249–258. https://doi.org/10.1016/S0012-821X(03)00145-6

McKergow, L. A., Prosser, I. P., Hughes, A. O., & Brodie, J. E. (2005a). Regional scale nutrient modelling: exports to the Great Barrier Reef World Heritage Area. *Marine Pollution Bulletin*, *51*(1–4), 186–199. https://doi.org/10.1016/j.marpolbul.2004.11.030

McKergow, L. A., Prosser, I. P., Hughes, A. O., & Brodie, J. E. (2005b). Sources of sediment to the Great Barrier Reef World Heritage Area. *Marine Pollution Bulletin*, *51*(1–4), 200–211. https://doi.org/10.1016/j.marpolbul.2004.11.029

Mitchell, A., Reghenzani, J. R., Faithful, J. W., Furnas, M. J., & Brodie, J. E. (2009). Relationships between land use and nutrient concentrations in streams draining a “wet-tropics” catchment in northern Australia. *Marine and Freshwater Research*, *60*(11), 1097–1108. https://doi.org/10.1071/MF08330

Mitchell, A. W., & Furnas, M. J. (2001). River loggers - a new tool to monitor riverine suspended particle fluxes. *Water Science and Technology*, *43*(9), 115–120. https://doi.org/10.2166/wst.2001.0520

Mitchell, C., Brodie, J. E., & White, I. (2005). Sediments, nutrients and pesticide residues in event flow conditions in streams of the Mackay Whitsunday Region, Australia. *Marine Pollution Bulletin*, *51*(1–4), 23–36. https://doi.org/10.1016/j.marpolbul.2004.10.036

National Land and Water Resources Audit (NLWRA) (2001). Australian Agriculture Assessment 2001, vol. 1. Appendix I. River Basin Budgets. In A. C. Turner (Ed.), *National Land and Water Resources Audit, 2001*. *Commonwealth of Australia*. https://catalogue.nla.gov.au/catalog/1588158

Neil, D. T., Orpin, A. R., Ridd, P. V, & Yu, B. (2002). Sediment yield and impacts from river catchments to the Great Barrier Reef lagoon. *Marine and Freshwater Research*, *53*(4), 733–752. https://doi.org/10.1071/MF00151

Neil, D. T., & Yu, B. (1996). Fluvial sediment yield to the Great Barrier Reef lagoon: Spatial patterns and the effect of land use. In H. M. Hunter, A. G. Eyles, & G. E. Rayment (Eds.), *Downstream effects of land use* (pp. 281–286). *Department of Natural Resources*. https://www.vgls.vic.gov.au/client/en_AU/vgls/search/detailnonmodal/ent:$002f$002fSD_ILS$002f0$002fSD_ILS:65774/ada?qu=Land+use+--+Environmental+aspects.&d=ent%3A%2F%2FSD_ILS%2F0%2FSD_ILS%3A65774~ILS~276&ic=true&ps=300&h=8

Nichols, K. K., Bierman, P. R., & Rood, D. H. (2014). ^{10}Be constrains the sediment sources and sediment yields to the Great Barrier Reef from the tropical Barron River catchment, Queensland, Australia. *Geomorphology*, *224*, 102–110. https://doi.org/10.1016/j.geomorph.2014.07.019

Olley, J. M., Brooks, A. P., Spencer, J. R., Pietsch, T. J., & Borombovits, D. (2013). Subsoil erosion dominates the supply of fine sediment to rivers draining into Princess Charlotte Bay, Australia. *Journal of Environmental Radioactivity*, *124*, 121–129. https://doi.org/10.1016/j.jenvrad.2013.04.010

Orpin, A. R., & Ridd, P. V. (2012). Exposure of inshore corals to suspended sediments due to wave-resuspension and river plumes in the central Great Barrier Reef: A reappraisal. *Continental Shelf Research*, *47*(15), 55–67. https://doi.org/10.1016/j.csr.2012.06.013

Packett, R. (2020). Riparian erosion from cattle traffic may contribute up to 50% of the modelled streambank sediment supply in a large Great Barrier Reef river basin. *Marine Pollution Bulletin*, *158*, 111388. https://doi.org/10.1016/j.marpolbul.2020.111388

Packett, R., Dougall, C., Rohde, K. W., & Noble, R. M. (2009). Agricultural lands are hot-spots for annual runoff polluting the southern Great Barrier Reef lagoon. *Marine Pollution Bulletin*, *58*(7), 976–986. https://doi.org/10.1016/j.marpolbul.2009.02.017

Pailles, C., McConchie, D. M., Arakel, A. V, & Saenger, P. (1993). The distribution of phosphate in sediments of the Johnstone Rivers catchment-estuary system, North Queensland, Australia. *Sedimentary Geology*, *85*(1–4), 253–269. https://doi.org/10.1016/0037-0738(93)90087-L

Pailles, C., & Moody, P. W. (1992). Phosphorus sorption-desorption by some sediments of the Johnstone Rivers catchment, northern Queensland. *Marine and Freshwater Research*, *43*(6), 1535-1545. https://doi.org/10.1071/MF9921535

Pietsch, T. J., Brooks, A. P., Spencer, J., Olley, J. M., & Borombovits, D. (2015). Age, distribution, and significance within a sediment budget, of in-channel depositional surfaces in the Normanby River, Queensland, Australia. *Geomorphology*, *239*, 17–40. https://doi.org/10.1016/j.geomorph.2015.01.038

Prosser, I. P. (2018). Improving how gully erosion and river sediment transport processes are represented in Queensland catchment models. *Department of Environment and Science*.

Rafiei, V., Ghahramani, A., An-Vo, D.-A., & Mushtaq, S. (2020). Modelling hydrological processes and identifying soil erosion sources in a tropical catchment of the Great Barrier Reef using SWAT. *Water*, *12*(8), 2179. https://doi.org/10.3390/w12082179

Roberts, M. E., & Ellis, R. J. (2019). Effects of temporal variation in sediment reduction following improved land management practices on end-of-system delivery: A modelling investigation of a grazed catchment in Queensland, Australia. *WIT Transactions on Ecology and the Environment*, *234*(2019), 9–20. https://doi.org/10.2495/RBM190021

Robson, B. J., & Dourdet, V. (2015). Prediction of sediment, particulate nutrient and dissolved nutrient concentrations in a dry tropical river to provide input to a mechanistic coastal water quality model. *Environmental Modelling & Software*, *63*, 97–108. https://doi.org/10.1016/j.envsoft.2014.08.009

Saha, N., Rodriguez-Ramirez, A., Nguyen, A. D., Clark, T. R., Zhao, J., & Webb, G. E. (2018). Seasonal to decadal scale influence of environmental drivers on Ba/Ca and Y/Ca in coral aragonite from the southern Great Barrier Reef. *Science of The Total Environment*, *639*, 1099–1109. https://doi.org/10.1016/j.scitotenv.2018.05.156

Saint-Amand, A., Grech, A., Choukroun, S., & Hanert, E. (2022). Quantifying the environmental impact of a major coal mine project on the adjacent Great Barrier Reef ecosystems. *Marine Pollution Bulletin*, *179*, 113656. https://doi.org/10.1016/j.marpolbul.2022.113656

Sherman, B. S., & Read, A. M. (2008). Uncertainty in Great Barrier Reef catchment soil nutrient data - Implications for land use management. In J. B. Sanchez-Marre, J. Comas, A. Rizzoli, & G. Guariso (Eds.), *Proc. iEMSs 4th Biennial Meeting - Int. Congress on Environmental Modelling and Software: Integrating Sciences and Information Technology for Environmental Assessment and Decision Making, iEMSs 2008* (Vol. 1, pp. 566–573). *International Congress on Environmental Modelling and Software*.

Smith, J., Douglas, G. B., Radke, L. C., Palmer, M., & Brooke, B. P. (2008). Fitzroy River Basin, Queensland, Australia. III. Identification of sediment sources in the coastal zone. *Environmental Chemistry*, *5*(3), 231–242. https://doi.org/10.1071/EN07094

Steven, A. D. L., Baird, M. E., Brinkman, R., Car, N. J., Cox, S. J., Herzfeld, M., Hodge, J., Jones, E. M., King, E., Margvelashvili, N., Robillot, C., Robson, B. J., Schroeder, T., Skerratt, J. H., Tickell, S., Tuteja, N. K., Wild-Allen, K., & Yu, J. (2019). eReefs: An operational information system for managing the Great Barrier Reef. *Journal of Operational Oceanography*, *12*(sup2), S12–S28. https://doi.org/10.1080/1755876X.2019.1650589

Tibby, J., Barr, C., Marshall, J. C., Richards, J., Perna, C. N., Fluin, J., & Cadd, H. R. (2019). Assessing the relative impacts of land-use change and river regulation on Burdekin River (Australia) floodplain wetlands. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *29*(10), 1712–1725. https://doi.org/10.1002/aqc.3151

Tims, S. G., Everett, S. E., Fifield, L. K., Hancock, G. J., & Bartley, R. (2010). Plutonium as a tracer of soil and sediment movement in the Herbert River, Australia. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *268*(7–8), 1150–1154. https://doi.org/10.1016/j.nimb.2009.10.121

Turner, R., Huggins, R. L., Wallace, R. M., Smith, R., Vardy, S., & Warne, M. S. J. (2013). Total suspended solids, nutrient and pesticide loads (2010-2011) for rivers that discharge to the Great Barrier Reef Great Barrier Reef Catchment Loads Monitoring 2010-2011. *Department of Science, Information*

Technology, Innovation and the Arts. https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0035/45989/2014-2015-gbr-catchment-loads-technical-report.pdf

Turner, R. D. R., Huggins, R. L., Wallace, R. M., Smith, R. A., Vardy, S., Warne, M. S. J., & Australian Government. (2012). Sediment, Nutrient and Pesticide Loads: Great Barrier Reef Catchment Loads Monitoring 2009-2010. *Department of Science, Information Technology, Innovation and the Arts*. https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0027/45981/2009-2010-gbr-catchment-loads-report.pdf

Wallace, J. F., Karim, F., & Wilkinson, S. N. (2012). Assessing the potential underestimation of sediment and nutrient loads to the Great Barrier Reef lagoon during floods. *Marine Pollution Bulletin*, *65*(4–9), 194–202. https://doi.org/10.1016/j.marpolbul.2011.10.019

Wallace, J. F., Stewart, L. K., Hawdon, A. A., & Keen, R. J. (2008). The role of coastal floodplains in generating sediment and nutrient fluxes to the Great Barrier Reef lagoon in Australia. *Ecohydrology & Hydrobiology*, *8*(2–4), 183–194. https://doi.org/10.2478/v10104-009-0014-z

Wallace, J. F., Stewart, L. K., Hawdon, A. A., Keen, R. J., Karim, F., & Kemei, J. (2009). Flood water quality and marine sediment and nutrient loads from the Tully and Murray catchments in north Queensland, Australia. *Marine and Freshwater Research*, *60*(11), 1123. https://doi.org/10.1071/MF08356

Wallace, R. M., Huggins, R. L., King, O. C., Gardiner, R., Thomson, B., Orr, D. N., Ferguson, B., Taylor, C., Severino, Z., Smith, R. A., Warne, M. S. J., Turner, R. D. R., & Mann, R. M. (2016). Total suspended solids, nutrient and pesticide loads (2014–2015) for rivers that discharge to the Great Barrier Reef – Great Barrier Reef Catchment Loads Monitoring Program. *Department of Science, Information Technology and Innovation*. https://pureportal.coventry.ac.uk/files/13233077/GBR_Loads_Report_2014_2015.pdf

Wallace, R. M., Huggins, R. L., Smith, R., Turner, R., Garzon-Garcia, A., & Warne, M. S. J. (2015). Total suspended solids, nutrient and pesticide loads (2012-2013) for rivers that discharge to the Great Barrier Reef - Great Barrier Reef Catchment Loads Monitoring Program. *Department of Science, Information Technology, Innovation and the Arts*.

Wallace, R. M., Huggins, R. L., Smith, R., Turner, R., Vardy, S., & Warne, M. S. J. (2014). Total suspended solids, nutrient and pesticide loads (2011-2012) for rivers that discharge to the Great Barrier Reef - Great Barrier Reef Catchment Loads Monitoring Program. *Department of Science, Information Technology, Innovation and the Arts*. https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0029/45983/2011-2012-gbr-catchment-loads-report.pdf

Wang, Y.-G., Kuhnert, P. M., & Henderson, B. L. (2011). Load estimation with uncertainties from opportunistic sampling data – A semiparametric approach. *Journal of Hydrology*, *396*(1–2), 148–157. https://doi.org/10.1016/j.jhydrol.2010.11.003

Wang, Y.-G., Wang, S. S. J., & Dunlop, J. (2015). Statistical modelling and power analysis for detecting trends in total suspended sediment loads. *Journal of Hydrology*, *520*, 439–447. https://doi.org/10.1016/j.jhydrol.2014.10.062

Waterhouse, J., Brodie, J. E., Lewis, S. E., & Audas, D.-M. (2016). Land-sea connectivity, ecohydrology and holistic management of the Great Barrier Reef and its catchments: time for a change. *Ecohydrology & Hydrobiology*, *16*(1), 45–57. https://doi.org/10.1016/j.ecohyd.2015.08.005

Webster, I. T., & Ford, P. W. (2010). Delivery, deposition and redistribution of fine sediments within macrotidal Fitzroy Estuary/Keppel Bay: Southern Great Barrier Reef, Australia. *Continental Shelf Research*, *30*(7), 793–805. https://doi.org/10.1016/j.csr.2010.01.017

Wilkinson, S. N., Dougall, C., Kinsey-Henderson, A. E., Searle, R. D., Ellis, R. J., & Bartley, R. (2014). Development of a time-stepping sediment budget model for assessing land use impacts in large river basins. *Science of The Total Environment*, *468–469*, 1210–1224. https://doi.org/10.1016/j.scitotenv.2013.07.049

Wilkinson, S. N., Hancock, G. J., Bartley, R., Hawdon, A. A., & Keen, R. J. (2013). Using sediment tracing to assess processes and spatial patterns of erosion in grazed rangelands, Burdekin River basin, Australia. *Agriculture, Ecosystems & Environment*, *180*, 90–102. https://doi.org/10.1016/j.agee.2012.02.002

Wilkinson, S. N., Olley, J. M., Furuichi, T., Burton, J. M., & Kinsey-Henderson, A. E. (2015). Sediment source tracing with stratified sampling and weightings based on spatial gradients in soil erosion. *Journal of Soils and Sediments*, *15*(10), 2038–2051. https://doi.org/10.1007/s11368-015-1134-2

Wolanski, E. C., & Hopper, C. (2022). Dams and climate change accelerate channel avulsion and coastal erosion and threaten Ramsar-listed wetlands in the largest Great Barrier Reef watershed. *Ecohydrology & Hydrobiology*, *22*(2), 197–212. https://doi.org/10.1016/j.ecohyd.2022.01.001

Yu, B., Joo, M., & Carroll, C. (2013). Land use and water quality trends of the Fitzroy River, Australia. In B. Arheimer, A. Collins, V. Krysanova, E. Lakshmanan, M. Meybeck, & M. Stone (Eds.), *IAHS-AISH Proceedings and Reports* (Vol. 361, pp. 313–320).

Supporting References

Bainbridge, Z. T., Lewis, S. E., Bartley, R., Fabricius, K. E., Collier, C. J., Waterhouse, J., Garzon-Garcia, A., Robson, B. J., Burton, J. M., Wenger, A. S., & Brodie, J. E. (2018). Fine sediment and particulate organic matter: A review and case study on ridge-to-reef transport, transformations, fates, and impacts on marine ecosystems. *Marine Pollution Bulletin*, *135*, 1205–1220. https://doi.org/10.1016/j.marpolbul.2018.08.002

Waterhouse, J., Brodie, J. E., Lewis, S. E., & Mitchell, A. (2012). Quantifying the sources of pollutants in the Great Barrier Reef catchments and the relative risk to reef ecosystems. *Marine Pollution Bulletin*, *65*(4–9), 394–406. https://doi.org/10.1016/j.marpolbul.2011.09.031

Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 3.3

Theme 3: Sediments and particulate nutrients – catchment to reef

Question 3.3 How much anthropogenic sediment and particulate nutrients are exported from Great Barrier Reef catchments (including the spatial and temporal variation in export), what are the most important characteristics of anthropogenic sediments and particulate nutrients, and what are the primary sources?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Ian Prosser	University of Canberra	Catchment sediment and nutrients	Lead author	All sections
2. Scott Wilkinson	CSIRO	Catchment sediment and nutrients	Contributor	Background, Key Findings