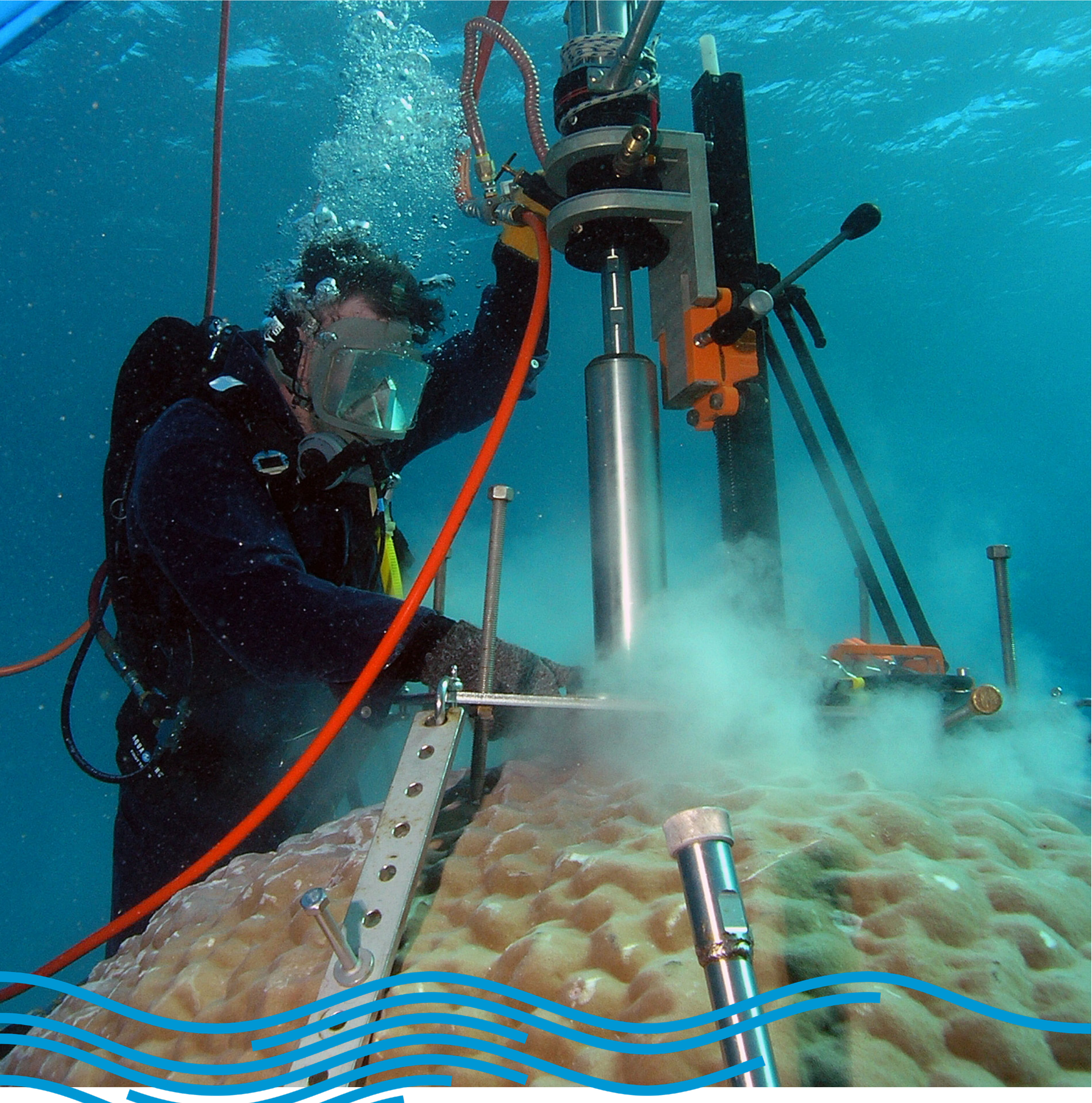

2022 Scientific Consensus Statement

Question 2.3 What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef?

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Cover image credit: Eric Matson.

Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

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

What is the Scientific Consensus Statement?

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

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

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

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

Method used to address the 2022 SCS Questions

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

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

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

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

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

Two methods were developed for the 2022 SCS:

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

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

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

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

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

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

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

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

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

Guidance for using the synthesis of evidence

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

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

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

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

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

Peer Review and Quality Assurance

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

Contents

Acknowledgements

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Executive Summary

Question

Question 2.3 What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef?

Background

It has long been perceived that the ecosystems of the Great Barrier Reef (GBR) are threatened by increased loads of suspended sediment, nutrients and pesticides due to land-use changes following the arrival of Europeans. Hence it is critical to synthesise the available evidence that documents the key land-use changes that have likely produced changes in riverine exports as well as the proxy-based evidence (i.e., environmental indicators that have the ability to quantify changes in terrestrial runoff) and modelling that quantifies the changes in river discharge and associated loads over this period. The catchment and marine proxy records also provide insights on the detection footprint that changes in loads have had at both spatial and temporal scales and serve as key background for several questions in the 2022 Scientific Consensus Statement (SCS).

This question reviews the available monitoring, proxy-based and modelling evidence for changes in land-based runoff from the pre-development estimates. Here land-based runoff is defined as freshwater, suspended sediments, nutrients and pesticides and includes runoff from both point and diffuse sources. The term "pre-development" is defined as the period prior to catchment modification following the arrival of Europeans (c. 1850). To address this question, the synthesis has been structured into three parts to provide: 1) background information about catchment modification since the arrival of Europeans (i.e., covers the definition of pre-development and post-development) to highlight the key land uses in the GBR catchment area and how they have changed over time; 2) a description of the methods available to quantify the increases in terrestrial runoff including coral cores (luminescent lines and geochemistry), sediment cores, water quality monitoring of land use contributions and modelling, and; 3) a summary of the key findings from the application of these methods.

Methods

- A formal Rapid Review approach was used for the 2022 SCS synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[5]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.
- Search locations included Web of Science, Scopus and Google Scholar.
- Main source of evidence was exclusively from the GBR catchments and lagoon and included only published peer-reviewed studies.
- A total of 1,542 potential studies were identified from the initial search results, of which 193 studies were shortlisted for secondary screening. A further 28 studies were identified manually through expert contact and personal collection. Following the secondary screening, a total of 128 studies were eligible for inclusion in the synthesis of evidence. All of these studies were obtainable and reviewed.

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.

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

- Only GBR derived studies were included.
- Studies were retrieved from two academic databases and Google Scholar.
- Only studies published after 1990 were included.
- Only peer-reviewed and published studies were included.
- Loads covering a limited time period (<20 years); time series for a broader area (i.e., whole of Queensland) or a localised area (i.e., smaller than a basin scale) were excluded.
- Studies that did not provide quantification of changes were excluded (i.e., no numbers provided for the pre-/post-European arrival or clearing provided.
- Review papers were excluded (i.e., not the primary source of information).
- GBR studies with no temporal data to apply the potential proxy (spatial analysis only) were excluded.
- GBR studies that are more relevant to longer term geological processes (>8,000 years) when sea level was vastly different to modern times were excluded.

Key Findings

Summary of evidence to 2022

- It is well accepted that loads of sediment, nutrients and pesticides have increased from most basins of the GBR catchment since the arrival of Europeans. The evidence for the increases have been gathered from water quality monitoring studies and proxy records, and the conclusions are supported by various modelling exercises.
- Time series of land use data for the GBR catchment area from 1860 to 2019 including human resident populations, livestock (cattle and sheep numbers), and agriculture area (total cropping, sugarcane, banana, cotton) highlight the varying land use pressures for each basin and show when major modifications in catchment land use took place. These records can be used in association with other catchment records (e.g., rainfall, streamflow etc.) to anticipate when major changes in sediment, nutrient and pesticides loads would likely have occurred and link with catchment and marine proxy records.
- Freshwater discharge to the GBR lagoon has increased considerably in both frequency of large events and the volume of such events since the 1850s and again since the 1950s against a long-term background extending over the past ~400 years. This increase is correlated with changes in the frequency and intensity of El Niño-Southern Oscillation (ENSO) events and the behaviour of the Indo-Australian monsoon across northern Australia. Catchment hardening due to the introduction of livestock in the catchment also likely contributes to increased runoff. However, the relative contribution of climatic factors (i.e., ENSO, Pacific Decadal Oscillation, Indo-Australian monsoon) and land-use changes (i.e., catchment hardening) to the increased discharge to the GBR has yet to be determined.
- The latest Source Catchments modelling suggests that sediment loads have more than tripled for most basins within the Burdekin, Mackay Whitsunday, Fitzroy, and Burnett Mary Natural Resource Management (NRM) regions (exceptions include the Black, Proserpine, Shoalwater, and Waterpark Basins)[6]. The basins of the Cape York NRM region have modelled load increases of 1.3-fold or less except for the Normanby Basin where projected loads have increased by 5-fold. These increases are supported/validated by multiple lines of independent evidence including a number of catchment proxy studies, land use-focused water quality monitoring data and coral core proxy geochemistry data.
- The latest Source Catchments modelling suggests that nearly half of the total dissolved inorganic nitrogen (DIN) load exported from the GBR catchments is exported from the Wet Tropics NRM region, and half of the total DIN load exported to the GBR lagoon is derived from sugarcane cropping areas. In general, the basins with intensive cropping have seen DIN loads increase by

[6] This includes basins that host large dams where the modelling suggests that sediment loads have increased since European arrival even following dam construction.

150-300%. Evidence of these increases is supported by land use-focused water quality monitoring data.

- Pesticides were absent prior to the arrival of Europeans and so loads/concentrations are entirely anthropogenic. Pesticide loads exported to the GBR lagoon have less ecological relevance than the concentrations of the residues in the water column of streams and in the GBR lagoon. Concentrations of some pesticides occasionally exceed proposed ecological protection guidelines for certain streams in the GBR catchments and also in some flood plumes. Monitoring programs from the inshore GBR lagoon have also shown an increasing trend in concentrations of some herbicides and an insecticide (imidacloprid) over the past ~15 years.
- The 'detection footprint' of changes in pollutant exposure since European arrival in the GBR lagoon is most pronounced in the estuarine and nearshore environments just offshore from river mouths but can be seen as far out as >100 km alongshore from the river mouth of influence. Further offshore in the middle and outer shelfs, the proxies that measure such changes in freshwater, sediment and nutrient discharge show variable results.
- New coral proxies including rare earth elements and nitrogen isotopes show great promise to help reconstruct changes in sediment and nutrient exposure, respectively in the GBR lagoon.

Recent findings 2016-2022

- The documentation of land use time series data to identify periods of major land-use change for each basin of the GBR catchment provides a foundational dataset to better link catchment conditions to marine proxies.
- The examination of stream/river gauge records coupled with multiple lines of evidence modelling approaches has improved quantification of the increased stream runoff from catchments cleared of Brigalow at the subcatchment scale, independent of climate variability.
- Additional analyses on the dataset from the paired Brigalow Catchment Study have quantified expected changes in freshwater, sediment and nutrient runoff when Brigalow vegetation is cleared.
- The potential for cattle tracks/ramps around creek lines to enhance erosion has been demonstrated in the Fitzroy Basin.
- There has also been spatial and temporal trend analysis of water quality data from both within the GBR catchments and lagoon.
- Studies of proxy evidence within the GBR catchments include a synthesis of new and existing Be-10 data from several basins to reveal key sediment erosion hotspots.
- Sediment cores from wetlands show changes in sediment accumulation and composition since European arrival or following major land-use changes.
- The timing and accumulation rates of fluvial bench and floodplain deposits have been examined which provide a long-term perspective of catchment erosion processes and changes throughout the Holocene.
- Numerous studies have examined the geochemistry of coral cores which offers improved understanding and interpretation of the long coral proxy records as well as the development of new proxies to assess changes in freshwater, sediment and nutrient exposure.
- Other coral reef proxy records have been developed using the geochemistry of coral microbialites to reconstruct past sediment fluxes and the nitrogen isotope composition of *Halimeda* bioherms to examine changes in long-term nutrient cycling.
- The accumulation rates and composition of sediment cores from inshore and midshelf coral reefs have been reported.
- The latest model of catchment pollutant loads provides a current baseline mean load as well as a pre-development load (i.e., pre-European arrival).
- Outputs from the eReefs model quantify the changes in exposure and water quality as a result of increased loads in the GBR lagoon. Model 'loading maps' have also been produced to highlight the increased spatial area of exposure as a result of increased loads.

Significance for policy, practice, and research

The evidence continues to show that freshwater runoff and the loads of sediments, nutrients and pesticides have increased greatly for most river basins over the past ~170 years. This finding has not changed over the past three decades. It is widely accepted that the loads of suspended sediment, dissolved and particulate nutrients (nitrogen and phosphorus) and pesticides have increased for most river basins of the GBR catchment area since the arrival of Europeans c.1850. This has occurred as a result of catchment modification for livestock grazing, cropping, urban development and mining as well as in response to shifts in climate variability that has led to more frequent and larger volume river discharge events. Evidence of such increases in catchment loads are preserved in a multitude of fluvial proxy records, coral core proxies, land use targeted water quality monitoring data and through catchment modelling exercises. The detection footprint of these increased loads in the GBR is most pronounced in estuaries and just offshore from river mouths while the proxies further offshore display more variable results, likely a reflection of the spatial variability in the exposure of river flood plumes.

Key uncertainties and/or limitations

- There is little uncertainty or dispute that the loads of sediments, nutrients and pesticides exported to the GBR lagoon have increased in most basins since the arrival of Europeans particularly relative to the past 400 years of records. However, the comparison of discharge and associated loads over a longer baseline that reflects the modern GBR (i.e., the past ~7,000 years) is more uncertain.
- The sparseness of the proxy records across the GBR lagoon means that the spatial exposure of the increased loads is difficult to define, and the spatial distributions of impacts are thus challenging to directly assess. Investigation of these impacts has largely been restricted to modelling exercises.
- The modelling exercises show that the increased loadings are most strongly concentrated on the inner shelf of the GBR lagoon.
- There are limited catchment or marine proxies to help quantify changes in nutrient loadings to the GBR and understand their transformation in the GBR lagoon. The proxies that exist reveal conflicting results and these need to be better understood.
- Selected literature was used to highlight key concepts that may explain apparent conflicting findings or to visualise the extent of freshwater plumes or changes to terrestrial influence in the GBR lagoon. For example, the concept that due to various hydrodynamic and bioturbation processes on coral reefs it is not expected that increased sediment loads will translate to increased sediment accumulation rates on inshore GBR coral reefs. The modelling/visualisation of the plume extents and the differences in the exposure of sediments and nutrients in the pre-/post-European arrival periods provides an important spatial context on where the greatest impacts in the GBR lagoon would occur in comparison to where the proxy records have been collected.

Evidence appraisal

The relevance of the body of evidence used to answer the question was High. The relevance of each individual indicator was Moderate to High for overall relevance to the question, Moderate for spatial relevance, and High for temporal relevance. The overall body of evidence showed a Medium to High level of consistency in the findings, a high abundance of research outputs (quantity) and a diversity of methods applied to address the question. A high sample size of the available peer-reviewed evidence has been captured across multiple fields to address this question. The consistency of findings is much higher when only the catchment evidence base is considered.

The overall confidence in the body of evidence used to answer the primary question is considered Moderate to High. This is based on the rating of the overall consistency and relevance of the body of evidence used. There is broad agreement that loads of sediments, nutrients and pesticides have increased from most river basins due to catchment modifications following the arrival of Europeans. The area of most contention is the spatial footprint of these increased loads within the GBR lagoon.

1. Background

It has long been perceived that the ecosystems of the Great Barrier Reef (GBR) are threatened by increased loads of suspended sediment, nutrients and pesticides due to land-use changes following the arrival of Europeans. Hence it is critical to synthesise the available evidence that documents the key land-use changes that have likely produced changes in riverine exports as well as the proxy-based evidence (i.e., environmental indicators that have the ability to quantify changes in terrestrial runoff) and modelling that quantifies the changes in river discharge and associated loads over this period. The catchment and marine proxy records also provide insights on the detection footprint that changes in loads have had at both spatial and temporal scales and serve as key background for several questions in the 2022 Scientific Consensus Statement (SCS).

1.1 Question

Primary question	**Q2.3** What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef?

This question reviews the available monitoring, proxy-based and modelling evidence for changes in land-based runoff from the pre-development estimates. Here land-based runoff is defined as freshwater, suspended sediments, nutrients and pesticides from both point and diffuse sources. The term “pre-development” is defined as the period prior to catchment modification following the arrival of Europeans (c. 1850). To address this question, the synthesis has been structured into three parts to provide: 1) background information about catchment modification since the arrival of Europeans (i.e., covers the definition of pre-development and post-development) to highlight the key land uses in the GBR catchment area and how they have changed over time; 2) a description of the methods available to quantify the increases in terrestrial runoff including coral cores (luminescent lines and geochemistry), sediment cores, water quality monitoring of land use contributions and modelling, and; 3) a summary of the key findings from the application of these methods.

1.2 Conceptual diagram

The conceptual diagram (Figure 1) highlights the key land uses that can change land-based runoff to the GBR (i.e., Part 1: define the level of modification to the catchments). Part 2 defines what is meant by land-based runoff which includes freshwater, suspended sediment, particulate and dissolved nutrients and pesticides. Part 3 reviews the availability of catchment and marine methods (observations, proxies, models) that can quantify the change various aspects of the land-based runoff and presents the key records.

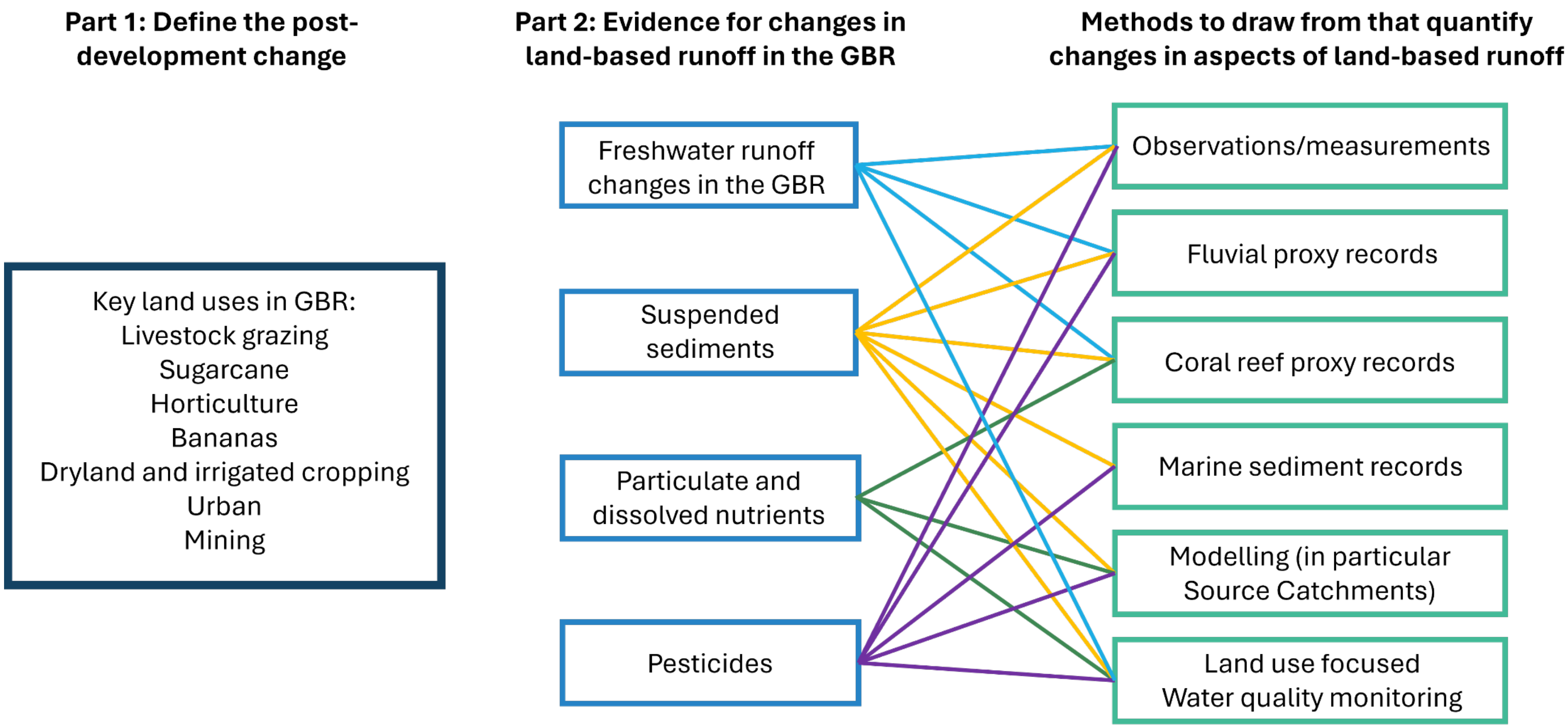


Figure 1. Conceptual diagram of the key drivers for changing loads of sediment, nutrients and pesticides (land use) and the proxies that can be applied across the catchment and marine environment to help quantify the changes in loads and their footprint in the GBR lagoon.

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 broad nature of this question links it to many other questions within the SCS but the primary question linkages are listed below.

Links to other related questions	**Q1.2/1.3/2.1** What is the extent and condition of Great Barrier Reef ecosystems and what are the primary threats to their health? **Q1.4** How are the Great Barrier Reef's key ecosystem processes connected from the catchment to the reef and what are the primary factors that influence these connections? **Q3.1** What are the spatial and temporal distributions of sediments and associated indicators within the Great Barrier Reef? **Q3.2** What are the measured impacts of increased sediment and particulate nutrient loads on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef? **Q3.3** How much anthropogenic sediment and particulate nutrients are exported from Great Barrier Reef catchments (including the spatial and temporal variation in export), what are the most important characteristics of anthropogenic sediments and particulate nutrients, and what are the primary sources? **Q3.4** What are the primary biophysical drivers of anthropogenic sediment and particulate nutrient loss to the Great Barrier Reef and how have these drivers changed over time? **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 export), what are the most important characteristics of anthropogenic dissolved nutrients, and what are the primary sources? **Q4.5** What are the primary biophysical drivers of anthropogenic dissolved nutrient loss to the Great Barrier Reef and how have these drivers changed over time? **Q5.1** What is the spatial and temporal distribution of pesticides across Great Barrier Reef ecosystems, what evidence is there for pesticide risk and what are the (potential or observed) ecological impacts in these ecosystems? **Q5.2** What are the primary sources of the pesticides that have been found in Great Barrier Reef ecosystems and what are the key factors that influence pesticide delivery from source to ecosystems?

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

2.1 Primary question elements and description

The primary question is: ***What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef?***

S/PICO frameworks (Subject/Population, Exposure/Intervention, Comparator, Outcome) can be used to break down the different elements of a question and help to define and refine the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods[8] 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?

Table 1. Description of question elements for Question 2.3.

Question S/PICO elements	Question term or implied terms in question	Description
Subject/Population	The Great Barrier Reef Catchment Area	The Catchment area is referred as the 35 basins or the 6 Natural Resource Management (NRM) regions including Cape York, the Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary.
	Land-based runoff	Includes freshwater, suspended sediment and particulate and dissolved forms of nitrogen and phosphorus, and pesticides.
Intervention, exposure & qualifiers	Key land use (implied)	Key land uses include livestock grazing, sugarcane, horticulture, bananas, dryland irrigated, cropping, urban and mining. Livestock grazing includes cattle and sheep. Urban is linked to population numbers. The Evidence Summary will attempt to capture changes in these land uses since European arrival at the six NRM region scale.

[7] 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

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

Question S/PICO elements	Question term or implied terms in question	Description
	Spatial distribution (implied)	Restricted to the Great Barrier Reef (GBR) catchment. Land use data will cover count numbers of people (estimated residential population), cattle and sheep and total area of sugarcane, horticulture, bananas, dryland/irrigated cropping. Mining will cover some historical context.
Comparator	N/A	
Outcome & outcome qualifiers	Changes from pre-development.	Available data indicate annual changes in flows since 1860. Evidence of changes in delivery of freshwater discharge, suspended sediments and dissolved and particulate forms of nitrogen and phosphorus, and pesticides to the GBR. The synthesis will summarise changes to loads between pre-development and current time period at the six NRM region scale and cover available modelling, sediment core, coral core and existing water quality monitoring data.

Table 2. Definitions for terms used in Question 2.3.

Definitions	
Land-based runoff	Changes in freshwater discharge, suspended sediments and dissolved and particulate forms of nitrogen and phosphorus, and pesticides that are delivered from the GBR Catchment Area (defined below) to the Great Barrier Reef World Heritage Area (GBRWHA).
Pre-development	Before the arrival of Europeans to the GBR catchment area c. 1850.
The Great Barrier Reef Catchment Area	The 35 major drainage basins or the 6 Natural Resource Management (NRM) regions including Cape York, the Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary (see Figure 2). **Basin:** There are 35 basins that drain into the Great Barrier Reef. A basin can be made up one or more rivers (e.g., North and South Johnstone rivers belong to one basin, the Johnstone Basin). Basins are primarily used here when discussing the relative delivery of a pollutant to the marine system. **Catchment:** The natural drainage area upstream of a point that is generally on the coast. It generally refers to the 'hydrological' boundary and is the term used when referring to modelling in this document. There may be multiple catchments in a basin.

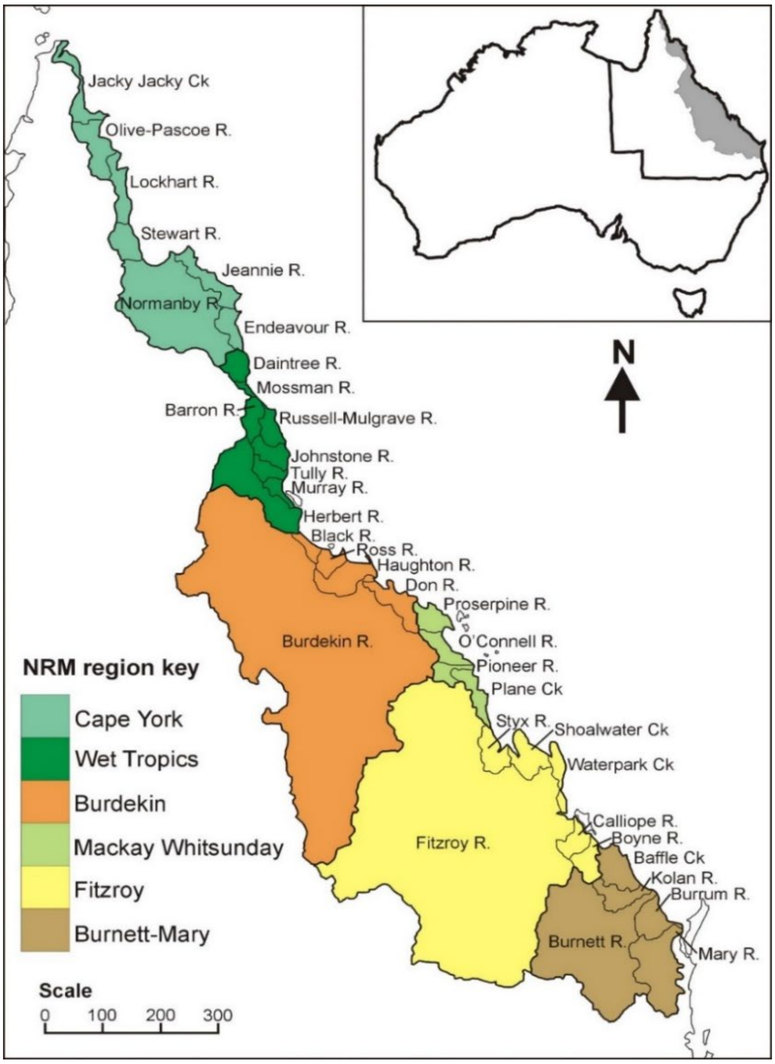


Figure 2. Map showing the Great Barrier Reef Catchment Area and its division into the six NRM regions and 35 basins.

2.2 Search and eligibility

a) Search locations

Searches were performed on:

- Web of Science
- Scopus
- Google Scholar

b) Search terms

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

Table 3. Search terms for S/PICO elements of Question 2.3.

Question element	Search terms
Subject/Population	Basin, catchment, region, loads, 'Great Barrier Reef', freshwater, discharge, sediment, 'total suspended solids', TSS, nitrogen, phosphorus, pesticides, herbicides, 'water quality'
Exposure or Intervention	Grazing, cattle, sheep, sugarcane, banana, horticulture, cotton, cropping, urban, mining

Question element	Search terms
Comparator (if relevant)	N/A
Outcome & qualifiers	coral core, sediment core, model, water quality, monitoring, time series

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 2.3.

Search strings
(Basin OR catchment OR region) AND loads AND 'Great Barrier Reef' AND (freshwater OR discharge OR sediment OR 'total suspended solids' OR TSS OR nitrogen OR phosphorus OR pesticides OR herbicides)
'Great Barrier Reef' AND (freshwater OR discharge OR sediment OR nitrogen OR phosphorus OR pesticides OR herbicides) AND ('coral core' OR 'sediment core' OR model OR 'water quality' OR monitoring)
'Great Barrier Reef' AND (Grazing OR cattle OR sheep OR sugarcane OR banana OR horticulture OR cotton OR cropping OR urban OR mining) AND 'time series'

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 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/ Population	Time series of freshwater discharge or sediment, nitrogen, phosphorus and pesticide/herbicide loads from either direct measurements, a model or a proxy at a basin NRM region level scale in the Great Barrier Reef catchment area or within the lagoon. Proxy may include water quality data comparing different land uses. Water quality data must contain data from a 'pristine or reference' location so that the impact of land-use change can be quantified.	1. Loads covering a limited time period (<20 years); time series for a broader area (i.e., whole of Queensland) or a localised area (i.e., smaller than a basin scale).
Exposure or Intervention	Time series of quantity or area of grazing or cattle or sheep or sugarcane or banana or horticulture or cotton or cropping or urban or mining at a basin NRM region level scale in the Great Barrier Reef catchment area.	2. Reporting of single numbers or time series for a broader area (i.e., whole of Queensland) or a localised area (i.e., smaller than a basin scale).
Comparator (if relevant)	N/A	N/A

Question element	Inclusion	Exclusion
Outcome	Amount of change in freshwater discharge and/or sediment, nitrogen, phosphorus and pesticide/herbicide loads since pre-development. Includes changes in the receiving environment.	Loads covering a limited time period (<20 years); time series for a broader area (i.e., whole of Queensland) or a localised area (i.e., smaller than a basin scale).
Language	English	Non-English studies
Study type	Peer-reviewed studies that present long term (>20 years) land use change time series in the basins or NRM region within the Great Barrier Reef catchment area. Peer-reviewed studies that present long term (20 individual years or 20 + years average intervals) loads of suspended sediments, nitrogen, phosphorus and pesticide/herbicides and freshwater discharge time series in the basins or NRM regions within the Great Barrier Reef catchment area. Peer-reviewed studies that quantify changes in freshwater discharge, suspended sediment, nitrogen, phosphorus before and after the arrival of Europeans (c. 1850).	Studies which have not been peer reviewed. 1. Loads covering a limited time period (<20 years); time series for a broader area (i.e., whole of Queensland) or a localised area (i.e., smaller than a basin scale). Spatial data that do not include a temporal component (i.e., pre-European estimation) – excludes GBR lagoon style studies. 2. Studies that do not quantify the changes over time. 3. No quantification given: no numbers provided for the pre-/post-European arrival or clearing provided. 4. Not a primary source of information: Review papers that present data from other primary sources. 5. GBR lagoon study with no temporal data to use the proxy (spatial analysis only). 6. GBR lagoon studies that are more relevant to longer term geological processes (>8,000 years) when sea level was vastly different to modern times.

3. Search Results

A total of 193 studies were identified through online searches for peer-reviewed and published literature. A further 28 studies were identified manually through literature submissions and from the personal collection of the authors, which represented 13% of the total evidence. From the online and manual searches, 128 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 (Google Scholar) and C) Manual searches.

Date (d/m/y)	Search strings	Sources	
A) Academic databases		Web of Science	Scopus
13/12/2022	*Search string 1: ((TI=(((Great Barrier Reef) AND (freshwater OR discharge or sediment or total suspended solids OR TSS OR nitrogen OR phosphorus OR pesticides OR herbicides) AND (coral core or sediment core or model or water quality or monitoring))))* *OR AB=(((Great Barrier Reef) AND (freshwater OR discharge or sediment or total suspended solids OR TSS OR nitrogen OR*	*574*	*198*

Date (d/m/y)	Search strings	Sources	
	phosphorus OR pesticides OR herbicides) AND (coral core or sediment core or model or water quality or monitoring)))) *OR KP=(((Great Barrier Reef) AND (freshwater OR discharge or sediment or total suspended solids OR TSS OR nitrogen OR phosphorus OR pesticides OR herbicides) AND (coral core or sediment core or model or water quality or monitoring)))*		
13/12/2022	*Search string 2: ((TI=(((basin OR catchment OR region) AND (loads OR runoff) AND (Great Barrier Reef) AND (freshwater OR discharge OR sediment OR total suspended solids OR TSS OR nitrogen OR phosphorus OR pesticides OR herbicides))))* *OR AB=(((basin OR catchment OR region) AND (loads OR runoff) AND (Great Barrier Reef) AND (freshwater OR discharge OR sediment OR total suspended solids OR TSS OR nitrogen OR phosphorus OR pesticides OR herbicides))))* *OR KP=(((basin OR catchment OR region) AND (loads OR runoff) AND (Great Barrier Reef) AND (freshwater OR discharge OR sediment OR total suspended solids OR TSS OR nitrogen OR phosphorus OR pesticides OR herbicides)))*	*204*	*196*
13/12/2022	*Search string 3: ((TI=(((Great Barrier Reef) AND (Grazing OR cattle OR sheep OR sugarcane OR banana OR horticulture OR cotton OR cropping OR urban OR mining) AND (time series))))* *OR AB=(((Great Barrier Reef) AND (Grazing OR cattle OR sheep OR sugarcane OR banana OR horticulture OR cotton OR cropping OR urban OR mining) AND (time series))))* *OR KP=(((Great Barrier Reef) AND (Grazing OR cattle OR sheep OR sugarcane OR banana OR horticulture OR cotton OR cropping OR urban OR mining) AND (time series)))*	*9*	
B) Search engine = Google Scholar			
16/12/2022	*Search string 1: ("Great Barrier Reef" AND 'freshwater OR discharge OR sediment OR nitrogen OR phosphorus OR pesticide OR herbicide' AND "coral core" OR "sediment core" OR model OR "water quality" monitoring)*	*161*	
16/12/2022	*Search string 2: "Great Barrier Reef" runoff change*	*20,700 (screened first 200)*	
	Total items online searches	***193 out of 1,542 (87 %)***	
C) Manual search			
Date	Source	Number of items added	
15/12/2022	*Author knowledge*	*25*	
18/2/2023	*Author knowledge*	*1*	
13/7/2023	*Reviewer feedback/submission*	*2*	
	Total items manual searches	***28 (13 %)***	

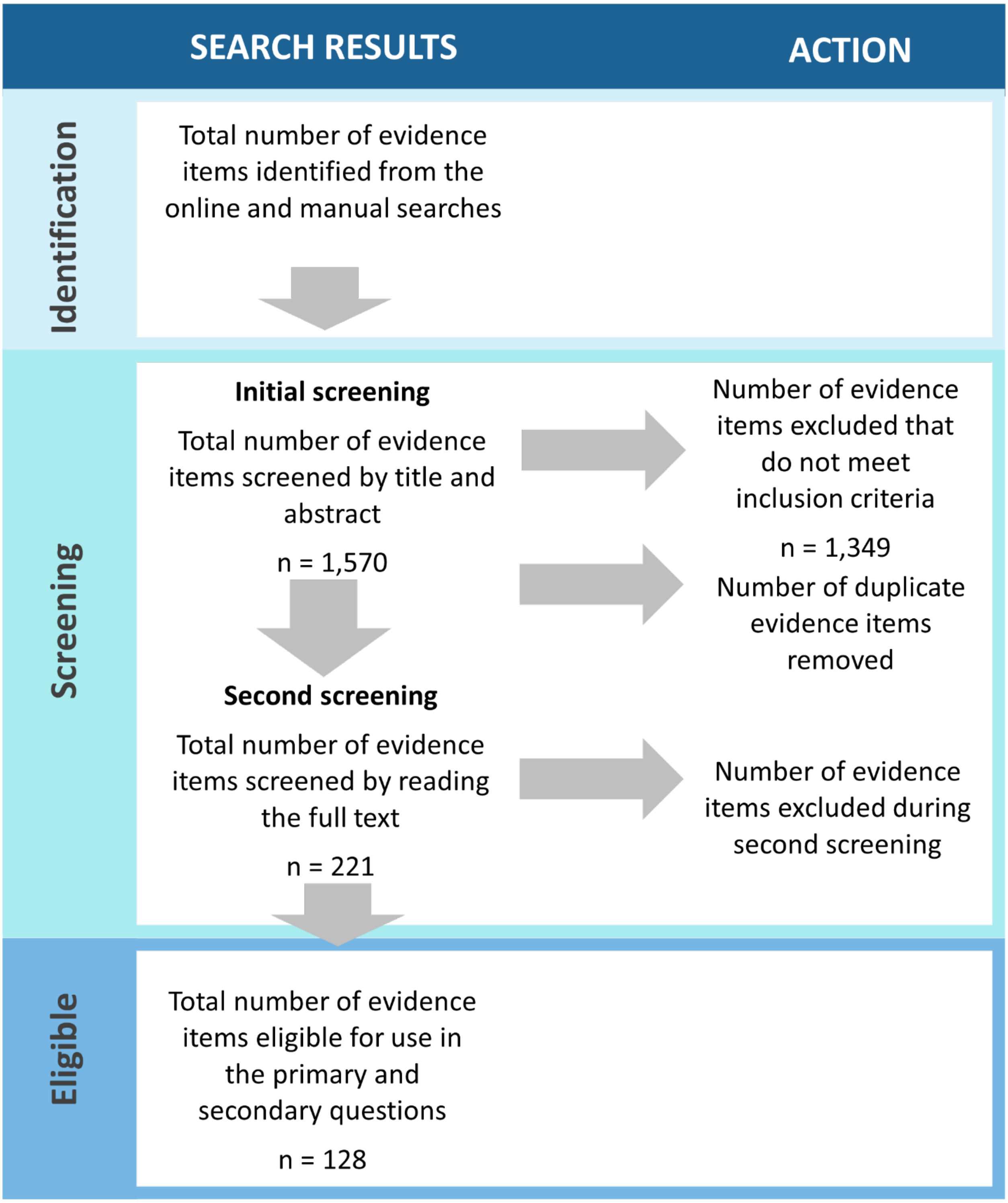


Figure 3. Flow chart of results of screening and assessing all search results for Question 2.3.

4. Key Findings

4.1 Narrative synthesis

4.1.0. Summary of study characteristics

A total of 128 eligible studies were found for this question. The characteristics of these studies are summarised in Table 7. The total numbers in the table reflect that some studies covered multiple parameters of interest. Only one study covered the time series of land uses for the basins of the GBR catchment area; this study produced time series of livestock grazing (cattle and sheep), total cropping area, sugarcane area, banana area, cotton area, other crops and resident human population numbers for each basin (except Cape York which is covered as an NRM region) from 1860 to 2019. A mining time series was presented for part of the Burdekin basin, but a reliable mining time series for the whole GBR catchment area was notably lacking. With this exception, the key land uses identified in the conceptual diagram (Section 1.2) have been captured in this synthesis.

A breakdown on the types/methods of the studies show that 12% were derived from observations (15 studies), 12% from fluvial (river/catchment) proxy records (15 studies), 33% from coral reef proxy records (coral cores, benthic forams, *Halimeda* bioherms) (42 studies), 20% from marine sediment cores (25 studies), 9% from modelling (12 studies) and 15% from land use focused monitoring efforts (19 studies). The studies included analysis of measurement and proxy data from the GBR catchment area (42 studies: 33%), the GBR marine lagoon (74 studies: 58%) and modelling of catchment loads (7 studies: 5%) and the extent or exposure of pollutants in the GBR lagoon (5 studies: 4%). Overall, each major parameter of interest has been well covered in the eligible studies with 37 studies examining changes in freshwater runoff, 84 studies investigating changes in sediment runoff, 36 studies focusing on changes in nutrient runoff and 18 studies on pesticides (Table 7; note some studies examined more than 1 parameter).

Of the 42 studies within the catchment, 9 (21%) focused on the whole or a large proportion of the GBR catchment area, 15 (36%) focused on the Fitzroy Basin, 9 (21%) were performed on the basins within the Wet Tropics NRM region, 6 (14%) focused on the Burdekin Basin and the 3 (7%) remaining studies examined either the Normanby Basin (2) or the basins of the Mackay Whitsunday NRM region (1). Of the 74 studies within the marine GBR lagoon setting, most studies (47 studies: 64%) were from the central GBR (Cairns to Mackay), followed by two or more areas (16 studies: 22%), the southern GBR (Mackay-south) with 10 (14%) studies and the northern GBR (Cairns-north) with only 1 study (1%). The northern GBR sites were included in 11 of the 16 studies that have a wider coverage across 2 or all 3 GBR areas. Most of these marine studies (66 of 74) were conducted exclusively within or contained inshore sites (within the 20 m isobath).

Table 7. Summary of the types of studies and the key parameters of focus.

Type of study	Freshwater	Sediments	Nutrients	Pesticides
Observations/measurements	7	2		5
Fluvial proxy records		14		1
Coral reef proxy records	25	24	13	
Marine sediment records		22		4
Modelling		9	9	2
Land use focused water quality monitoring	5	13	14	6
Total	**37**	**84**	**36**	**18**

The temporal coverage of the observational/measurement records only capture the years following European arrival. The land use compilation covers the period 1860 to 2019 while the water quality monitoring data within the GBR catchment area cover periods ranging from only ~1 season up to ~35 years. The freshwater runoff measurements range from 40 to ~100 years. In contrast, the fluvial proxy records that examine changes in freshwater or sediment runoff range from ~100 years to ~20,000 years before present. The observations/measurements of freshwater and pesticide extent range from 1 season (i.e., the large 2010/11 discharge year) to 14 years. The temporal coverage of the identified coral core records (coral reef proxy records) range from 8 to 428 years with most records covering the pre- and post-European arrival period. Some coral core records (n = 3) cover periods within the mid Holocene and hence capture broader climatic and oceanographic variability within the GBR. The two long-term studies on the composition of benthic foraminifera in sediment cores cover the past 1,000 to 1,500 years, while the nutrient proxy record using *Halimeda* bioherms captures the past 5,000 years. One coral reef proxy record of changes in terrigenous sediment exposure using coral microbialite records covers the period between 8,200 and 1,800 years before present. Most marine sediment core records which examine changes in accumulation rates and/or composition cover the past 1,000 years and, in total range from the past 230 years to ~8,000 years before present. The marine sediment records which examine the presence/absence of pesticide residues are mostly represented by relatively recently collected surface grab samples.

Differences in the number of studies found across the parameters and study types are likely reflected by the proportionate search effect where search efforts were particularly focused on covering the past 200 to 1,000 years (to cover the period before and after European arrrival). Hence, the number of papers covering pesticides which have only been present in GBR catchments since European arrival have received less attention. In addition, papers from observational/measurements and land use focused water quality monitoring contributions were restricted to only cover contributions that demonstated a clear change in the parameters under specific land uses, or to highlight the extent of terrestrial runoff in the GBR lagoon.

4.1.1 Summary of evidence to 2022

There has been a wealth of monitoring, proxy-based research and modelling from the GBR catchment area that has investigated long-term changes in sediment, nutrient and pesticide runoff and resultant variations in exposure of areas within the GBR lagoon to these changes (Figure 4). Overall, there remains broad agreement that the loads of sediment, nutrients and pesticides have increased from most basins of the GBR catchment area following land-use changes (i.e., urban, livestock, cropping and mining) after the arrival of Europeans (c. 1850). Indeed, extensive modification of catchment land use occurred in most NRM regions within the GBR catchment area following the arrival of Europeans with marked increases over the past 50 years in resident human population (2.37-fold increase over the 1965-1969 to 2015-2019 periods), cattle numbers (1.41-fold increase) and cropping areas (total cropping: 1.24-fold increase; sugarcane: 1.64-fold increase; banana: 16.3-fold increase; cotton: 7.99-fold increase) (Lewis et al., 2021). Considerable increases in the volume and frequency of large (90th percentile) flood events have also occurred over the ~170 years since 1850 (i.e., 90th percentile flood was 12.0 GL with a 1 in 14.3 year frequency in the 1648-1747 period compared to 21.9 GL with a 1 in 5.8 year frequency in the 1948-2011 period) (Lough et al., 2015). The latest catchment information from monitoring, proxy records and modelling suggests that sediment loads have increased more than 3-fold for the most intensively developed basins within the dry tropics while monitoring data and modelling outputs suggest that DIN loads have increased by 1.5 to 3.0-fold in the basins that host large areas of cropping (e.g., D'Olivo & McCulloch, 2022; Lewis et al., 2014; McCloskey et al., 2021a; 2021b). Pesticides were absent prior to the arrival of Europeans and so loads and/or concentrations emanating from the GBR catchment area are entirely anthropogenic. The 'detection footprint' of the increase in pollutant loads since European arrival in the GBR lagoon is most pronounced just offshore from river mouths. Marine modelling exercises highlight increased exposure of particular areas within the inshore GBR lagoon to pollutants as a result of increased catchment loads (Baird et al., 2021; Gruber et al., 2020; Moran et al., 2022; Waterhouse et al., 2017). However, the results derived from proxy records are more variable, in part reflecting the differences in the sensitivity with which they may preserve records of changes in pollutant exposure since European arrival. New coral core proxies including rare earth elements and nitrogen isotopes show great promise to help reconstruct spatial changes in sediment and nutrient exposure respectively in the GBR lagoon (e.g., Erler et al., 2020; Marion et al., 2021; Saha et al., 2019a; 2021; Wyndham et al., 2004), and offer opportunites for improved validation of marine modelling outputs.

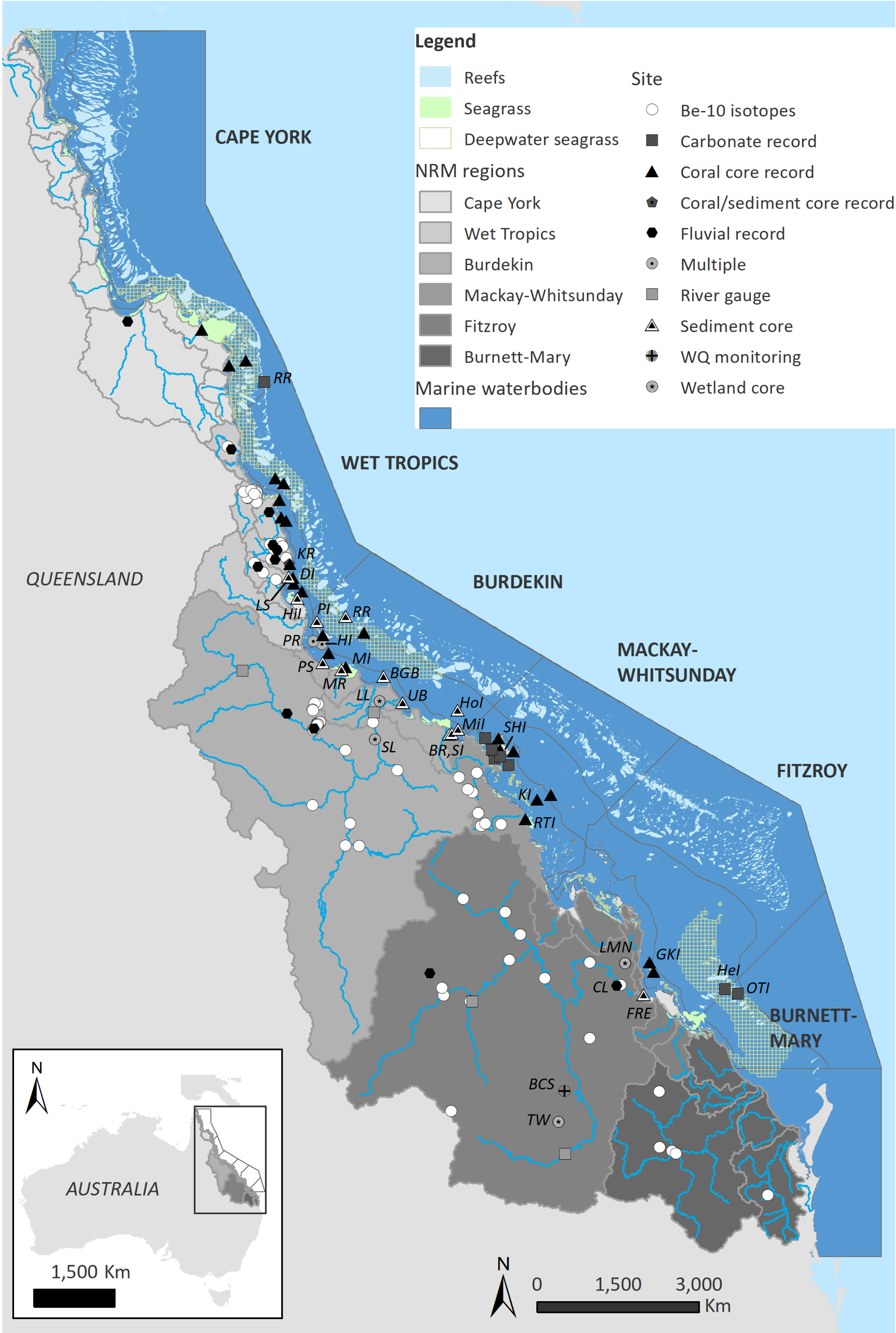


Figure 4. Map highlighting the key study locations within the Great Barrier Reef catchment area and lagoon (Refer to Table 8 for site abbreviations used in this figure).

Table 8. Abbreviations used for the sites shown in Figure 4.

Site name	Abbreviation	Site name	Abbreviation
Swan’s Lagoon	SL	Ribbon Reefs	RR
Labatt Lagoon	LL	Heron Island	HeI
Lake Mary North	LMN	One Tree Island	OTI
Tulka Wetland	TW	Hinchinbrook Island	HiI
Brigalow Catchment Study	BCS	Upstart Bay	UB
Crescent Lagoon	CL	Bowling Green Bay	BGB
Magnetic Island	MI	Fitzroy River estuary	FRE
Havannah Island	HI	Middle Reef	MR
Pandora Reef	PR	Paluma Shoals	PS
Great Palm Island	GPI	Rib Reef	RR
King Reef	KG	Lugger Shoal	LS
Great Keppel Island	GKI	Pelorus Island	PI
Cid Harbour Island	CHI	Bramston Reef	BR
Dunk Island	DI	Stone Island	SI
Round Top Island	RTI	Middle Island	MiI
Keswick Island	KI	Holbourne Island	HoI

Catchment modification since the arrival of Europeans

Lewis et al. (2021) compiled annual time series of land-use change across the river basins of the GBR catchment area including human resident population, livestock (cattle and sheep numbers), total cropping area, sugarcane area, cotton area, banana area, cotton area and other crops from 1860 to 2019. Several of these land uses have recorded their highest numbers/areas since the year 2000 including human resident population, cattle numbers and the areas of sugarcane, bananas and cotton (Figure 5). On a Natural Resource Management (NRM) region or basin scale, the data reveal finer-scale variability such as steep increases in cattle numbers and total cropping area in the Fitzroy, Burdekin and Burnett Mary NRM regions coinciding with the large-scale clearing of the Brigalow vegetation from the 1960s to 1980s and the decline in the sugar area in the Burnett Mary NRM region and in particular the Baffle and Burnett basins (Figure 6). Importantly, these annual time series data document land-use changes since the arrival of Europeans in the GBR catchment area (c. 1850) and can now be directly compared to the observational data and proxy records, allowing causal relationships between land-use change and changes in land-based runoff to be better assessed (Lewis et al., 2021).

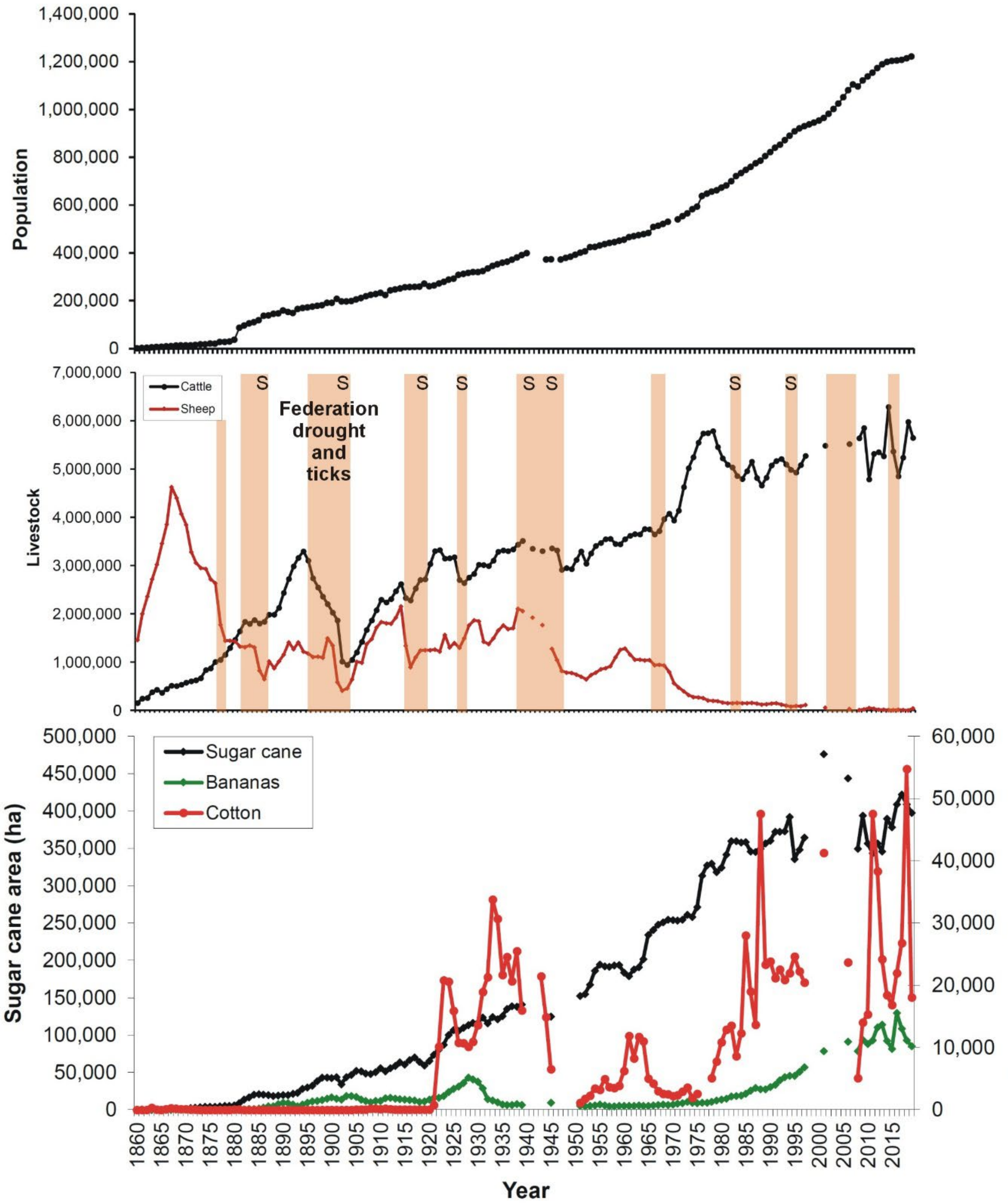


Figure 5. Land-use change for the Great Barrier Reef catchment area (resident human population, cattle and sheep numbers and sugarcane, banana and cotton area; from Lewis et al., 2021).

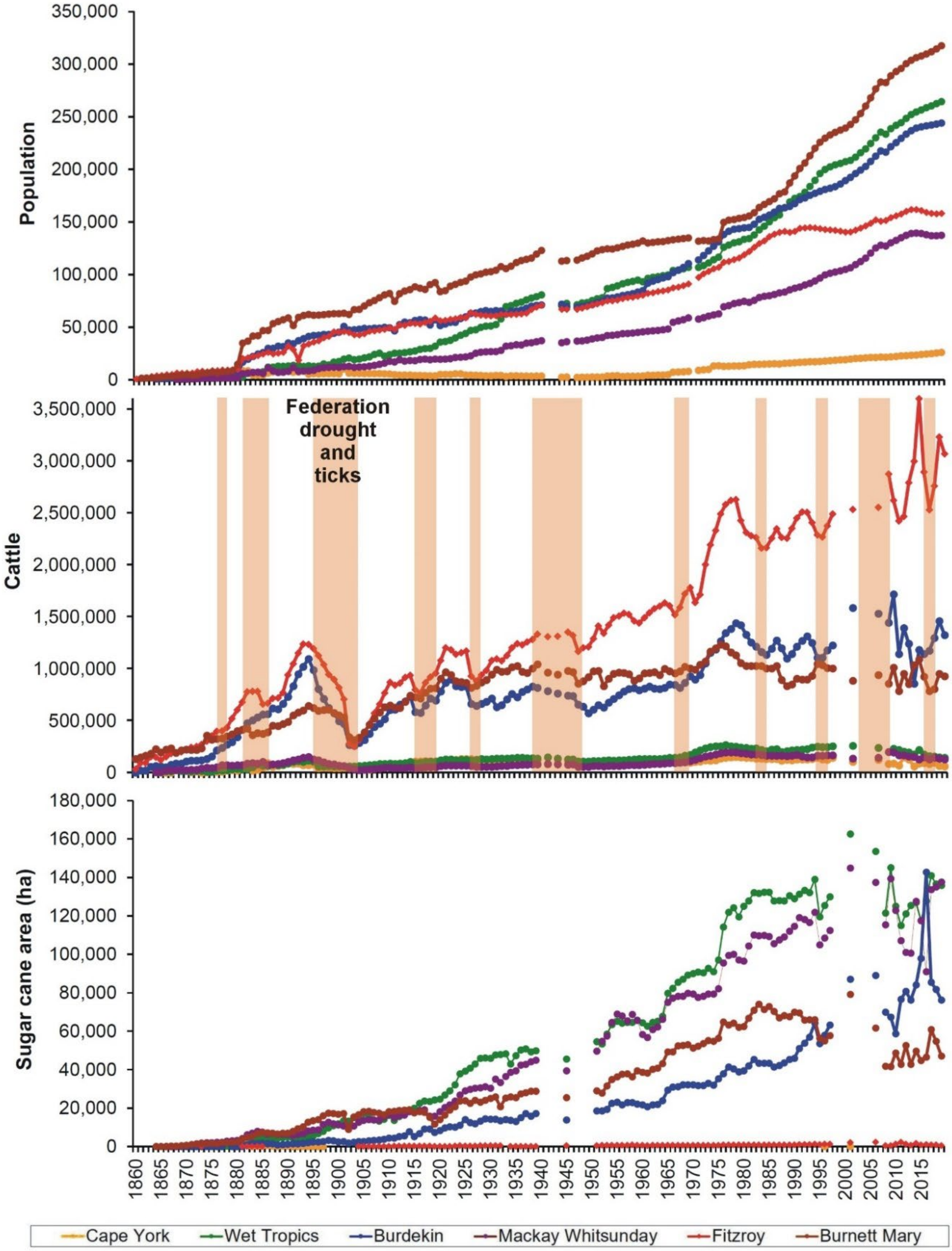


Figure 6. Land-use change for the NRM regions of the Great Barrier Reef catchment area (resident human population, cattle numbers and sugarcane area; from Lewis et al., 2021).

Catchment-based measurements and proxies

Of the 22 catchment proxy (i.e., environmental indicators that have the ability to quantify changes in terrestrial runoff) studies that cover the period before and after European arrival or the observational/measurement studies that are able to directly quantify changes due to land clearing (i.e., from the Brigalow Catchment Study or flow gauges in operation before and after land clearing), 17 show clear evidence for increased fluvial discharge and/or sediment erosion due to catchment modification (Table 9). These 17 studies were conducted in the Fitzroy, Burdekin or Normanby Basins. Another study of sediment cores collected from two freshwater wetlands in the Fitzroy Basin revealed contrasting records of sediment accumulation over the past 100 years (Hanson et al., 2021). The remaining four studies, which were conducted exclusively within the basins of the Wet Tropics NRM region, suggested that sediment delivery since European arrival had not markedly increased over this time or had even, in fact, reduced. One of these four studies used Beryllium (Be)-10 isotopes to quantify long-term denudation rates in the Barron Basin and compared these to modern fluxes (Nichols et al., 2014) while the other three studies used optically stimulated luminescence dating of fluvial terraces/benches and floodplain deposits to document periods of increased accretion or erosion (Hughes & Croke, 2017; Leonard & Nott, 2015; 2016). These three studies revealed evidence for multiple active phases of floodplain stripping (i.e., increased sediment fluxes) and subsequent floodplain accretion in the basins of the Wet Tropics during the mid to late Holocene. The magnitude of flood discharges and sediment yields associated with the stripping events far exceed any events of the past two centuries (Table 9).

Four contributions from the Brigalow Catchment Study reveal mixed changes to nutrient loads as a result of the clearing of the Brigalow vegetation. Specifically, the data provide evidence that phosphorus loads increased upon land clearing and conversion to grazing or cropping lands, while nitrogen loads (total, oxidised and dissolved forms) reduced when cleared Brigalow land is converted to grazing or is similar to when cleared Brigalow is converted to cropping as the Brigalow vegetation is legumous (Elledge & Thornton 2012; 2017; Thornton & Elledge, 2021; 2022). Excluding the nitrogen load findings from the Brigalow lands (which represents a special case), water quality monitoring and obervational records from agricultural (i.e., grazing and cropping) and urban land uses show clear increases in suspended sediment, nutrients (nitrogen and phosphorus) and pesticide concentrations compared to pristine locations within the same catchment areas (Table 9). Obervational data demonstrate that cattle ramps/tracks around stream courses increase sediment erosion (Packett, 2020), while longer-term monitoring data indicate that sediment loads increase when drought-breaking floods occur in parched catchments with low vegetation cover, often exacerbated by cattle grazing (Bartley et al., 2010; 2014; Kuhnert et al., 2012). Pesticide residues measured in catchment-based water quality monitoring programs show clear links to use within the agricultural industry (Table 9). As pesticides were absent in the GBR catchment area prior to European arrival, the concentrations and loads measured are entirely anthropogenic.

Table 9. Summary of the number and types of catchment studies by parameter, and their key findings.

Catchment study type	Freshwater		Sediment		Nutrient		Pesticides	References
	Increase	No change / decrease	Increase	No change / decrease	Increase	No change / decrease		
Be-10 studies			2	1				Bartley et al., 2015; Mariotti et al., 2021; Nichols et al., 2014
Fluvial studies (Optically stimulated luminescence dating [OSL] ages of benches/ terraces)			4	3				Bartley et al., 2018; Brooks et al., 2013; Hughes & Croke, 2017; Hughes et al., 2010; Leonard & Nott, 2015; 2016; Pietsch et al., 2015
Sediment core accumulation rates/composition			3.5	0.5				Douglas et al., 2010; Hanson et al., 2021; Hughes et al., 2009; Tibby et al., 2019

Catchment study type	Freshwater		Sediment		Nutrient		Pesticides	References
	Increase	No change / decrease	Increase	No change / decrease	Increase	No change / decrease		
Water quality monitoring studies	7.5	2.5	14		12	2	6	Bainbridge et al., 2009; Bartley et al., 2010; 2014; Brodie & Mitchell, 2005; Chen & Yu, 2019; Elledge & Thornton, 2012; 2017; Hunter & Walton, 2008; Kuhnert et al., 2012; Liu et al., 2018; 2021a; 2021b; Mitchell et al., 2009; Packett et al., 2009; Pailles et al., 1993; Peña-Arancibia et al., 2012; Rohde et al., 2008; Siriwardena et al., 2006; Smith et al., 2012; Thornton et al., 2007; Thornton & Elledge, 2021; 2022; Thornton & Yu, 2016; Warne et al., 2020; 2022
Observational changes in land condition			1					Packett, 2020
Measurement of mercury (Hg) in water and sediment (fungicide proxy)							1	Turull et al., 2018

Coral reef proxy and marine sediment records

Of the 46 marine proxy studies that cover the period before and after European arrival or following major land-use change, 16 show clear evidence for increased freshwater runoff and/or sediment runoff and/or nutrient runoff due to climatic changes and/or catchment modification (Table 10). The variability in the findings largely reflects the location of the proxy record within the GBR lagoon, the type of proxy and developments of the proxy metholodogy. Coral luminescence records from sites that receive freshwater plumes from adjacent river catchments show strong evidence for increased freshwater discharge from around 1850-1870 that coincides with changes in the frequency and intensity of the El Niño-Southern Oscillation (ENSO) (Hendy et al., 2003; Lough, 2011b; Lough et al., 2015 and references therein). A recent palaeo-discharge reconstruction using tree ring records from 1413 to 2005 CE for the Daly River, a relatively unmodified catchment in the Northern Territory of northern Australia, shows highly comparable trends to the Lough et al. (2015) reconstruction[9]. Catchment hardening due to the introduction of livestock in the catchment also likely contributes to increased runoff (Lough et al., 2015). However, the relative contribution of climatic factors (i.e., ENSO, Pacific Decadal Oscillation, Indo-Australian monsoon) and land-use changes (i.e., catchment hardening) to the increased discharge to the GBR has yet to be determined. There are three coral luminescence proxy records from the mid-Holocene period that cover ~4,300 to 6,200 years before present, two of which show evidence for reduced freshwater discharge from coastal catchments over this time (Leonard et al., 2016; Lough et al., 2014) and one record covering a 30-year period ~4,700 years before present that shows evidence for increased freshwater runoff (Roche et al., 2014). The only other coral luminescence record that suggests freshwater discharge to the GBR lagoon has not increased since the European arrival was reconstructed by Isdale et al. (1998); this record used an older method of measuring the coral luminescence which has

[9]Higgins, P. A., Palmer, J. G., Rao, M. P., Andersen, M. S., Turney, C. S. M., & Johnson, F. (2022). Unprecedented High Northern Australian Streamflow Linked to an Intensification of the Indo-Australian Monsoon. Water Resources Research, 58(3), e2021WR030881.

since been re-examined and updated to correct for age artefacts (Lough, 2011a). Subsequent measurements on these same coral cores originally analysed by Isdale et al. (1998) all reveal clear evidence of increased runoff following 1850-1870 (Hendy et al., 2003; Lough, 2011b; Lough et al., 2015), and suggest further increases since the 1950s (Lough et al., 2015).

All of the long (i.e., >150 year records) coral geochemistry proxy records of freshwater and/or sediment discharge establish a marked increase since the 1850-1870s through either Barium (Ba) to Calcium (Ca) ratios or Manganese (Mn) and Yttrium (Y) concentrations (D'Olivo & McCulloch, 2022; Lewis et al., 2007; 2012a; McCulloch et al., 2003). Whether these proxies represent indicators of freshwater or sediment runoff (or both) remains the subject of some debate; the complex desorption/biological processes active during the transport of materials within the flood plumes and the variable dispersal and movement of plumes in the GBR lagoon contribute to this uncertainty (see D'Olivo & McCulloch, 2022; Lewis et al., 2018). However, these long records provide unequivocal evidence of increased exposure of the inshore GBR lagoon (e.g., Figure 7) from Cairns to the Whitsunday Islands to fluvial inputs following European arrival (Table 10). The long coral core Ba/Ca record from South Molle Island (Whitsunday Islands) is an exception as ratios do not increase following the arrival of Europeans (Cantin et al., 2019). Coral Vanadium/Calcium (V/Ca) ratios in a coral core from Great Keppel Island (receiving waters for the Fitzroy River) have been used as a proxy to highlight evidence for increased runoff of ash due to the burning of the cleared Brigalow vegetation (Saha et al., 2019b). Recent studies have shown that rare earth elements measured within coral skeletons provide a reliable proxy of changes in terrigenous sediment exposure (i.e., wave resuspension, dredging and flood plumes) at coral reefs (Saha et al., 2019a, 2021; Wyndham et al., 2004), although unfortunately no long-term records exist to examine changes following the arrival of Europeans. The measurement of nitrogen (N) isotopes in coral skeletons as a proxy of nutrient runoff has yielded mixed results. Long-term coral N isotope records (>150 years) from Pandora Reef, Havannah Island and Magnetic Island (path of the Burdekin River flood plume) showed a considerable decline in the $^{15}N/^{14}N$ ratio (i.e., towards more depleted values) over this period which was interpreted as evidence for increased coastal nitrogen fixation as opposed to anthropogenic nitrogen inputs (Erler et al., 2016; 2020). In comparison, coral cores from reefs exposed to Pioneer River discharge reveal highly enriched ^{15}N values that coincide with large flood pulses from the Pioneer River postulated to reflect transformation of the nitrogen in the Pioneer River flood plume (Marion et al., 2021) (Table 10). The measurement of annual mean phosphorus (P) to calcium (P/Ca) ratios in coral cores from Dunk Island (receiving waters for the Tully River) showed an increase that coincided with greater use of phosphorus-based fertilisers in the Tully basin and annual P/Ca ratios were correlated with measured particulate phosphorus loads between the years 1988 and 2000 (Mallela et al., 2013). The supplement of Mallela et al. (2013) indicates that higher temporal resolution measurements of the coral P/Ca ratios reveal that the annual peak P/Ca ratios appear to lag behind the river discharge event by several months which may be related to the period of time required for the desorption of the particulate P into the water column.

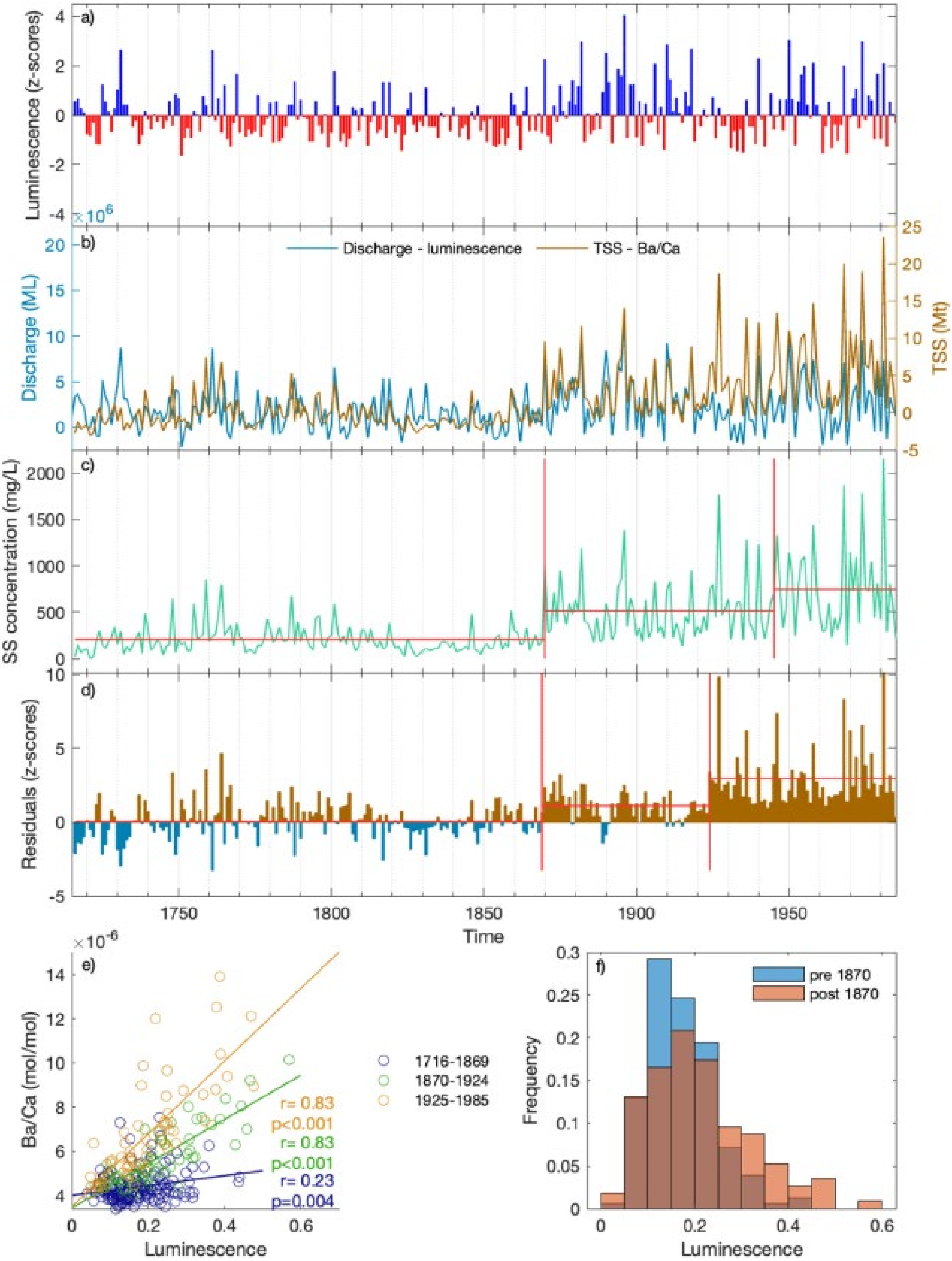


Figure 7. Coral core luminescence and geochemistry records reveal increased terrestrial exposure since European arrival (from D'Olivo & McCulloch, 2022).

Coral reef proxy records that use the composition of benthic foraminifera (i.e., the foram index) in sediment cores as a measure of changing water quality (light and nutrients) also show different results depending on the location in the GBR lagoon. While there were spatial differences in the composition of benthic foraminifera in sediment cores from Pandora Reef and Havannah Island, the individual cores show no clear changes over the past 1,000 years (Reymond et al., 2013). In contrast, cores from the inner parts of the Whitsunday Island Group show considerable changes in the composition of benthic foraminifera over the past 150 years compared to a long-term baseline of 1,500 years; this record was interpreted as representing a decline in water quality in this section of the GBR (Uthicke et al., 2012) (Table 10). Other coral reef proxy records using the rare earth element composition of coral microbialite records from One Tree Island and Heron Island reveal major changes in sediment fluxes over the Holocene (8200 to 1800 years BP) but do not show evidence for the pre- and post-European arrival period (Salas-Saavedra et al., 2022). Nitrogen isotopes in *Halimeda* bioherms from the Ribbon Reefs (outer northern GBR) cover a 5,000-year period and show variability related to the frequency and intensity of the ENSO and show no discernible changes since European settlement (McNeil et al., 2021).

Sediment cores from the inshore GBR lagoon also reveal differing results likely driven by local factors. Of the 15 reported studies which reveal no detectable change in sediment accumulation rate and/or coral composition in the period following European arrival, 6 studies were from Paluma Shoals (Browne et al., 2013; Johnson et al., 2017; 2019; Palmer et al., 2010; Perry et al., 2008; 2013), 2 studies from Middle Reef (Perry et al., 2012; Browne et al., 2013), 2 studies from Edgecumbe Bay (Ryan et al., 2016; 2018), 2 studies from the Whitsunday Island Group (Heap et al., 2001; 2002) and individual studies from King Reef (Roche et al., 2011), Lugger Shoal (Perry et al., 2009), Havannah Island and Pandora Reef (Roff et al., 2015) and the Fitzroy River estuary (Bostock et al., 2007). Indeed the study on the Fitzroy River estuary suggested the budget may have been highly variable over the past 8,000 years (Bostock et al., 2007) while a synthesis by Brooke et al. (2006) showed there has been an increase in sediment accumulation in the Fitzroy River estuary and floodplain over the last 100-200 years. Similarly, a sediment core off the mouth of the Burdekin River indicates an approximately 10-fold increase in sediment accumulation rates over the past 200 years (Lewis et al., 2014). U-series dating of dead *Acropora* assemblages from sediment cores from the coral reef at Pelorus Island suggest a collapse in these coral species between 1920 and 1955 whereas prior to this period coral cover at this site had been stable in the long-term (Roff et al., 2013).

Pesticides in the GBR lagoon

The sediments of the inshore GBR lagoon have also been examined for pesticide residues. Pesticides are also covered in Questions 5.1 (Negri et al., this SCS) and 5.2 (Templeman & McDonald, this SCS). An early study demonstrated that while organochlorine pesticide residues (i.e., long banned insecticides) could be easily detected in the soils of sugarcane paddocks, these residues were below detectable limits in samples collected offshore from the Herbert and Burdekin Rivers (Cavanagh et al., 1999). In contrast, a subsequent study by Haynes et al. (2000) sampled pesticide residues in sediments from the breadth of the inshore GBR and detected organochlorine pesticide residues and current herbicides including diuron and atrazine. A decade later Davis et al. (2012) detected diuron in the inshore sediments of Bowling Green Bay, where Haynes et al. (2000) had not previously detected it. The presence of elevated mercury in sediments in the GBR lagoon also provide evidence of its use in the historical gold mining efforts in the catchment (~1870s-1890s) or as part of a common fungicide used in the sugarcane industry (from the 1940s) (Walker & Brunskill, 1996). Elevated mercury concentrations in sediment cores coinciding with the 1940s have been reported in sediment cores collected near the mouth of the Burdekin River and Herbert River (Walker & Brunskill, 1996).

Water quality measurements of pesticide residues within river flood plumes and passive samplers highlight the 'low level' (i.e., generally below ecological protection guidelines) exposure of pesticides in the inshore GBR lagoon (Kennedy et al., 2012; Lewis et al., 2012b; Shaw & Müller, 2005; Shaw et al., 2010; Taucare et al., 2022). Grab sample results show occasional exceedance of herbicide guidelines in the areas near certain river mouths (Lewis et al., 2012b) and trends in the long-term passive sampler deployments suggest that some herbicide residues have displayed an increasing trend in concentration at several monitoring sites over the 14-year monitoring program (Taucare et al., 2022).

Observations of plume extent in the GBR lagoon

Aerial surveys and satellite images allow the extent of flood plumes in the GBR lagoon to be determined (e.g., Devlin et al., 2012; Moran et al., 2022). Importantly, the discharge volume and wind speed and direction are two key factors that control the extent and movement of flood plumes and their associated contaminants in the GBR lagoon. Lough et al. (2015) highlighted that the 2011 flood was likely the largest in the GBR for several hundreds of years (i.e., the proxy record which dates back to 1648) and hence the 2011 plume extent map presented in Devlin et al. (2012) provides evidence of the maximum extent of post-European floodwaters in the GBR lagoon (Figure 8). Remote sensing is widely used as a tool to map the annual extent of river plumes in the GBR lagoon (Gruber et al., 2020; Moran et al., 2022).

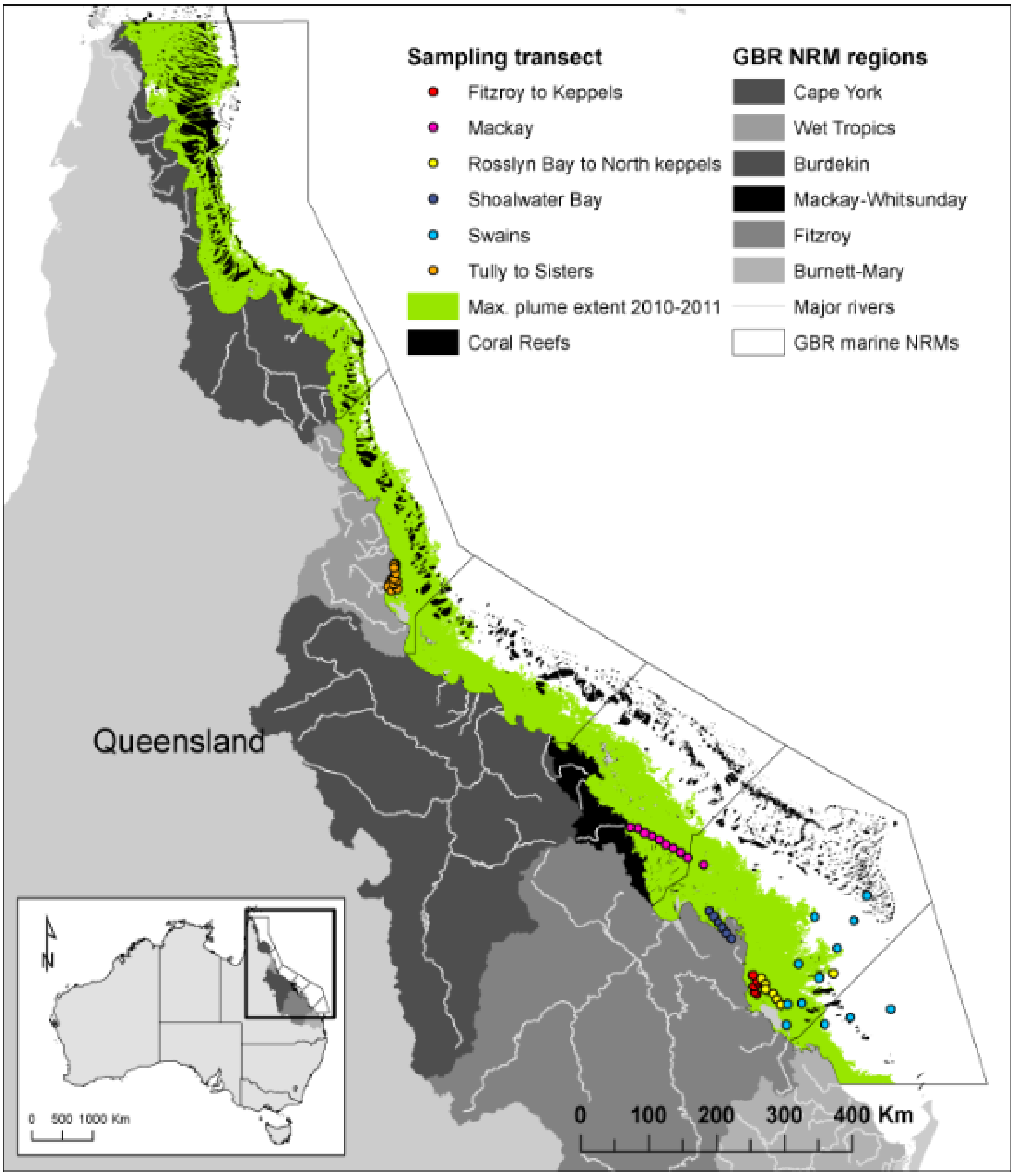


Figure 8. Observed maximum extent of the 2011 flood plumes in the GBR lagoon (from Devlin et al., 2012).

Table 10. Summary of the marine studies by parameter and their findings.

Marine study type	Freshwater		Sediment		Nutrient		Pesticides	References
	Increase	No change/ decrease	Increase	No change/ decrease	Increase	No change/ decrease		
Coral reef proxy/sediment core development	N/A							Alibert et al., 2003; Browne et al., 2012; Carricart-Ganivet et al., 2007; Erler et al., 2015; Gottschalk et al., 2007; Jupiter et al., 2008; Kosnik et al., 2007; Larcombe & Woolfe, 1999; Leonard et al., 2019; Lewis et al., 2018; Lough, 2011a; Lough et al., 2002; Saha et al., 2018a; 2018b; 2019a; 2021; Sinclair, 2005; Sinclair & McCulloch, 2004; Uthicke & Nobes, 2008; Uthicke et al., 2010; Walther et al., 2013; Wyndham et al., 2004
Coral luminescence records	7	2						Hendy et al., 2003; Isdale et al., 1998; Leonard et al., 2016; Lough, 2007; 2011b; Lough et al., 2014; 2015; Roche et al., 2014; Rodriguez-Ramirez et al., 2014
Coral reef proxies	4		6	3	3	5		Cantin et al., 2019; D'Olivo & McCulloch, 2022; Erler et al., 2016; 2020; Lewis et al., 2007; 2012a; Mallela et al., 2013; Marion et al., 2021; McCulloch et al., 2003; McNeil et al., 2021; Reymond et al., 2013; Saha et al., 2019b; Salas-Saavedra et al., 2022; Uthicke et al., 2012
Sediment cores/Sediment deposits			3	15			4	Bostock et al., 2007; Brooke et al., 2006; Browne et al., 2013; Cavanagh et al., 1999; Davis et al., 2012; Haynes et al., 2000; Heap et al., 2001; 2002; Johnson et al., 2017; 2019; Lewis et al., 2014; Palmer et al., 2010; Perry et al., 2008; 2009; 2012; 2013; Roche et al., 2011; Roff et al., 2013; 2015; Ryan et al., 2016; 2018; Walker & Brunskill, 1996
Water quality measurements							5	Kennedy et al., 2012; Lewis et al., 2012b; Shaw & Müller, 2005; Shaw et al., 2010; Taucare et al., 2022
Observational changes in plume extent	N/A							Devlin & Schaffelke, 2009; Devlin et al., 2012; Gruber et al., 2020; Moran et al., 2022

Modelling studies across the catchment to reef

There have been several efforts to model the current and anthropogenic loads of suspended sediments and nutrients exported to the GBR over the past two to three decades. Only some of these studies are captured in Table 11 as the latest model results (McCloskey et al., 2021a; 2021b) have superseded the earlier estimates and are considered the best available, although some of the earlier model iterations have been captured to examine the consistency of estimates over time. There have been fewer studies to estimate the loads of photosystem-II (PS-II) herbicides to the GBR (Table 11). Overall, while the specific model outputs of sediment and nutrient loads have changed over time, all models broadly agree that loads have increased considerably since European arrival (Table 12). As the latest Source Catchments model has improved over the years due to the availability of measured load data for validation and calibration and more reliable catchment layer inputs (McCloskey et al., 2021a; 2001b), modelled outputs of the anthropogenic increase in loads have generally decreased with some exceptions (Table 12). The latest available Source Catchments modelling suggests that sediment loads have increased by more than threefold for most basins within the Burdekin, Mackay Whitsunday, Fitzroy, and Burnett Mary NRM regions (exceptions include the Black, Proserpine, Shoalwater, and Waterpark Basins) (McCloskey et al., 2021a)[10]. The basins of the Cape York NRM region have modelled load increases of 1.3-fold or less except for the Normanby Basin from which loads have been projected to have increased 5-fold (McCloskey et al., 2021a). The latest modelling suggests that nearly half of the total DIN load exported from GBR catchments is from the Wet Tropics NRM region and half of the total DIN load exported to the GBR lagoon is derived from sugarcane cropping areas (McCloskey et al., 2021b). In general, DIN loads increase 1.5 to 3.0-fold in basins with intensive cropping (Table 12; McCloskey et al., 2021b).

Exposure modelling to show pollutants dispersed within the GBR lagoon as a result of the increased loads has been performed using different methods (Table 11). Recently, two independent methods have emerged including loading maps which distribute the annual basin loads through a modelled plume extent (e.g., Gruber et al., 2020; Moran et al., 2022; Waterhouse et al., 2017; Figure 9) and the longer modelling of the water quality changes as a result of increased loads through the eReefs model platform (Baird et al., 2021). Importantly, the different methods all show similar results and highlight the key areas of the GBR lagoon that are exposed to anthropogenic loads of suspended sediments, nutrients and herbicides.

Table 11. Summary of the modelling studies.

Model study type	Sediment	Nutrient	Pesticides	References
Catchment model	4	4	2	Kroon et al., 2012; Lewis et al., 2011; McCloskey et al., 2021a; 2021b; McKergow et al., 2005a; 2005b; Neil et al., 2002
Marine pollutant extent and change since European arrival (marine)	4	5	1	Baird et al., 2021; Gruber et al., 2020; Maughan & Brodie, 2009; Moran et al., 2022; Waterhouse et al., 2017; Wooldridge et al., 2006

[10]This includes basins that host large dams where the modelling suggests that sediment loads have increased since European arrival even following dam construction.

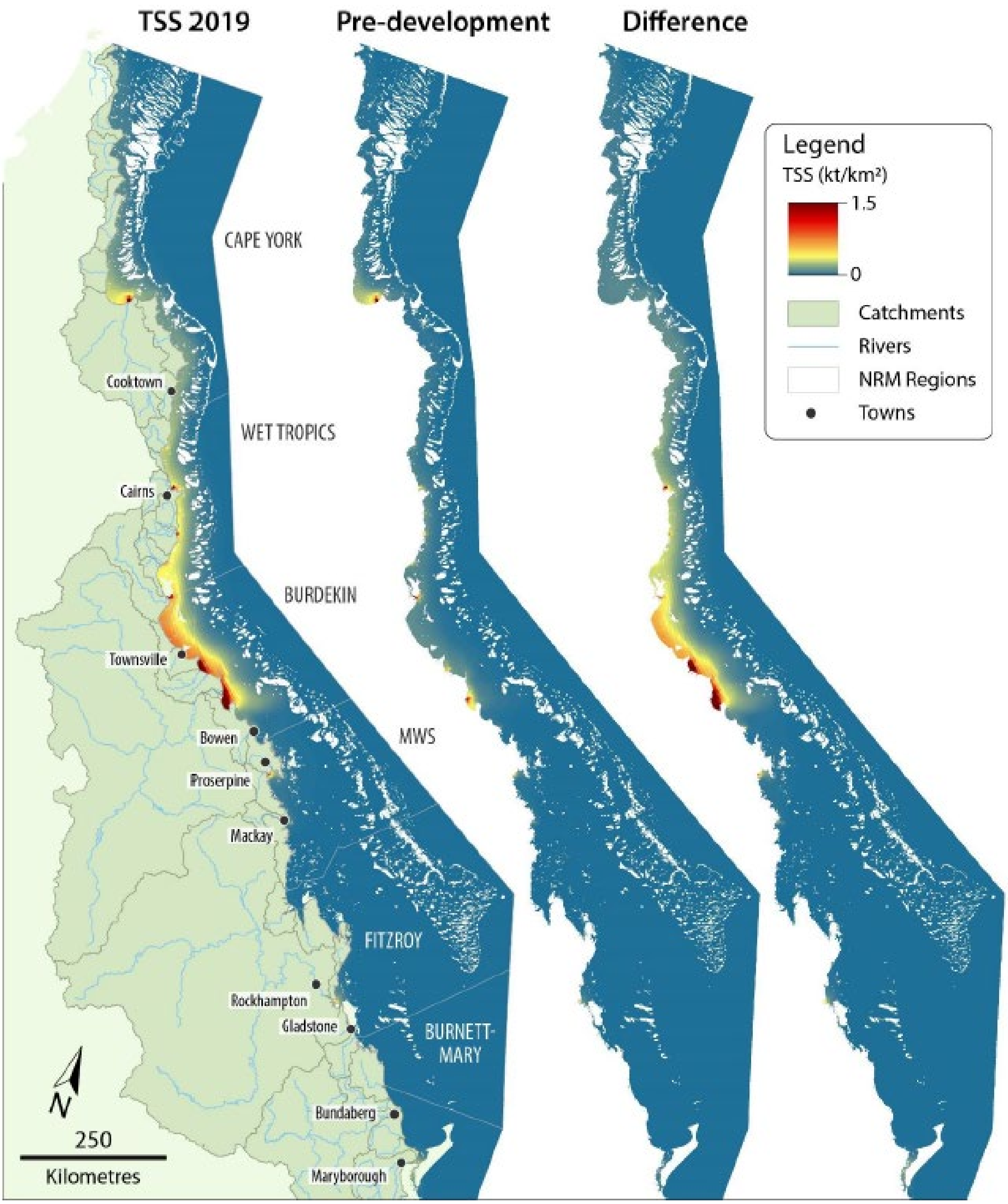


Figure 9. Example of flood plume loading maps for total suspended solids for 2019 water year and the modelled difference in exposure between current and pre-development loads (from Gruber et al., 2020).

Table 12. Example of load factor increases since European arrival for suspended sediment and dissolved inorganic nitrogen over different modelling exercies.

Basin	Mean fine sediment load increase Neil et al. (2002)	Mean fine sediment load increase McKergow et al. (2005a)	Mean fine sediment load increase Kroon et al. (2012)	Mean fine sediment load increase McCloskey et al. (2021a)	Mean dissolved inorganic nitrogen load increase Kroon et al. (2012)	Mean dissolved inorganic nitrogen load increase McCloskey et al. (2021b)
Jacky Jacky Creek	3.6 (Northeast Cape York)	5.6	5.6	1.2	2.0	1.0
Olive Pascoe River		5.8	5.8	1.3	2.0	1.0
Lockhart River		5.4	5.4	1.0	2.0	1.0
Stewart River		4.9	5.0	1.2	2.0	1.0
Normanby River		5.9	6.1	5.0	1.8	1.0
Jeannie River		3.6	3.6	1.3	1.7	1.0
Endeavour River		5.3	5.3	1.2	1.8	1.0
Daintree River	1.6 (Mossman-Daintree)	3.7	4.0	1.2	3.8	1.1
Mossman River		7.0	5.9	1.4	7.6	1.7
Barron River	2.7	3.0	4.0	2.2	0.8	2.4
Mulgrave-Russell River	2.7	6.9	5.1	2.0	10.0	1.5
Johnstone River	2.8	9.5	7.8	1.7	8.8	1.5
Tully River	0.8 (Tully-Murray)	8.0	3.8	1.5	4.9	1.7
Murray River		6.0	4.6	1.8	6.5	2.5
Herbert River	3.5	6.4	3.5	2.3	5.0	2.7
Black River	3.1 (Ross-Black)	5.4	2.1	1.9	1.7	1.5
Ross River		4.0	4.0	3.1	3.1	2.6
Haughton River	4.7 (Burdekin-Haughton)	9.9	10.3	6.8	8.1	5.5
Burdekin River		5.9	8.3	5.2	1.8	1.4
Don River	3.9	10.5	7.2	8.7	3.6	1.3
Proserpine River	3.4	7.8	6.9	2.6	5.3	3.8
O'Connell River	3.7 (Pioneer-O'Connell)	8.0	6.4	3.5	3.8	4.0
Pioneer River		8.1	1.0	3.5	3.2	6.0
Plane Creek	3.4 (Shoalwater Bay-Sarina)	10.9	10.2	3.5	5.7	5.4
Styx River		10.5	10.4	5.8	2.0	1.2
Shoalwater Creek		4.3	4.3	2.2	1.2	1.1
Waterpark Creek		8.9	8.9	1.2	1.9	1.1
Fitzroy River	4.8	10.6	3.1	5.3	1.3	1.3
Calliope River	3.5 (Curtis Coast)	10.6	10.5	3.4	2.2	1.1
Boyne River		1.0	1.0	3.4	1.9	1.1
Baffle Creek		8.6	8.0	3.1	1.5	2.5
Kolan River	3.7 (Burnett-Kolan)	2.8	5.9	3.7	2.5	10.3
Burnett River		4.8	14.1	3.8	1.9	6.5
Burrum River		9.1	10.4	3.7	3.6	15.8
Mary River	3.2	4.5	12.2	5.3	1.9	5.0

Trends or patterns in outcomes or effects including consistencies or heterogeneity within study findings and reasons why

As demonstrated in the evidence above, there is broad agreement in the scientific literature that loads of suspended sediments, nutrients and pesticides have increased substantially from most river basins of the GBR catchment area since European arrival. This is underpinned by multiple lines of evidence including the catchment modelling, water quality monitoring data of different land uses and proxy-based reconstructions from the catchments and coral core records. This finding is consistent with evidence reported in Questions 3.3 (Prosser & Wilkinson, this SCS) and 4.4 (Prosser & Wilkinson, this SCS). Evidence also demonstrates that the temporal pattern of freshwater discharge to the GBR has changed over the same period, with larger volume flood events increasing in both volume and frequency since the 1850s and again since the 1950s measured relative to a long-term flood history capturing the past ~400 years (Lough et al., 2015). Points of contention in the literature revolve around the level of spatial impact that these increased loads have had within the GBR lagoon. One of the clear inconsistencies within the compiled studies is the findings from the different proxy data from the Pandora and Havannah Island coral reef sites. Specifically the subannually resolved coral core records provide strong evidence of increased terrestrial runoff (freshwater and/or sediment) since the arrival of Europeans (c. 1850s: D'Olivo & McCulloch, 2022; McCulloch et al., 2003) while other proxy records using the composition of benthic foraminiferia and sediment/reef accretion rates show no evidence of major changes before and after European arrival (Reymond et al., 2013; Roff et al., 2015). Nitrogen isotope records in coral cores from these locations have been interpreted as showing no influence of anthropogenic nitrogen inputs, although a clear decreasing trend in the record since the arrival of Europeans is attributed to increased nitrogen fixation (Erler et al., 2020), presumably due to increased inputs of phosphorus.

Indeed, the evidence for increased loads in the GBR lagoon since the arrival of Europeans is strongest near the river mouths and particularly along the 'turbid' river plume exposure zones. The discrepancies between different proxies are likely a response to the complexity of specific exposure to the river flood plumes at different sites in the GBR lagoon, the temporal resolution of the proxy (i.e., subannual resolution 'acute exposure' versus lower resolution records of 'chronic exposure'), regional and local hydrodynamics including sediment transport, and the location within the GBR lagoon (i.e., midshelf sites). In fact, it is well-recognised that increases in catchment sediment loads do not commonly translate to increases in sediment accumulation on inshore coral reef sites (Larcombe & Woolfe, 1999) and that the unconsolidated sediments from coral reefs further offshore on the mid and outer shelf may be actively mixed by bioturbation (Kosnik et al., 2007). The complexity of the catchment to reef connection is emphased well by Ryan et al. (2018 p. 12) who states "*Determining the effects of terrigenous input on the present condition of reefs in Edgecumbe Bay and those further offshore on the mid- and outer-shelf is complex. The main potential anthropogenic impacts on inshore coral reefs of the GBR are related to the increase in the runoff of land-based sediment and nutrients that have followed European land-use changes in coastal catchments. Accordingly, a catchment-to-reef understanding of the sources, transport, and fate of these sediments and nutrients is required to fully understand their impacts. The spatial impact of increased sediment delivery since European settlement on coral reefs of the GBR is dependent on a number of factors, including how much the erosion and export of sediments and nutrients from the key coastal catchments have increased, the degree to which any reef is exposed to river flood plumes (which is related to the distance of the reef from the river mouth and the size of the river discharge), the natural environmental conditions under which the coral reef has developed (i.e., turbidity tolerant species), the character of sediments exported from the catchment (particle size, mineralogy and organic content) and the geomorphology and bathymetry of the coastline and adjacent continental shelf, which influence sediment storage and flushing periods*".

The fluvial proxy records also provide some interesting spatial differences in the GBR catchments. Records from the large and higher sediment load contributing river catchments of the Fitzroy, Burdekin and Normanby show clear evidence of increased erosion since European arrival against a relatively long-term Holocene background, while evidence from the Wet Tropics NRM region shows increased erosion (i.e., flood plain stripping) during earlier periods of the mid-late Holocene prior to European arrival.

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

A wealth of new research has helped consolidate the synthesis and provides a clear path for the future. Key studies include the documentation of land use time series data (Lewis et al., 2021) to identify periods of major land-use change for each basin of the GBR catchments which provides a foundational dataset to better link catchment conditions to marine proxies. The examination of stream gauge records coupled with multiple lines of evidence modelling approaches has improved quantification of the increased stream runoff from catchments cleared of Brigalow at the subcatchment scale, independent of climate variability (Cheng & Yu, 2019). Additional analyses on the dataset from the paired Brigalow Catchment Study have quantified changes in runoff of freshwater, sediment and nutrients expected when Brigalow vegetation is cleared (Elledge & Thornton, 2017; Thornton & Elledge, 2021; 2022; Thornton & Yu, 2016). The potential for cattle tracks/ramps around creek lines to enhance erosion has been demonstrated in the Fitzroy Basin (Packett, 2020). There has also been spatial and temporal trend analysis of water quality data from both within the GBR catchments and lagoon (Liu et al., 2018; 2021a; 2021b; Taucare et al., 2022; Warne et al., 2020; 2022).

Important studies of proxy evidence within the GBR catchments include a synthesis of new and existing Be-10 data from several basins to reveal key sediment erosion hotspots (Mariotti et al., 2021) and sediment cores from wetlands which show changes in sediment accumulation and composition since European arrival or following major land-use changes (Hanson et al., 2021; Tibby et al., 2019). The timing and accumulation rates of fluvial bench and floodplain deposits have been examined which provide a long-term perspective of catchment erosion processes and changes throughout the Holocene (Bartley et al., 2018; Hughes & Croke, 2017; Leonard & Nott, 2016).

Within the GBR lagoon, numerous studies have examined the geochemistry of coral cores which offers improved understanding and interpretation of the long coral proxy records as well as the development of new proxies to assess changes in freshwater, sediment and nutrient exposure (D'Olivio & McCulloch et al., 2022; Erler et al., 2016; 2020; Lewis et al., 2018; Marion et al., 2021; Saha et al., 2018a; 2018b; 2019a; 2019b; 2021). Other coral reef proxy records have also been developed using the geochemistry of coral microbialites (Salas-Saavedra et al., 2022) and the isotope composition of *Halimeda* bioherms (McNeil et al., 2022). The accumulation rates and composition of sediment cores from inshore and midshelf coral reefs have also been reported (Johnson et al., 2017; 2019; Ryan et al., 2016; 2018).

Finally, the latest model of catchment pollutant loads that provide a current baseline mean load as well as a pre-development load (i.e., pre-European arrival) have recently been published (McCloskey et al., 2021a; 2021b). Outputs from the eReefs model quantify the resulting changes in exposure and water quality as a result of increased loads within the GBR lagoon (Baird et al., 2021). Model 'loading maps' have also been produced to highlight the increased spatial area of exposure as a result of increased loads (Gruber et al., 2020; Moran et al., 2022).

4.1.3 Key conclusions

- There are multiple lines of evidence demonstrating that loads of sediment, nutrients and pesticides have increased from most basins of the GBR catchment since the arrival of Europeans. The evidence for the increases has been gathered from water quality monitoring studies and proxy records, and the conclusions are supported by various modelling exercises.
- Time series of land use data for each basin of the GBR catchment from 1860 to 2019 including human resident population, livestock (cattle and sheep numbers), and agriculture area (total cropping, sugarcane, banana, cotton) highlight the varying land use pressures for each basin and show when major modifications in catchment land use took place. These records can be used in association with other catchment records (e.g., rainfall, streamflow etc.) to anticipate when major changes in sediment, nutrient and pesticides loads would likely have occurred and link with catchment and marine proxy records.
- Freshwater discharge to the GBR lagoon has increased considerably in both frequency of large events and the volume of such events since the 1850s and again since the 1950s against a long-term background extending over the past ~400 years. This increase is correlated with changes in the frequency and intensity of ENSO events and the behaviour of the Indo-Australian monsoon

across northern Australia. Catchment hardening due to the introduction of livestock in the catchment also likely contributes to increased runoff. However, the relative contribution of climatic factors (i.e., ENSO, Pacific Decadal Oscillation, Indo-Australian monsoon) and land-use changes (i.e., catchment hardening) to the increased discharge to the GBR has yet to be determined.

- The latest Source Catchments modelling suggests that sediment loads have more than tripled for most basins within the Burdekin, Mackay Whitsunday, Fitzroy, and Burnett Mary NRM regions (exceptions include the Black, Proserpine, Shoalwater, and Waterpark Basins)[11]. The basins of the Cape York NRM region have modelled load increases of 1.3-fold or less except for the Normanby Basin where projected loads have increased by 5-fold. These increases are supported/validated by multiple lines of independent evidence including a number of catchment proxy studies, land use-focused water quality monitoring data and coral core proxy geochemistry data.
- The latest Source Catchments modelling suggests that nearly half of the total DIN load exported from the GBR catchments is exported from the Wet Tropics NRM region, and half of the total DIN load exported to the GBR lagoon is derived from sugarcane cropping areas. In general, the basins with intensive cropping have seen DIN loads increase by 150-300%. These increases are mostly supported/validated by land use-focused water quality monitoring concentration data.
- Pesticides were absent prior to the arrival of Europeans and so loads/concentrations are entirely anthropogenic. Pesticide loads exported to the GBR lagoon have less ecological relevance than the concentrations of the residues in the water column of streams and in the GBR lagoon. Concentrations of some pesticides occasionally exceed proposed ecological protection guidelines for certain streams in the GBR catchments and also in some flood plumes. Monitoring programs from the inshore GBR lagoon have also shown an increasing trend in concentrations of some herbicides and an insecticide (imidacloprid) over the past ~15 years of data.
- The 'detection footprint' of changes in pollutant exposure since European arrival in the GBR lagoon is most pronounced in the estuarine and nearshore environments just offshore from river mouths but can be seen as far out as >100 km alongshore from the river mouth of influence. Further offshore in the middle and outer shelfs, the proxies that measure such changes in freshwater, sediment and nutrient discharge show variable results.
- New coral proxies, including rare earth elements and nitrogen isotopes, show great promise to help reconstruct changes in sediment and nutrient exposure, respectively in the GBR lagoon.

4.1.4 Significance of findings for policy, management and practice

This Evidence Summary has examined the evidence for changes in land runoff to the GBR since the arrival of Europeans c. 1850. The evidence continues to show that freshwater runoff and the loads of sediments, nutrients and pesticides have increased greatly for most river basins over the past ~170 years. This finding has not changed over the past three decades. However, the evidence for change across the marine proxies in the GBR is more varied and related to both the spatial location of the proxy and the type of proxy itself.

4.1.5 Uncertainties and/or limitations of the evidence

- There is little uncertainty or dispute that the loads of sediments, nutrients and pesticides exported to the GBR lagoon have increased in most basins since the arrival of Europeans particularly relative to the past 400 years of records. However, the comparison of discharge and associated loads over a longer baseline that reflects the modern GBR (i.e., the past ~7,000 years) is more uncertain.
- There are limited catchment and marine proxy-based records for evidence of changes in loads from the Cape York and Burnett Mary regions.

[11]This includes basins that host large dams where the modelling suggests that sediment loads have increased since European arrival even following dam construction.

- The sparseness of the proxy records across the GBR lagoon means that the spatial exposure of the increased loads is difficult to define, and the spatial distributions of impacts are thus challenging to directly assess. Investigation of these impacts has largely been restricted to modelling exercises.
- The modelling exercises show that the increased loadings are most strongly concentrated on the inner shelf of the GBR lagoon.
- There are limited catchment or marine proxies to help quantify changes in nutrient loadings to the GBR and understand their transformation in the GBR. The proxies that exist reveal conflicting results and these need to be better understood.
- Selected literature was used to highlight key concepts that may explain apparent conflicting findings or to visualise the extent of freshwater plumes or changes to terrestrial influence in the GBR lagoon. This includes the concept that increased sediment loads are not expected to translate to increased sediment accumulation rates on inshore GBR coral reefs due to various hydrodynamic and bioturbation processes on coral reefs (e.g., Larcombe and Woolfe, 1999; Kosnik et al., 2007). The modelling/visualisation of the plume extents and the differences in the exposure of sediments and nutrients in the pre-/post-European arrival periods provides an important spatial context on where the greatest impacts in the GBR lagoon would occur in comparison to where the proxy records have been collected (e.g., Devlin et al., 2012; Devlin & Schaffelke, 2009; Gruber et al., 2020; Maughan & Brodie, 2009; Moran et al., 2022; Wooldridge et al., 2006).

4.2 Contextual variables influencing outcomes

Table 13. Summary of contextual variables for Question 2.3.

Contextual variables	Influence on question outcome or relationships
Climate change (or climate variability) including El Niño-Southern Oscillation	Notable shifts in climate variability in the northern Australian region from the ~1850s and the ~1950s have resulted in greater variability in river discharge including more frequent and higher volume discharge events interspersed with intense droughts (Lough et al., 2015). Greater river flows mean that higher loads of sediments, nutrients and pesticides can also be delivered to the GBR, particularly during drought-breaking flood events. It is also important to recognise changes over the longer Holocene timeframe (Leonard et al., 2016; Lough et al., 2014; Roche et al., 2014). In addition, the large inter-annual variability in rainfall/river discharge can also lead to considerable year-to-year changes in constituent loads exported from the rivers (e.g., Kuhnert et al., 2012).
Land-use change	The expansion of agricultural lands and particularly the use of synthetic fertilisers and pesticides from the ~1950s are linked to increased sediment, nutrient and pesticide loads delivered to the GBR lagoon (Lewis et al., 2021). The introduction and subsequent increase in livestock numbers in the GBR catchment area has resulted in increased loads of sediments delivered to the GBR lagoon (Bartley et al., 2018; Lewis et al., 2021). Increased human resident populations have resulted in increased nutrients and pesticides delivered to the GBR lagoon (Lewis et al., 2021) while mining developments result in increased sediments delivered to the GBR lagoon (Bartley et al., 2018; Lewis et al., 2021).
Method development	A selection of the literature that demonstrates the utility of and/or aids the interpretation of the proxy records was used to provide important context for the key records. Earlier studies were also used to highlight the evolution of the field over time (e.g., Alibert et al., 2003; Browne et al., 2012; Carricart-Ganivet et al., 2007; Erler et al., 2015; Gottschalk et al., 2007; Jupiter et al., 2008; Kosnik et al., 2007; Leonard et al., 2019; Lewis et al., 2018; Lough, 2011a; Lough et al., 2002; Saha et al., 2018a; 2018b; 2019a; 2021; Sinclair, 2005; Sinclair & McCulloch, 2004; Uthicke & Nobes, 2008; Uthicke et al., 2010; Walther et al., 2013; Wyndham et al., 2004).

4.3 Evidence appraisal

Relevance

The relevance of the body of evidence used to answer the question was High. The relevance of each individual indicator was Moderate to High for overall relevance to the question, Moderate for spatial relevance, and High for temporal relevance. The question of if (and by how much) freshwater volumes and corresponding loads of suspended sediment, nutrients and pesticides have increased since the modification of the catchments following the arrival of Europeans has been subject to multiple modelling exercises and observational, fluvial and marine proxy studies for the past three decades. This research has been conducted across a broad spatial area of the GBR catchment, although there are comparatively less studies to draw from for some regions including the Burnett Mary and Cape York. As this question is specific to the GBR catchment area, there was little need to consider and draw on data from elsewhere; indeed, several of the catchment and marine proxies have been developed and tested within the GBR.

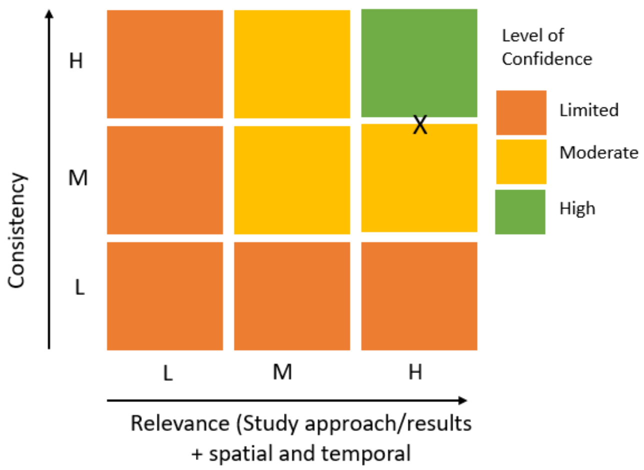
Consistency, Quantity and Diversity

The overall body of evidence showed a Medium to High level of consistency in the findings, a High abundance of research outputs (quantity) and a High diversity of methods applied to address the question. A high sample size of the available peer-reviewed evidence has been captured across multiple fields to address this question. The consistency of findings is much higher when only the catchment evidence base is considered. In that case, 17 of the 22 catchment proxy studies (comprised of lake/wetland sediment cores, sediment accumulation in fluvial benches and floodplains and Be-10 measurements of catchment erosion rates) showed evidence for clear increases in sediment erosion rates since European arrival. One of the 22 proxy studies showed mixed evidence (1 lake record shows evidence for increase and the other record did not) and the remaining 4 of 22 catchment proxies studies, all from the Wet Tropics NRM region, showed no evidence of increase in sediment erosion rates. Moreover, all modelling studies compiled show clear evidence of increases for most basins of the GBR catchment area. The vast majority of the observational studies also provided evidence for increases in freshwater runoff and sediment, nutrient and pesticide loads as a result of catchment land-use change. The findings from the studies conducted in the marine environment (GBR lagoon) are less consistent with 16 of 46 contributions showing clear evidence for increases in terrestrial runoff since the arrival of Europeans, presumably because of spatial variability in the exposure of sites within the GBR lagoon. The marine proxy records have also been gathered using diverse methods including coral reef proxy records (coral cores, benthic foraminifera, coral microbialites, *Halimeda* bioherms) and sediment cores. Modelling exercises also reveal where increased exposure to terrestrial runoff is spatially concentrated in the GBR lagoon.

Confidence

The overall confidence in the body of evidence used to answer the primary question is considered Moderate to High (Table 14). This is based on the rating of the overall consistency and relevance of the body of evidence used. There is broad agreement that loads of sediments, nutrients and pesticides have increased from most river basins due to catchment modifications following the arrival of Europeans. The area of most contention is the spatial footprint of these increased loads in the GBR lagoon.

Table 14. Summary of results for the evidence appraisal of the whole body of evidence used in addressing Question 2.3. 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	Moderate to High	
-Spatial	Moderate	
-Temporal	High	
Consistency	Moderate to High	
Quantity	High (128 studies)	
Diversity	High (44% proxy, 20% marine sediment cores, 15% monitoring, 12% observational and 9% modelling type studies)	

4.4 Indigenous engagement/participation within the body of evidence

There is no evidence of any Indigenous engagement or participation within the literature used to address this question.

4.5 Knowledge gaps

Key research gaps are identified and summarised and what the potential outcomes could be for policy/management if these research gaps were addressed in Table 15.

Table 15. Summary of knowledge gaps for Question 2.3.

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
Spatial influence/detection footprint of the increased loads in the GBR lagoon.	The production of more targeted spatial marine proxy records (i.e., informed by eReefs marine modelling) will help resolve the key spatial area of influence of the river basins of the GBR catchment area.	This would lead to a better appreciation of the area of the GBR influenced by increased catchment loads and lead to better prioritisation of basins.
The magnitude of pollutant load increases (i.e., while it is widely accepted that loads have increased, there is still some uncertainty regarding the amount of increase or	A better consolidation of catchment water quality monitoring data for use in the catchment model will help improve the pre-European arrival load estimates and allow for a more reliable	A more reliable quantification of anthropogenic loads leads to improved marine model outputs on the spatial influence/impact of anthropogenic loads which then allows more robust water quality targets as well as better targeted

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
the quantification of the 'anthropogenic load').	quantification of anthropogenic loads.	treatment strategies and methods to be derived.
A better appreciation of catchment-marine connectivity (i.e., an increase in sediment load of xx tonnes leads to yy change in sediment exposure at site zz) including improved hydrographic understanding	The production of long (200-year +) coral core records using rare earth elements will provide the evidence for spatial changes in sediment exposure at coral reef sites.	Such records will help form a stronger narrative of the catchment to reef connection and quantify the level of change in the GBR lagoon as a result of increased terrestrial runoff especially when coral core records can be linked to flood hydrology records within catchments and at the end of river.
Additional land-use time series records particularly for mining and forestry.	The further compilation of 'missing' land-use change time series in the GBR catchments such as mining and forestry records will provide a more complete insight on land-use change in the GBR catchments since European arrival.	Such records will enhance the narrative on land-use change (i.e., all key land uses will then be captured). In addition, a complete land use time series will allow greater confidence to compare catchment modifications with proxy records.
Improved knowledge of longer-term (Holocene) fluvial inputs to the GBR.	A more complete knowledge of river discharge variability over the past ~7,000 years will allow long-term climate and fluvial histories to be better understood in the GBR lagoon.	A better understanding of long-term fluvial discharge to the GBR lagoon will provide a much stronger baseline with which to put the current discharge and associated loads into perspective (i.e., Current discharge and loads over the past 100 years have been much higher compared to the previous 300 years but how do they compare to more millennial-scale variability?).

5. Evidence Statement

The synthesis of the evidence for **Question 2.3** was based on 128 studies undertaken in the Great Barrier Reef published between 1990 and 2022. The synthesis includes a *High* diversity of study types (44% proxy, 20% marine sediment cores, 15% monitoring, 12% observational and 9% modelling type studies), and has a *Moderate-High* confidence rating (based on *Moderate-High* consistency and *High* overall relevance of studies).

Summary findings relevant to policy or management action

There are multiple lines of evidence demonstrating that the loads of suspended sediment, dissolved and particulate nutrients (nitrogen and phosphorus), and pesticides have increased for most river basins of the Great Barrier Reef catchment area since the arrival of Europeans c. 1850. Evidence of increases in catchment loads comes from fluvial proxy records, coral core proxies, water quality monitoring and subcatchment and catchment-scale modelling exercises. The increases in loads have largely occurred because catchments have been modified for the major land uses of livestock grazing (73% of catchment area), irrigated and dryland cropping (2.8%), sugarcane (1.2%), horticulture and bananas (0.2%), urban development (0.7%) and mining (0.3%). These modifications, combined with climate variability, result in more frequent, larger-volume river discharge events interspersed with drought periods that reduce ground cover, which then leads to higher sediment yields during 'drought-breaking' rainfall events. The footprint of increased land-based runoff and pollutant loads within the Great Barrier Reef is most pronounced in estuarine and nearshore environments, but based on coral cores and other proxy records can be seen on the inner Great Barrier Reef shelf over 100 km alongshore from the river mouth of influence. However, proxy records derived from reefs in some parts of the inner shelf, but particularly for the middle and outer shelfs[12], are more subtle and variable in showing direct association with land-based sediments than those derived from the nearshore settings. This variability will reflect the spatial differences of exposure to land-based runoff but also the complex bio-geochemical processes that are active within flood plumes during the transport of materials over greater distances.

Supporting points

- Time series data of land use change in the Great Barrier Reef catchment area from 1860 to 2019 show extensive modification of most river basins for livestock grazing, cropping and urban developments.
- A range of fluvial proxy records - including Beryllium-10 isotopes, sediment deposition records from lakes, floodplains and river benches, water quality and observational measurements from different land uses - almost universally indicates increased sediment erosion since European arrival.
- Catchment modelling of river basin loads of fine sediment and nutrients identify substantial increases during the post-European arrival period for most Great Barrier Reef basins. Exceptions include basins that have relatively low areas of intensive land use modification, which are mainly situated within the Cape York Natural Resource Management region.
- The latest Source Catchments modelling suggests that sediment loads have more than tripled for most basins within the Burdekin, Mackay Whitsunday, Fitzroy, and Burnett Mary regions (exceptions include the Black, Proserpine, Shoalwater, and Waterpark Basins). The basins of the Cape York region have modelled load increases of 1.3-fold or less except for the Normanby Basin where projected loads have increased 5-fold. These increases are validated by multiple lines of independent evidence including a number of catchment proxy studies, land use-focused water quality monitoring data and coral core proxy data.
- Based on the latest Source Catchments modelling, dissolved inorganic nitrogen loads from basins with intensive cropping, such as sugarcane areas in the Wet Tropics region, have

[12]In terms of bathymetry, which is linked to sediment characteristics, the Great Barrier Reef is defined as inner shelf (up to 20 metres depth), middle shelf (20 to 40 metres depth) and outer shelf (more than 40 metres depth).

increased by 1.5 to 3-fold from pre-development loads. Evidence of these increases is supported by land use-focused water quality monitoring data.

- Luminescent lines in corals (proxy for river discharge) from various locations on the Great Barrier Reef show a marked increase in the frequency and size of river discharge events from the 1850s, and again from the 1950s, when compared to a long-term background dataset extending over the past 400 years. This increase is correlated with changes in the frequency and intensity of El Niño Southern Oscillation (ENSO) events and the behaviour of the Indo-Australian monsoon across northern Australia, as well as from increased runoff likely due to widespread land clearing (and resulting catchment hardening).
- Chemical elements incorporated within coral cores highlight increased land-based runoff (i.e., freshwater discharge and sediment) at a multitude of inshore sites within the Great Barrier Reef following the arrival of Europeans. Evidence of increased nitrogen loads using coral core proxies is less conclusive.
- New coral proxies to help reconstruct changes in sediment and nutrient exposure, including rare earth elements and nitrogen isotopes respectively, are under development for application in the Great Barrier Reef.

6. References

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

Body of Evidence

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Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 2.3

Themes 1 and 2: Values, condition and drivers of health of the Great Barrier Reef

Question 2.3 What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Stephen Lewis	James Cook University	Land-use change, water quality, coral core records	Lead Author	All Sections
2. Zoe Bainbridge	James Cook University	Land-use change, water quality	Contributor, consistency checker of data extractions, review and editing	All Sections
3. Scott Smithers	James Cook University	Water quality, fluvial and marine records	Contributor, review and editing	All Sections