2022 Scientific Consensus Statement

Question 3.2 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?

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Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

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

What is the Scientific Consensus Statement?

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

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

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

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

Method used to address the 2022 SCS Questions

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

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

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 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

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

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

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

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

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

Guidance for using the synthesis of evidence

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

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

   - ***Search Results:*** Contains details about the number of evidence items identified, sources, screening and the final number of evidence items used in the synthesis of evidence.
   - ***Key Findings:*** The **main body of the synthesis**. It includes a summary of the study characteristics (e.g., how many, when, where, how), a deep dive into the body of evidence covering key findings, trends or patterns, consistency of findings among studies, uncertainties and limitations of the evidence, significance of the findings to policy, practice and research, knowledge gaps, Indigenous engagement, conclusions and the evidence appraisal.
3. **Evidence Statement:** Provides a succinct, high-level overview of the main findings for the question with supporting points. The Evidence Statement for each Question was provided as input to the 2022 Scientific Consensus Statement Summary and Conclusions.

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

Peer Review and Quality Assurance

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

Contents

Acknowledgements

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Executive Summary

Question

Question 3.2 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?

Background

This question reviews the impacts of increased sediments from both terrigenous sources and dredging on Great Barrier Reef (GBR) ecosystems. These ecosystems are found in marine and coastal environments and include coral, sponge, macroalgae, seagrass, plankton, fish as well as the freshwater aquatic habitats of the GBR catchments.

The review focuses on the influence of fine sediment and total suspended solids (TSS) because they are the main concern in the GBR; however, all sediment is considered. This includes terrigenous sediments and sediments from dredging. Size fractions and the composition are not always differentiated or comparable between studies. This review also focused on particulate nutrients because terrestrially-derived sediments may be organic rich. Furthermore, the effects of particulates may not always be discernible from other water quality impacts and so the review also considered more general concepts including water quality, discharge and floods.

Multiple lines of evidence are needed to answer the primary question. The first line of evidence is that river loads of particulates have increased due to human activities (Question 2.3, Lewis et al., this SCS). It is well accepted that the loads of sediments exported to the GBR lagoon have increased in most basins over the last 170 years, particularly compared to the previous 400 years. However, their influence on ecosystems are superimposed over a gradient of natural variability. The second line of evidence is that years with greater sediment loads are associated with prolonged and worse turbidity (Question 3.1, Lewis et al., this SCS). The third line of evidence is based on the literature summarised in this review on biological responses to higher levels of particulates and the mechanisms through which they act.

This review summarises the evidence that connects ecosystem impacts to changes in particulates including short-term (pulsed/seasonal) and persistent impacts.

Where possible, based on the available evidence, this question was examined in three parts:

- What are the measured impacts (and indicators) of increased sediments and particulate nutrients?
- What are the mechanisms for those impacts?
- Where is there evidence of this occurring in the GBR?

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[5]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Review method was used.

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

- A conceptual model was developed from the authors' broad understanding of the question and from a selection of review papers. There were many individual or potential impacts for the range of ecosystems and the search was constrained to high-level summaries of these impacts and pathways to yield a manageable number of studies to review. These were: impact, degradation, threat, effect, water quality, light, irradiance, turbidity, pressure.
- Search locations included Scopus, Web of Science and Google Scholar.
- The main source of evidence was from studies derived within the GBR although a few studies from outside of the GBR were included.
- An initial screening was conducted based on a review of the titles and abstracts to determine their potential eligibility to answer the question based on a list of exclusion criteria. This resulted in 460 references from all academic databases and search engines after initial screening. These were further screened by reading the papers in full. Eligible papers known to the authors were also manually added if they were not found through the search. This resulted in the inclusion of 196 references in the synthesis.
- Information was extracted from each of the selected papers using a data extraction spreadsheet template with some additional options added specifically for this question. This included information that would enable the relevance (including spatial and temporal), consistency, quantity, diversity and reliability of the studies to be assessed.
- The narrative synthesis was written following this document template.

Method limitations and caveats to using this Evidence Review

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

- Only studies written in English were included.
- Only two academic databases were searched.
- Predominantly only GBR derived studies were included.
- Only studies published during or after 1990 were included.

Key Findings

Summary of evidence to 2022

Of all of the GBR ecosystems considered, the number of studies on coral reef habitats (coral, non-coral invertebrates, algae) was higher than for other ecosystems (142 on reefs, 91 on coral specifically), with a high diversity of study types (observational, experimental, modelling and review), and numerous that were of high relevance to the question leading to a Moderate to High level of consistency in the findings. The key findings included:

- Suspended sediments and particulate nutrients attenuate light, settle on and smother corals and other reef organisms and increase nutrient supply.
- Increased loads of sediment and particulate nutrients to inshore habitats have persistent impacts on reef composition, leading to greatly compressed depth zonations, reduced depth limit for reef development, lower coral diversity and suppression of many other sensitive species in favour of macroalgae.
- High abundance of healthy persistent coral species can be found in 1-3 m water depth in some turbid inshore settings with favourable hydrodynamics.
- Deeper down, low light levels can cause sublethal stress and partial mortality of corals after only short exposure (days to weeks). Here, communities are typically dominated by turbidity-tolerant species with high levels of heterotrophy and filter feeders, rather than phototrophic taxa.
- Sediments and particulate nutrients are suppressing reef recovery following disturbances due to their strong negative effects on the early life stages of corals and coral recruitment.

- For sponges, short-term exposure to high levels of suspended sediment affect growth, while long-term exposure reduces their abundance possibly limiting recruitment.
- Many other sensitive calcifying species such as crustose coralline algae and large benthic photosynthetic foraminifera are also negatively affected by suspended particulates and water quality through a variety of mechanisms.

Seagrass had a Moderate number of studies (45), only one that was highly relevant, and the majority were of Low to Moderate relevance to the study question because they were not specifically on particulates nor included a direct measure of particulates (many were about light). The key findings included:

- The distribution, abundance and composition of seagrass species are impacted by particulate loads and change in light availability.
- There is evidence of these impacts in the inshore areas of all Natural Resource Management (NRM) regions at different times, although to a lesser degree in Cape York.
- Seagrass meadows are dynamic and will often recover, with recovery rates depending on the extent of decline and the local and regional conditions that follow. Protracted recovery has been observed in several locations.
- Research on the mechanisms driving loss have focused on reductions in light caused by suspended particulate matter, and much less is known about the processes influencing recovery.

Fish studies were predominantly experimental and focused on damselfishes, with only one observational study and five reviews. The key findings included:

- Suspended sediments can affect the growth and time to metamorphosis of juvenile fish, juvenile gill morphology, foraging time, body condition and mortality.
- Suspended sediments can also interfere with visual cues for juvenile fish to settle into habitat, distinguish between live and dead coral, and settlement time.
- Herbivorous fish communities are strongly shaped by water clarity, with flow-on effects on algal communities.
- Settled sediment directly or indirectly affects herbivorous grazing by altering algal substrate palatability.

Most of the evidence on freshwater systems is compiled from Australian and global sources. The limited information available indicates that aquatic organisms are generally able to tolerate short-term exposure to elevated sediments in pulsed runoff. Chronic turbidity has an impact on streams that are naturally clear but is less likely to affect rivers that permanently have low photic depths. This review highlights a critical knowledge gap on the effects of sediment and particulate nutrients on freshwater wetlands and estuarine wetlands such as mangroves, marshes and supratidal forests in the GBR.

Recent findings 2016-2022

There were 94 new studies since the previous 2017 SCS and there have been considerable advancements in several key areas:

- Fourteen new studies from the GBR addressed dredging-relevant influences of sediments, particulate nutrients and light reduction on corals, particularly on coral recruitment, and six on sponges.
- There were nineteen new seagrass studies covering a range of topics including light thresholds, water quality and sediment loads, burial, reviews, data synthesis and modelling.
- There were several new studies that used data from maturing long-term monitoring programs and those that applied eReefs or other advanced modelling.

Significance for policy, practice, and research

The review, combined with evidence from related questions, identified strong and consistent evidence that increased levels of suspended sediment and particulate nutrients impact the diversity and resilience of GBR ecosystems. Multiple lines of evidence are needed to address this question. The first line of evidence is that river loads of particulates have increased due to human activities (Question 2.3 Lewis et al., this SCS). The second line of evidence is that years with greater sediment loads are associated with prolonged and worse turbidity (Question 3.1 Lewis et al., this SCS), which affects ecosystems through multiple pathways. The third line of evidence is based on the biological responses to higher levels of particulates that show that as they increase, ecosystem state declines. Reductions in loads could therefore improve the extent, abundance, diversity and health of GBR ecosystems, and their recovery rate from climate-related disturbances.

Some key messages include:

- The strength of evidence is influenced by dose-response relationships, effect size, logical time sequences of change, specificity of the responses of indicators to stressors, and strong agreement between study types.
- This review also supports the precautionary principle to reduce sediment and particulate nutrients as a management action.
- The composition of particulates, including grain size, sedimentology and particulate nutrient content has a large influence on the ecological response, and more information on the distribution, concentration and composition of sediments in freshwater and marine ecosystems will improve our understanding of risk.
- Sedimentation on reefs and changes to sediment substrate (e.g., seagrass sediments) affects recovery and resilience.
- There is a need to understand ecological processes (e.g., fish symbiosis with reef habitat), resilience and recovery, and functional traits of organisms, to improve risk assessments and management outcomes.

Key uncertainties and/or limitations

There are many limitations and uncertainties. These include:

- This review is not about the measured impacts of the increase in loads above the background baseline per se because research methods do not enable that to be addressed in any one study for several reasons as described throughout.
- Quantitative synthesis including thresholds of response for the indicators was beyond the scope of this question brief but could also add further insight by summarising ecosystem and species responses over a range of sediment concentrations. This would also enable graphical data presentations e.g., summarising the response of various coral recruitment stages to a range of sediment concentrations.
- There are a number of pertinent elements of this question that are the focus of other SCS questions and so have been excluded from the studies and narrative here. The most relevant questions include:
  - Q2.3 What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef? (Lewis et al.)
  - Q2.4 How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems? (Uthicke et al.)
  - Q3.1 What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef? (Lewis et al.)
  - 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? (Prosser and Wilkinson)
  - Q4.1 What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef? (Robson et al.)
  - 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? (Diaz-Pulido et al.)
- GBR ecosystems are diverse and complex. There is very little relevant information or long-term monitoring data to inform this question on freshwater and estuarine systems, mangroves, inter-reef habitats, crustose coralline algae (CCA) and fauna that are dependent on these habitats (e.g., dugong, turtle, most fish).
- There is a lack of long-term information on the concentrations and properties of suspended and settled sediments and particulate nutrients in most ecosystems except at some inshore reef sites.
- Data on nutrient dynamics and the role and influence of these on how particulate nutrients affect GBR ecosystems are especially lacking.
- This question has focused on sediments and particulate nutrients, but the effect of these is influenced by local conditions and cumulative impacts.
- The level and ranges of sediments and particulate nutrients in experiments needs to be placed in context of the levels and ranges occurring in ecosystems, so that the responses observed can be placed into a realistic context. A number of studies do this for the site where the organisms are collected, but compiling that information at the GBR scale and presenting that for all ecosystems was beyond the scope of this review. In the absence of this summary data, this review has also not focused on presenting thresholds. This is recommended as a future priority.
- There are important contextual variables needed to understand the impacts of particulates and these include: mineralogy and organic content, dissolved nutrients and other water quality variables, climate change, chronic and acute exposure, season/timing/duration/frequency, trajectories/thresholds/tipping points/feedbacks, region/year, depth, ecological interactions including herbivory.

Evidence appraisal

The overall relevance of the body of evidence to the question was Moderate (6.0). The relevance was Moderate (2.3) for relevance of the study approach, spatial (1.8) and temporal relevance (1.6). Some studies that ranked the highest specifically address and are designed to answer questions on the impacts of sediments (suspended or settled) or particulate nutrients on ecosystems, and further address either mechanisms or the locations for where there is evidence. Low ranked studies were included because they provide some insight into the effects of particulates on ecosystems, or on variability of indicators but it was not the focus of the study. The spatial relevance of studies was Moderate (1.8). The highest ranked studies were based on GBR-wide datasets, often based on the monitoring programs including the Long-Term Monitoring Program (LTMP) or Marine Monitoring Program (MMP), or other broad-scale surveys and included sites in several regions. Low ranked studies were conducted at just one site or cannot be extrapolated from the site because analysis indicated site level factors were important. Temporal relevance was Moderate and it was ranked lower than spatial generalisability with several studies falling into the low category. High ranked studies used a long-term data set (MMP or LTMP), back-dating techniques spanning decades or centuries, or was a study over multiple years and included a range of different conditions especially discharge events. Low ranked studies were measured at a single time or under specific environmental conditions that limit how it can be extrapolated (e.g., during a dry period).

GBR ecosystems have always been and clearly continue to be impacted by suspended sediments, particulate nutrients and associated water quality properties. The Consistency of this finding is High and was demonstrated through many observational and experimental studies; however, it is important to note that contextual information is needed to understand which ecosystems and indicators are impacted at any point in time, and the mechanisms driving responses. The Quantity of studies used for the synthesis was ranked Low to Moderate and depended on the ecosystem. There was no information found for some ecosystems, especially freshwater habitats. Based on this, the overall measure of Confidence of the evidence used in this review is Moderate.

1. Background

Sediments are deleterious for ecosystems of the Great Barrier Reef (GBR) at excessive levels as outlined in several previous reviews (Bainbridge et al., 2018; Brodie et al., 2017b; Haynes et al., 2007; Hutchings et al., 2019; Jones et al., 2016; Kroon et al., 2014; Schaffelke et al., 2005; Waycott et al., 2005). Terrestrially derived sediments may be organic rich (Bainbridge et al., 2018) and so this review examines the effects of both sediments and particulate nutrients. In response to growing recognition of the risk to the GBR from pollutant loads, joint Australian and Queensland government policy was developed in 2003 to provide guidance for improving the quality of water entering the GBR (Reef 2050 Water Quality Improvement Plan). Targets for reducing anthropogenic loads of sediments and particulate nutrients provide the end-of-catchment load reductions needed to meet marine water quality guidelines and improve the health of the GBR (Brodie et al., 2017a).

This review is about the impacts of increased sediment and particulate nutrients on ecosystems and addresses this through multiple lines of evidence presented in linked questions. The first line of evidence is that models have been used to show that river loads have increased due to human activities (Question 2.3, Lewis et al., this Scientific Consensus Statement (SCS)). Quantifying loads and fate of particulates and attributing them to a particular source is complicated because of the large spatial scale of the GBR, the range of transformations that occur during transport and in the marine environment and the number of additional disturbances that affect ecological condition (Bainbridge et al., 2018; Bartley et al., 2014; Fabricius & De'ath, 2004). Particulates were delivered to the GBR prior to catchment modification after European arrival and seagrass and reefs have grown in the turbid inshore for millennia as persistent marginal reefs (Johnson et al., 2017; Perry & Larcombe, 2003; Risk, 2014). This has prompted some debate over whether human activities have increased loads of particulates to levels that are detrimental for reef ecosystems and some alternative perspectives on the effects of agricultural runoff on inshore water quality and ecosystems were put forward by Larcombe and Ridd (2018), but these were rebutted by a consortium of scientists (Schaffelke et al., 2018). This topic is addressed further in Question 3.1 (Lewis et al., this SCS). The highest terrigenous sediment (i.e., sediment originally eroded from the land) flux to the continental shelf occurred during sea level rise between approximately 16 and 8 thousand years ago (Question 3.1 Lewis et al., this SCS). Question 2.3 (Lewis et al., this SCS) addresses the evidence for changes in land-based runoff following European development. The conclusions are that it is well accepted that the loads of sediments exported to the GBR lagoon have increased in most basins since the arrival of Europeans, particularly compared to the previous 400 years. The 'detection footprint' of changes in pollutant exposure in the GBR lagoon is most pronounced just offshore from river mouths. But the spatial extent effect of the increased loads is difficult to define, and the spatial distributions of impacts are thus challenging to directly assess while further offshore the proxies that measure such changes show variable results. Question 3.1 (Lewis et al., this SCS) on the spatial and temporal distributions of terrigenous sediments further concludes that river discharge and associated loads significantly influence turbidity and photic depth regimes along areas of the inner and middle shelfs of the GBR lagoon.

The second line of evidence is that satellite imagery has been used to show that years with greater sediment loads are associated with prolonged and worse turbidity (Question 2.3, Lewis et al., this SCS). Photic depth is the depth that biologically-relevant light penetrates through the water column so when it is more turbid, photic depth is reduced. Photic depth progressively declines when river flows start and then recovers when river flows subside (Question 3.1, Lewis et al., this SCS).

The third line of evidence is the biological responses to increased levels of sediment and this evidence stems from a range of sources described in this review. Conceptual models (Haynes et al., 2007), the use of an epidemiological matrix (Fabricius & De'ath, 2004), several chain of evidence studies (Hairsine, 2017) and previous Scientific Consensus Statements and risk assessments (Waterhouse et al., 2017) provide the evidence to attribute cause (increasing loads) to effects (declines in ecological condition). Furthermore, global analyses and reviews demonstrate that the concern over increasing particulate loads on marine ecosystems is widespread (Jones et al., 2016; Kroon et al., 2014; Turschwell et al., 2021). The Inshore GBR Marine Monitoring Program (MMP) and the Australian Institute of Marine Science (AIMS) Long-Term Monitoring Program (LTMP) provide essential long-term data on water quality, reefs and seagrass and the datasets are growing and now span a range of riverine discharges including well below and above the long-term median in combination with other disturbances. This review is an update on the growing body of evidence that increased sediments and particulate nutrients are detrimental for organisms of the GBR, but also examines the mechanisms of impact and where the impacts are occurring.

This review also covers freshwater and estuarine ecosystems, which are ecologically significant habitats. They also affect the fate and transport of sediments and nutrients to the reef (Adame et al., 2021). Despite this, there is no long-term monitoring in GBR freshwater habitats and an alarming lack of research into the effects of particulates on freshwater and estuarine ecosystems.

The question is addressed descriptively in the Narrative Synthesis and follows a Rapid Review process. Information was extracted into a data extraction template that forms the basis of this review. A detailed quantitative update of ecologically significant thresholds (e.g., of sensitive life history stages, comparison amongst species/functional groups) for comparison to water guidelines is feasible and necessary but was beyond the scope of this review.

1.1 Question

Primary question	**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?

This question is interpreted as reviewing and describing the impacts of increased sediments from both terrigenous sources and dredging on ecosystems. Sediment loads have increased in most basins over the last 170 years contributing to increases in nearshore turbidity (see Question 2.3, Lewis et al., this SCS) but this is superimposed over a gradient of natural variability.

The ecosystems include marine and coastal ecosystems of the Great Barrier Reef World Heritage Area (GBRWHA) including coral reefs, seagrass, mangroves, plankton and other benthic communities, and the wetlands and streams of GBR catchments. Where possible, this has extended to the animals that are dependent on these habitats, such as fish, dugongs and turtles. The search was not constrained by any particular type of ecosystem.

In many cases the evidence items were in relation to ecosystem impacts from general water quality decline or periods of elevated discharge, and ascribing impacts to sediment and particulate nutrient loads individually was not possible in all cases.

Where possible, based on the available evidence, this question was examined in three parts:

- What are the measured impacts (and indicators) of increased sediments and particulate nutrients?
- What are the mechanisms for those impacts?
- Where is there evidence of this occurring in the GBR?

The review focused on literature published from 1990 onwards and was largely restricted to studies derived within the GBR.

1.2 Conceptual diagram

The following conceptual model (Figure 1) was developed based on previous reviews (Bainbridge et al., 2018; Bartley et al., 2014; Brodie et al., 2012; Haynes et al., 2007; Kroon et al., 2014) prior to the searches being conducted. The conceptual models (Figure 1, Figure 2) were initially used to develop the search criteria including the ecosystem components, indicators and processes in addition to the core question elements on sediments and particulate nutrients. This yielded over 5,000 studies and many of them were not relevant to the primary study question. Therefore, the search was simplified to overarching terms that substitute for the indicator responses and focuses on the effect (e.g., ‘impacts’) as described below. The detailed model has been retained to show how the ecosystem components interact and where this question fits in relation to Question 3.1 *What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef?* (Lewis et al., this SCS) and Question 4.2 *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?* (Diaz-Pulido et al., this SCS). This model was not updated based on the findings but was developed for the purpose of defining the search, according to the SCS methodology.

1.3 Links to other questions

This synthesis of evidence addresses one of 30 questions that are being addressed as part of the 2022 SCS. The questions are organised into eight themes: values and threats, sediments and particulate nutrients, dissolved nutrients, pesticides, other pollutants, human dimensions, and future directions, that cover topics ranging from ecological processes, delivery and source, through to management options. As a result, many questions are closely linked, and the evidence presented may be directly relevant to parts of other questions. The relevant linkages for this question are identified in the text where applicable. The primary question linkages for this question are listed below.

Links to other related questions	**Q2.3** What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef? **Q3.1** What are the spatial and temporal distributions of terrigenous sediments 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?

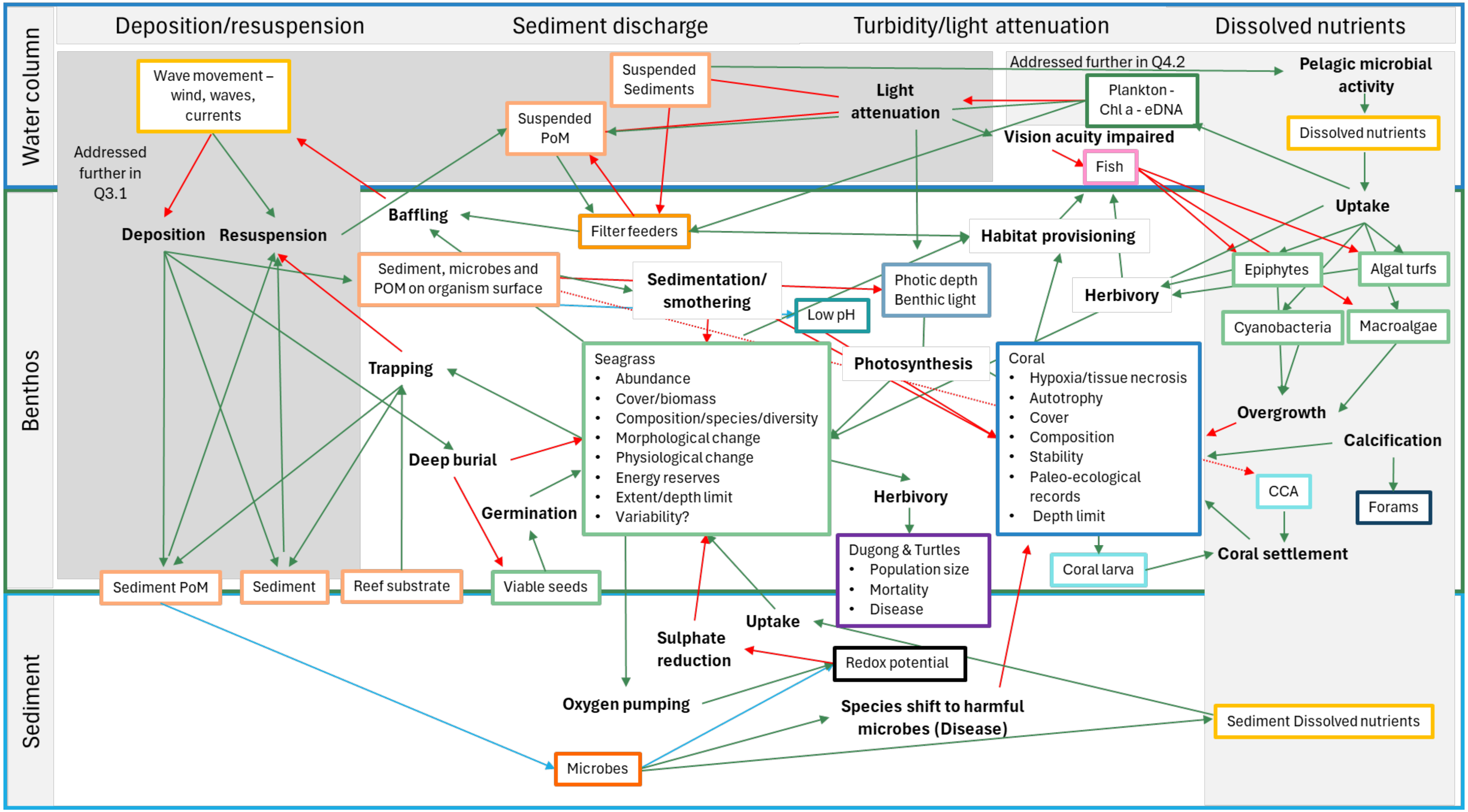
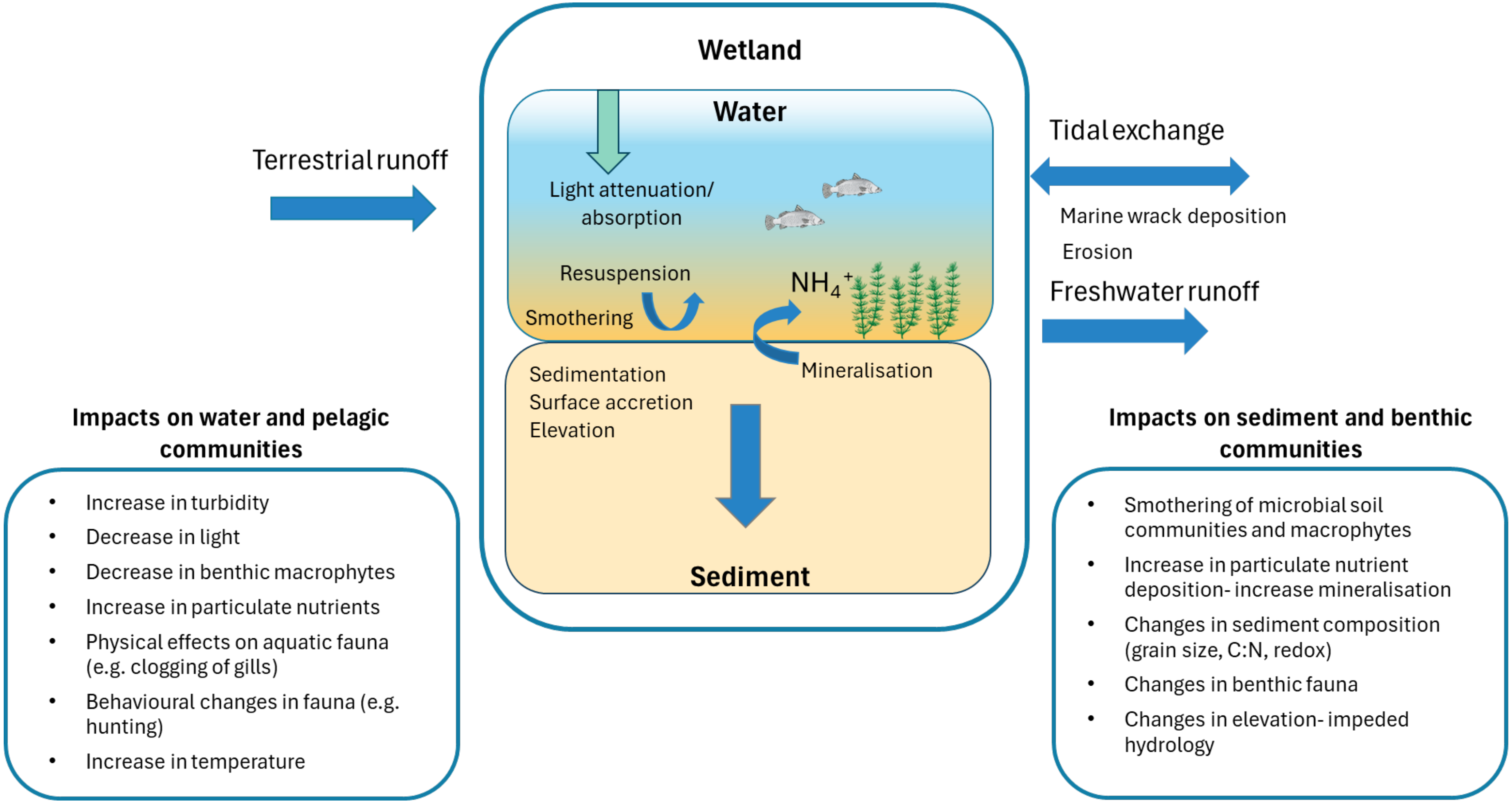


Figure 1. Marine processes conceptual model used to define the search terms for Question 3.2. Boxed items are ecosystem elements. Bold type are processes. Positive influence = green, negative influence = red, neither = blue.



Impacts on water and pelagic communities

- Increase in turbidity
- Decrease in light
- Decrease in benthic macrophytes
- Increase in particulate nutrients
- Physical effects on aquatic fauna (e.g. clogging of gills)
- Behavioural changes in fauna (e.g. hunting)
- Increase in temperature

Impacts on sediment and benthic communities

- Smothering of microbial soil communities and macrophytes
- Increase in particulate nutrient deposition- increase mineralisation
- Changes in sediment composition (grain size, C:N, redox)
- Changes in benthic fauna
- Changes in elevation- impeded hydrology

Figure 2. Wetlands processes model for Question 3.2.

2. Method

A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid Reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[6]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Review method was used.

2.1 Primary question elements and description

The primary question is: ***What are the measured impacts of increased sediment and particulate nutrient loads on GBR ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the GBR?***

S/PICO frameworks (Subject/Population, Exposure/Intervention, Comparator, Outcome) can be used to break down the different elements of a question and help to define and refine the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods[7] but other variations are also available.

- **Subject/Population:** Who or what is being studied or what is the problem?
- **Intervention/exposure:** Proposed management regime, policy, action or the environmental variable to which the subject populations are exposed.
- **Comparator**: What is the intervention/exposure compared to (e.g., other interventions, no intervention, etc.)? This could also include a time comparator as in 'before or after' treatment or exposure. If no comparison was applicable, this component did not need to be addressed.
- **Outcome:** What are the outcomes relevant to the question resulting from the intervention or exposure?

Table 1. Description of question elements for Question 3.2.

Question S/PICO elements	Question term	Description
Subject/ Population	Sediment loads	Focus on the influence of fine sediment, also referred to as total suspended solids (TSS) because they are the main concern in the GBR; however, all sediment will be covered. This includes terrigenous sediments and sediments from dredging. Size fractions may not always be differentiated. The influence of sediments may not always be discernible from other water quality impacts and so the review will also consider more general concepts including water quality, discharge, runoff, flood, and extreme events. The spatial and temporal distributions of terrigenous sediments is covered in Question 3.1 (Lewis et al., this SCS).
	Particulate nutrient loads	Focus on particulate nutrients because anthropogenically derived sediments may be organic rich. Particulate nutrients

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

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

Question S/PICO elements	Question term	Description
		are included where a direct link between particulate nutrients and ecosystem health is made. Particulate nutrients can also be internally generated (plankton, marine snow etc.). Particulate nutrients will also influence dissolved inorganic nutrients and vice versa and so dissolved nutrients are important for understanding the mechanisms of impacts and are included in the conceptual model for context. Ecosystem impacts of dissolved nutrients are covered in greater detail in Question 4.2 (Diaz-Pulido et al., this SCS) and the spatial and temporal distribution of nutrients are covered in Question 4.1 (Robson et al., this SCS).
	GBR ecosystems	See list of definitions
Intervention, exposure & qualifiers	Wetlands	Natural and near-natural wetlands, palustrine, lacustrine, estuarine and riverine habitats of GBR catchments. Constructed and artificial wetlands will not be included.
	Water quality	The effects of sediment loads (terrigenous and dredging) and associated water quality indicators including turbidity, suspended sediments, light. Focus on particulate nutrients. Dissolved inorganic nutrients are not the focus, but their influence may be difficult to distinguish or exclude.
	Coastal habitats	Coastal habitats including saltmarsh, mangrove and seagrass.
	Marine ecosystems	Reef ecosystems including reefs, coral, plankton, microbes, fish, dugong, turtle. The influence of sediment and particulate nutrients on ecosystem services such as the interactions between habitats and dependant species will be included.
	Mechanisms for impacts	Mechanisms involved in how sediments and particulate matter affect GBR ecosystems. These mechanisms may include a series of linked processes and feedbacks.
Comparator	N/A	
Outcome & outcome qualifiers	Impacts	Adverse changes in the condition, extent or function of habitats and their dependant species.
	Health and resilience of GBR ecosystems	Indicators of ecosystem health in relation to anthropogenic sources (terrigenous and dredging) where they can be differentiated.
	Indicators of increased loads	Indicators of changes in sediment and particulate nutrient loads will be included where they are observed in GBR ecosystems (e.g., paleo-ecological records) even if there is no discernible impact to health and resilience.

Question S/PICO elements	Question term	Description
	Variability	Spatial and temporal variability in the condition of GBR ecosystems particularly in relation to anthropogenic sources (terrigenous and dredging) where they can be differentiated. Paleo-ecological records will be included in the review. This does not include change over geological timescales or change due to climate change, which are addressed in other questions (Questions 2.2, Fabricius et al., and 2.3, Lewis et al., this SCS).
	Spatial distribution	Includes all areas of the GBRWHA, including catchments and marine areas (all waterbodies), and ports. Inshore areas of the GBR are more likely to be affected and to be the focus in the literature.

Table 2. Definitions for terms used in Question 3.2.

Definitions	
Increased	Anthropogenically-derived increases in sediments and particulate nutrients from terrigenous sources and dredging. This excludes natural variability though it may be difficult to differentiate in some cases.
Sediment loads	Mineral sediment added to GBR ecosystems through runoff and dredging. Of greatest concern to GBR ecosystems are fine sediments or total suspended solids (TSS), which are the fraction <20 µm, but all sediment sources are considered.
Particulate nutrients	Nutrients (nitrogen or phosphorus) that are in a particulate form as particulate organic matter (POM) sourced from terrigenous or marine (e.g., plankton) sources. POM can be defined as those organic carbon molecules that are retained on a filter with a pore size between 0.1 µm and 0.8 µm. Light POM is the remains of plants, animals and microbes and heavy particulate matter (POM) is attached to mineral particles. Particulate nitrogen may also be adsorbed to the surface of sediments as particulate inorganic nitrogen and be readily bioavailable and particulate inorganic phosphorus may also be present in mineral forms but are not particularly bioavailable.
GBR ecosystems	Marine (coral, seagrass, pelagic, benthic + plankton communities), estuarine (estuaries, mangroves, saltmarsh), freshwater (freshwater wetlands – see specific wetland types below, floodplain wetlands).
Mechanisms	Processes governing how interacting parts of the ecosystem are affected by sediments and particulate nutrients.
Health	An ecological system is healthy and free from distress syndrome if it is stable and sustainable, i.e., if it is active and maintains its organisation and autonomy over time, and is resilient to stress (Costanza, 1992)[8].
Water quality	The physical, chemical and biological characteristics of water and the measure of its condition relative to the requirements for one or more biotic species and/or to any human need or purpose.

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[8] Costanza R (1992) Ecosystem Health: New goals for environmental management. Costanza, R., Norton, B.G. and Haskell, B.D. (eds), Island Press.

2.2 Search and eligibility

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

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

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

a) Search locations

Searches were performed on the following databases:

- Scopus
- Web of Science and
- Google Scholar

b) Search terms

Table 3 shows a list of the search terms used to conduct the online searches. An initial and detailed trial of the searches was conducted based on the conceptual models, and listed the same subjects, but specified the ecosystems (e.g., wetlands, microbes, coral) and included a range of outcomes listed as processes and indicators (e.g., settlement, herbivory, connectivity). This yielded thousands of references. These were screened, and many were not relevant to the primary question on impacts. As such the outcomes were expressed as broader synonyms for ‘impact’ and water quality variables. The same search was used for Web of Science and Scopus, but adapted slightly for Google Scholar to add ’Northern Australia’ to try and identify more wetlands papers, and to add the additional outcome of ‘turbidity’.

Table 3. Search terms for S/PICO elements of Question 3.2.

Question element	Search terms
Subject/Population	Total suspended sediment, fine sediment, particulate nutrients, particulate organic matter, organic, particulates, POM
Exposure or Intervention	Increased, anthropogenic, gradients, spatial, loads
Comparator	N/A
Outcome	Impact, degradation, threat, effect, water quality, light, irradiance, turbidity, pressure
Other outcomes from conceptual model (not included in final search)	Smothering, burial, light, light attenuation, photic depth, Kd, irradiance, chlorophyll, anoxia, anoxic, habitat, recruitment, trapping, cover, biomass, density, abundance, composition, species, diversity, recruitment, settlement, morphology, physiology, paleo-ecological, eDNA, cores, herbivory, pH, disease, redox, larvae, seeds, connectivity

c) Search strings

Table 4. Search strings used for electronic searches for Question 3.2.

Search strings
Web of Science TS= (("total suspended sediment" OR "fine sediment" OR sediment OR "particulate nutrient*" OR "particulate organic matter" OR pom) AND ("Great Barrier Reef" OR gbr OR queensland OR "northern Australia") AND (impact OR degradation OR threat OR effect OR "increased sediment" OR "excess sediment" OR "water quality" OR light OR irradiance))
Scopus TITLE-ABS-KEY(("total suspended sediment" OR "fine sediment" OR sediment OR "particulate nutrient*" OR "particulate organic matter" OR pom) AND ("Great Barrier Reef" OR gbr OR queensland OR "northern Australia") AND (impact OR degradation OR threat OR effect OR "increased sediment" OR "excess sediment" OR "water quality" OR light OR irradiance))
Google Scholar (Publish or Perish) "total suspended sediment" |sediment* | "particulate nutrient*" | particulate* |pom "Great Barrier Reef"|gbr| "northern Australia" impact | degradation | threat | effect | "water quality"|light | irradiance|turbidity|pressure

d) Inclusion and exclusion criteria

Table 5. Inclusion and exclusion criteria for Question 3.2 applied to the search returns. [Numbers correspond to the ranked exclusion criteria used in the Data Extraction & Appraisal Spreadsheet during second screening].

Question element	Inclusion	Exclusion
Subject/Population	Total suspended sediment, fine sediment, particulate nutrients, particulate organic matter, POM, water quality, loads, run-off, discharge.	1. Methods papers on how to quantify loads. 3. Topics covered under Question 3.1 on the spatial and temporal distributions of terrigenous sediments and associated indicators within the GBR. 4. Papers on biophysical drivers of sediment and particulate nutrient loss covered in Questions 3.4 or 3.5. 5. Metals and other pollutants. 15. Studies that include sediment, particulates or other indicators such as light, but do not help to inform the primary question on 'impacts of increased loads'. 17. Geomorphological studies unrelated to understanding anthropogenic loads (e.g., shelf geology). 18. Social studies (e.g., practice change), tourism studies (e.g., refer to water quality from an aesthetic perspective). 21. Papers related to Question 4.1 on the spatial and temporal distribution of nutrients and associated indicators within the GBR.

Question element	Inclusion	Exclusion
		22. Papers more related to Question 2.4 on how water quality and climate change interact to influence the health and resilience of GBR ecosystems. Unless there is unique insight to be gleaned about sediments or particulate nutrients as individual (or combined) factors.
Comparator	N/A	
Outcome	Impact, degradation, threat, effect, "water quality", light, irradiance, turbidity, pressure	2. Methods papers on water quality and indicators. 6. Studies on impacts of salinity where they are distinct from loads of sediment or particulate nutrients. 7. Studies on GBR ecosystems that are not on water quality but may mention nutrients (e.g., plant/animal physiology) or sediments in other contexts (e.g., biological sediment production). 8. Studies that are not on water quality but mention sediment type, water quality, light etc. as descriptors of the study site or experimental set-up only. 9.Topics covered under Question 4.2 on the measured impacts of (dissolved) nutrients on GBR ecosystems. 10. Constructed wetlands (including rehabilitated mines). 11. Papers on the efficacy of wetlands including natural and near-natural wetlands in improving water quality. 12. Studies on terrestrial systems and agriculture including studies on water management (e.g., irrigation). 13. Regions outside of the GBR (unless it addresses a key gap in understanding on mechanisms that are relevant to the GBR). 14. Papers on the spatial and temporal distribution of pesticides across GBR ecosystems and the potential or observed ecological impacts to these ecosystems (covered in Question 5.1). 16. Geological timescales (i.e., longer than what is needed to understand anthropogenic influence). 19. Reviews that are superseded and/or were used for the conceptual model. 20. Papers that are to assist with management prioritisation.
Language	English	
Study type	Observational, Experimental, Modelling, Reviews (recent)	Studies published before 1990.

3. Search Results

A total of 1,796 studies (1,527 from Web of Science plus 148 new in Scopus and 159 in Google Scholar (first 500 checked) were identified through online searches for peer reviewed and published literature, and 414 were retained after initial screening. 46 studies were identified manually through expert contact and personal collection, which represented 10% of the total evidence considered. Following screening, 196 studies were eligible for inclusion in the synthesis of evidence (Table 6). This is also summarised in Figure 3.

Table 6. Search results table separated by A) Academic databases, B) Search engines (i.e., Google Scholar) and C) Manual searches.

Date (d/m/y)	Search strings	Sources	
A) Academic databases		Web of Science	Scopus
25/01/2023 *27/01/2023*	*TS= ((“total suspended sediment” OR “fine sediment” OR sediment OR “particulate nutrient*” OR “particulate organic matter” OR pom) AND (“Great Barrier Reef” OR gbr OR queensland OR “northern Australia”) AND (impact OR degradation OR threat OR effect OR “increased sediment” OR “excess sediment” OR “water quality” OR light OR irradiance))*	*309 of 1,527*	*148 (110) of 1,091, (38 new)*
B) Search engines (Google Scholar)			
27/01/2023	*total suspended sediment |sediment* | “particulate nutrient*” | particulate* |pom “Great Barrier Reef”|gbr| “northern Australia” impact | degradation | threat | effect | “water quality”|light | irradiance|turbidity|pressure*	*159 of first 500 (67 new)*	
	Total items online searches	***414 retained after initial screening (i.e., 90 %)***	
C) Manual search			
Date	Source	Number of items added	
	Search of key authors Google Scholar, author’s database, citations in papers found in searches	*46*	
	Total items manual searches	***46 (10 %)***	
	Total searches	460	

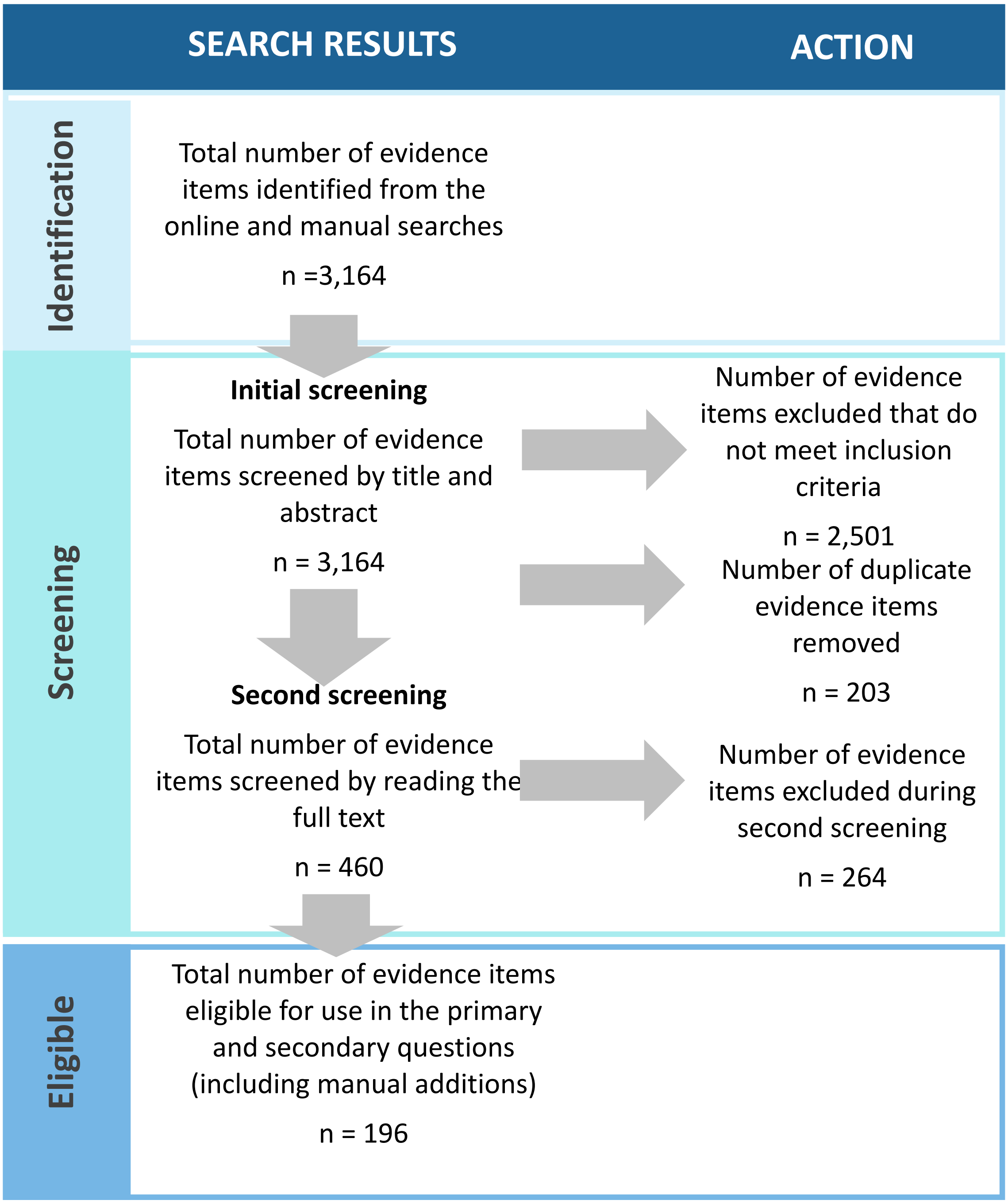


Figure 3. Flow chart of results of screening and assessing all search results for Question 3.2.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

There were 196 studies found using the search strategy that met the criteria for this question. Because of the large body of evidence for this question, the review was constrained to studies conducted within or using organisms from the GBR, with just a few exceptions from adjacent areas including Hervey Bay and Moreton Bay and some global reviews if they offered novel insight relevant to the question elements. The largest number of studies were observational (79), and experimental (76) making up 79% of studies and the remainder were modelling or review papers (Table 7).

Table 7. Primary study type for literature included in Question 3.2.

Primary study type	Number of studies	Percentage
Experimental	76	39%
Modelled	13	7%
Observational	79	40%
Review	26	13%
Meta analysis	2	1%
Total	196	

Multiple lines of evidence are needed to answer the primary question on **the measured impacts of increased sediment and particulate nutrient loads on GBR ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the GBR.** This is further supported by related questions on evidence for changes in loads and fate of them in the GBR lagoon. There is no single study and method that can examine the particular response or level of response of ecosystems to elevations in sediments and particulate nutrients above a pre-European baseline. This is because the effects of anthropogenic activities on sediment and particulate nutrient loads have been superimposed on existing natural gradients.

Observational studies were largely focused on understanding the impacts of sediments and particulate nutrients on abundance (e.g., coral or seagrass cover) and composition, with a smaller portion that also examined mechanisms of response by assessing physiological, recruitment and behavioural changes. Observational studies also addressed ecological processes such as grazing and predator-prey interactions. Observational studies provide the main source of information on ‘where is there evidence’ of the impacts of sediments and particulate organic matter. Observational studies were also used to identify thresholds leading to ecologically-relevant spatial and temporal variation in indicators and have been pivotal to the development of water quality guidelines (e.g., De’ath & Fabricius, 2010; Petus et al., 2018).

Experimental studies tended to focus more on mechanisms of response (e.g., physiological, recruitment indicators) because these processes are more easily observed in controlled environments. They also enable careful manipulation of specific water quality variables, namely sediments and particulate nutrients so that the effect of these can be determined in isolation or in combination with other stressors. This is useful in understanding the influence of water quality indicators as there are parameters that correlate in waters of the GBR. Experimental studies were also used to identify thresholds at which indicators respond to levels of a stressor and some of these have been pivotal to the development of guidelines for coastal development including dredging (e.g., Chartrand et al., 2016; Collier et al., 2016a; Collier et al., 2016b). Some experimental studies also used *in situ* measurement of sediments or particulate nutrients to extrapolate from experimental response profiles to partially address the question on 'where is there evidence'. Some experiments included other contextual variables such as climate change (e.g., temperature) and these were included in this analysis if the study added to the body of evidence for sediments or particulate organic nutrients (e.g., single factor effects were presented and were a significant part of the study) (e.g., Brunner et al., 2021).

Modelling studies enabled complex patterns to be discerned, particularly to estimate the effects of sediments or particulate nutrients on ecosystems. These were often paired with observations within the same study, although many used existing and published data to answer specific elements. Modelling can also be used to combine information on ecosystem indicators from a range of different studies to scale-up the findings. For example, combining information on how various stages of coral recruitment from different studies scale up and may respond to spatial variability in water quality (e.g., Bozec et al., 2022).

Reviews provided another way to combine information from different studies to provide broader and synthesised perspectives, including how consistent the impacts observed in the GBR are with those observed globally. Older reviews were excluded from the data extraction and do not feature in the summary of findings, but they are included to a more limited extent in the background material and to form the initial conceptual models that drove the research question.

By dominant ecosystem type in each study, coral was the most common (91 studies) making up 46% of studies, followed by seagrass (45) and algae (32) (Table 8). There were no studies on inter-reef habitats that were related to this question. There were only nine on estuarine or freshwater habitats.

Impacts of pressure indicators include the primary question elements of suspended sediment and particulate nutrients, as well as suspended particulate matter (i.e., combination of both), settled sediment, light (a consequence of high particulate loads), water quality and nutrients (in which case the effects of particulate or dissolved are not separated). There is abundant literature on the influences on turbidity (i.e., water clarity) and photic depth (i.e., the depth in the water column that photosynthetically usable light can reach) for the inshore GBR, showing that wave-driven resuspension is the dominant driver, with tidal resuspension acting as a secondary influence (Question 3.1, Lewis et al., this SCS). Suspended sediment (or turbidity) followed by settled sediment were the focus of the majority of studies for most ecosystems although seagrass ecosystems had an even greater focus on light (Table 9). There were also numerous studies on light for coral ecosystems.

Many studies on water quality variability used statistical modelling to identify the relative contribution of sediments or particulate matter to the impacts observed in cross-shelf gradients or through time. There were several studies that did not separate these effects and are listed as 'water quality' and so the specific effect of particulates were not known (Table 9). There may be overlap in the narrative and citations for these studies with Question 4.2 (Diaz-Pulido et al., this SCS) which is focused on dissolved nutrients. There were few studies on particulate organic matter with only seven on coral, three on reefs (non-coral), one for fish and two on estuaries/freshwater systems.

Table 8. Primary study type and ecosystem component.

	Experimental	Modelled	Observational	Review	Meta analysis	Total
Coral	35	6	34	14	2	91
Reef (non-coral)	11	0	7	0	0	19
Microbes and foraminifera	5	0	10	1	0	16
Fish	11	0	1	4	1	17
Algae	13	0	12	6	1	32
Seagrass	7	8	18	11	0	45
Mangroves	0	0	1	2	0	3
Freshwater / estuarine	1	0	4	4	0	9
Total	76	13	79	26	2	196

Table 9. Ecosystem and pressure. An individual study could include more than one ecosystem type (e.g., coral and fish), or pressure metric (e.g., light and settled sediment).

	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients (including particulate nutrients)	Other	Total
Coral	53	30	7	22	15	9	6	91
Reef (non-coral)	9	10	3	3	2	1	1	19
Microbes and foraminifera	6	1	1	2	4	4	4	16
Fish	13	9	1	2	1	0	0	17
Algae	12	13	0	5	7	5	2	32
Seagrass	19	10	0	24	8	2	3	45
Mangroves	1	0	0	0	1	2	0	3
Freshwater/estuarine	6	1	2	1	1	3	0	9
Total	95	58	13	50	32	19	13	196

Observational studies relevant to this question were predominantly conducted inshore with some examining cross-shelf gradients (Table 10). There was a strong bias towards studies conducted in the Burdekin closely followed by the Wet Tropics and then the Mackay Whitsunday region and only one observational study conducted in the Burnett Mary.

The abundance of organisms (e.g., coral and seagrass cover), was overwhelmingly the dominant indicator measured featuring in 34% of studies (Table 11). This was followed by physiological indicators (e.g., photosynthetic efficiency, pigments) in 26% of studies, composition (or diversity) in 20% of studies, mortality in 14% of studies and growth in 13% of studies. Complex indicators such as resilience and ecological processes (e.g., predator-prey interactions) were not common in the literature.

Table 10. Summary of the primary characteristics evaluated, and the study approach used for observational GBR studies. Note: The total represents the total number of studies making up that column. A single study may be conducted in more than one region so could be listed in multiple rows. There were also four studies in adjacent areas and two studies from outside of the GBR.

Region	Inshore	Midshelf	Inshore and midshelf	Inshore, midshelf, offshore	Catchment	Total
Cape York	1	0	3	2	0	6
Wet Tropics	19	0	4	6	2	31
Burdekin	22	0	2	4	1	29
Mackay Whitsunday	13	0	3	1	0	17
Fitzroy	6	1	1	0	2	10
Burnett Mary	1	0	1	0	0	2
All	2	0	2	8	0	12
Total	43	1	10	16	5	73

Table 11. Summary of the primary characteristics evaluated, and the study approach used for GBR studies. One study can be included in more than 1 category. 'Multiple refers to reviews and/or modelling papers that include 5 or more indicators.

	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients (including particulate nutrients)	Other (includes sediment type)	Total
Abundance	29	14	2	19	17	6	4	66
Behaviour	3	6	1	1	0	4	1	10
Bleaching	2	4	0	3	2	0	0	9
Composition	23	6	3	7	16	0	7	39
Disease	0	1	0	0	2	0	1	3
Distribution	1	0	0	2	3	1	0	6
Feeding (coral)	1	0	2	2	0	2	1	5
Feeding behaviour (fish)	3	5	1	0	0	0	0	8
Growth	9	8	2	9	2	0	2	26
Morphology	3	5	0	5	4	1	0	14
Mortality	12	13	3	8	0	0	1	27
Multiple	12	10	1	4	0	0	0	12
Other	4	2	0	2	2	3	2	10
Physiology	17	12	3	22	6	7	3	50
Productivity	0	2	1	1	2	2	0	7
Reproduction	16	6	2	4	3	2	0	24
Resilience	3	0	0	2	2	0	0	5
Symbionts	2	2	0	0	0	0	0	3
Total	93	57	13	50	32	19	13	194

Suspended sediment was observed and impacts tested in consistent units as mg L^{-1} although in observational studies it was also common to report on turbidity as Nephelometric Turbidity Units (NTUs). Observational studies also often included suspended sediment as turbidity (measured with a nephelometer, either handheld or logged), and as sieved sediments of various size classes especially the amount of fine sediment <63 µm and the mean/median of the grain size observed. Recent research recognises that the mineral <20 µm fraction travels the furthest in riverine flood plumes, forms the nucleus of organic-rich sediment flocs, is more easily resuspended from the seabed and hence likely disproportionately contributes to reductions in water clarity (Bainbridge et al., 2018; 2021; Fabricius et al., 2016). While the <20 µm fraction would be a desirable particle size class to capture in the marine environment, the complexities of the aggregation of particles with organics and the presence of carbonates mean that considerable sample pre-treatments are required prior to analysis (e.g., Bainbridge et al., 2021). The inherent spatial and temporal variation in the GBR lagoon makes it complicated to define 'natural' experimental particle size distributions. Several studies focus on the fine fractions that are the most easily transported and pose the greatest threat, generally <63 µm (e.g., Humanes et al., 2017b; Humphrey et al., 2008) or <20 µm (e.g., Humanes et al., 2017b), while others use larger size classes (Chase et al., 2020). Some experimental studies grind collected samples such as carbonates and then report size as mean (or median) and ranges in the size of the sediments (e.g., Jones et al., 2020; Ricardo et al., 2018) or sieved into distinct size classes (e.g., Chase et al., 2020; Luter et al., 2012; Philipp & Fabricius, 2003; Stafford-Smith, 1993), while others use commercially available clays that are very fine (e.g., Wenger et al., 2013). Quantitative data extraction on the size classes and concentrations in experimental and field studies was beyond the scope of this review, but would be a valuable step in assessing risk posed to GBR ecosystems.

A high proportion of studies involved siliciclastic sediments taken from estuarine or marine habitats for use on organisms from the same site or sites influenced by those sediments. Other studies used carbonates collected on reefs or ground from dead coral skeletons. Particulate nutrients were not presented with consistent units. Experimental studies used particulates from varied sources including plankton and fish emulsions. Some studies classified particulates (sediment and nutrients) with very detailed composition and size class analysis and generated equations that could be used to extrapolate findings (Garzon-Garcia et al., 2018; Weber et al., 2006).

Suspended sediment concentrations and turbidity are highly variable through space and time and across gradients of the inshore reef (Question 3.1, Lewis et al., this SCS). They are influenced by resuspension caused by wind and currents, river discharge and by coastal development and dredging over small areas which create large spikes in turbidity. D90 values (i.e., exceeded 10% of the time) on the inshore reef (Burdekin, Mackay Whitsunday and Wet Tropics) range from 0.8 to 15 NTU (see Question 3.1, Lewis et al., this SCS). The conversion to suspended sediment concentrations is a multiplication of ~1-4 to achieve mg L^{-1} (i.e., D90 could range from ~0.8 to 60mg L^{-1}, but it is particularly dependent on sediment grain size and colour (Question 3.1, Lewis et al., this SCS). The mean annual water quality guideline for the open coastal and midshelf zones is 2 mg L^{-1} (De'ath & Fabricius, 2008; GBRMPA, 2010). Experimental studies on suspended sediments included concentrations of up to 1,000 mg L^{-1} (Ricardo et al., 2016a). Higher concentrations were used to generate dose-response curves (Ricardo et al., 2016a), a distinct sediment response (e.g., in interactive experiments) and when mechanistic and behavioural responses were being tested (e.g., Fabricius & Wolanski, 2000), but the spatial and temporal generalisability of the highest concentrations is limited. Low concentrations (<10 mg L^{-1}) were also frequently applied especially when dose-response relationships were being tested and low-level response thresholds were being reported such as the EC10 values (e.g., the concentration leading to a 10% inhibition such as fertilisation success) (e.g., Abdul Wahab et al., 2019; Ricardo et al., 2018). The concentrations tested were not extracted in a numeric manner as this was not a quantitative review.

Settled sediment was not consistently reported, and included depth of sediment (Benham et al., 2019), percent cover (Ceccarelli et al., 2005), weight on SedPods (Duckworth et al., 2017) weight standardised to area of coral skeleton (Bessell-Browne et al., 2017c) or on standardised tiles. They were also single dose or repeat dose including daily (Chase et al., 2020) experiments and those that based the level of sedimentation on weight after application and some before application. Experimental studies often collect or grind sediments and then report mean (or median) and ranges in the size of sediments and so direct comparisons with composition of experimental sediments and measured density of sediments *in situ* is not straightforward.

There were few studies on the impacts of particulate nutrients, making it difficult to account for the risk they pose to GBR ecosystems (Bainbridge et al., 2018). The impacts of particulate nutrients were not always differentiated from dissolved nutrients. Studies on nutrients met the criteria if the primary focus or application was particulate nutrients even though the mechanisms of uptake were as dissolved nutrients. For example, particulate nutrient sources were used to provide a slow release of dissolved nutrients to corals (Humanes et al., 2017b) and the effects of particulates on algae were observed in the field and the response was likely due to dissolved nutrients (Schaffelke, 1999).

Quantifying how temporal variability of ecosystems is impacted by water quality, in particular sediments and particulate nutrients, is complicated for numerous reasons (Lam et al., 2018; McKenzie et al., 2022; Thompson et al., 2022). Extreme conditions co-occur with elevated discharge including cloudiness and low incoming solar radiation (leading to low light), large waves and currents during storms can have direct physical effects on organisms as well as indirect effects through resuspension, and other water quality variables that co-vary with discharge (e.g., dissolved nutrients, herbicides, low salinity) leading to cumulative pressures. These also affect daily, monthly and annual variations in light levels even in the absence of extreme weather events (O'Brien et al., 2018a). There are also lag times in biological responses with some accumulating over multiple years (Lambert et al., 2021), while others such as coral recruits, plankton and microbes respond rapidly (e.g., coral recruits die within 48 hours under marine snow (Fabricius et al., 2003)). These are cross-cutting complications that affect all ecosystem elements in the GBR and the interpretation of sediment and particulate nutrient impacts.

There is also a lack of long-term ecological data that are associated to sediments and particulate nutrients. For example, there are no direct measures of water quality (except light) paired to long-term seagrass monitoring and therefore, no data to examine impacts of sediments and particulate nutrients. There are long-term monitoring programs on coral reefs, seagrass and water quality but not for other elements of the ecosystem.

4.1.1 Summary of evidence to 2022

The question was broken into three components.

- The impacts of increased sediments and particulate nutrients (195 studies)
- What are the mechanisms (69 studies)
- Where is there evidence (43 studies)

The key findings for these questions are addressed separately (under different sub-headings) for corals and reefs. For all other ecosystem elements, there is just one section covering all three components as the range of literature was lower.

Corals and reefs

Coral studies included hard corals with a bias towards studies on *Acropora* spp., and one species of octocoral (Table 12).

Table 12. Genera of coral in studies relating to Question 3.2.

Coral genera	Number of studies
Acropora	36
Pocillopora	12
Montipora	11
Isopora	1
Porites	13
Turbinaria	8
Goniastrea	2
Pachyseris	2
Pavona	1
Astreopora	1
Echinopora	1
Fungia	1
Galaxea	1
Merulina	1
Pectinia	1
Alcyoniidae (octocoral)	1

Corals and reefs were the ecosystem component with the largest number of studies, and these have been summarised in Table 13 according to the indicator category and pressure that relates to the primary question. The effects of suspended sediment (or turbidity) were primarily investigated using indicators of abundance, species composition, mortality, physiology and behaviour (e.g., cleaning), and effects of settled sediment in relation to behaviour and physiology (Table 13).

The studies on impacts to coral reefs included those investigating acute short-term changes, seasonal/intra-annual responses (e.g., flood plumes), and chronic change or multi-year variability.

Impacts to coral communities caused by chronic exposure to increased sediment or particulate nutrients were assessed *in situ* where there were a range of water quality and other environmental conditions that may influence the responses. As such modelling was subsequently used to identify the effects of suspended sediments or particulate nutrients as quantitative or relative effects. These studies have been informed by major survey campaigns and long-term monitoring including the Inshore Marine Monitoring Program (MMP) and the Long-Term Monitoring Program (LTMP).

The MMP assesses and reports on the condition of 30 inshore coral reefs and results are presented in the context of pressures and their ramifications for the long-term health of inshore coral (Haynes et al., 2007; Thompson et al., 2022). The LTMP has assessed between 80 and 130 reefs each year for more than 35 years, with more than 490 reefs surveyed throughout the program history (AIMS, 2022).

Table 13. Studies that investigated corals in relation to pressures related to the primary question, also showing the indicator category that was the focus of the question. A reference may be listed in multiple categories.

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Abundance	Bozec et al., 2022; De'ath & Fabricius, 2008; 2010; Fabricius et al., 2005; 2012; Lam et al., 2018; Mellin et al., 2019; Morgan et al., 2016; Ridd et al., 2011; Sommer et al., 2021; Thompson et al., 2014; 2022	Done et al., 2007; Sommer et al., 2021		Mellin et al., 2019; Morgan et al., 2016	Fabricius et al., 2005; 2012; Fabricius & De'ath, 2004; Thompson et al., 2022		De'ath & Fabricius, 2010; Fabricius & De'ath, 2004
Behaviour	Bessell-Browne et al., 2017b; 2017c	Bessell-Browne et al., 2017a; 2017c; Duckworth et al., 2017; Stafford-Smith & Ormond, 1992; Weber et al., 2006		Bessell-Browne et al., 2017b		Anthony, 2000; Fabricius & Dommisse, 2000; Stafford-Smith & Ormond, 1992; Weber et al., 2006	Fabricius & Dommisse, 2000
Bleaching	Jones et al., 2020; Luter et al., 2021	Cantin et al., 2021; De'ath & Fabricius, 2011; Philipp & Fabricius, 2003; Weber et al., 2006		Jones et al., 2021; Luter et al., 2021	De'ath & Fabricius, 2011; MacNeil et al., 2019		
Composition	De'ath & Fabricius, 2008; 2010; Fabricius et al., 2005; 2012; Mellin et al., 2019; Morgan et al., 2016; Perry et al., 2008; 2009; Ridd et al., 2011; Sommer et al., 2021; Thompson et al., 2022; Uthicke et al., 2010	Done et al., 2007; Sommer et al., 2021	Uthicke et al., 2010	Mellin et al., 2019; Morgan et al., 2016	Fabricius et al., 2005; 2012; Fabricius & De'ath, 2004; Johnson et al., 2017; Perry et al., 2008; 2009; Thompson et al., 2022		De'ath & Fabricius, 2010; Fabricius & De'ath, 2004; Roff et al., 2013
Disease					Haapkyla et al., 2011; MacNeil et al., 2019		Haapkyla et al., 2011

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Distribution				(Muir et al., 2015)			
Feeding (coral)	Anthony & Connolly, 2004		Anthony, 1999; Anthony & Fabricius, 2000	Anthony & Connolly, 2004; Anthony & Fabricius, 2000		Anthony, 2000; Fabricius & Dommisse, 2000	Fabricius & Dommisse, 2000
Growth	Browne, 2012; Browne et al., 2012; Cooper et al., 2007; Humanes et al., 2017a; Jones et al., 2020; Sofonia & Anthony, 2008	D'Olivo et al., 2013	Anthony & Fabricius, 2000	Anthony & Fabricius, 2000; D'Olivo et al., 2013; Jones et al., 2021	Cooper et al., 2007; Rocker et al., 2017		Humanes et al., 2017a
Morphology	Fabricius et al., 2012; Morgan et al., 2016	D'Olivo et al., 2013; Stafford-Smith & Ormond, 1992		D'Olivo et al., 2013; Morgan et al., 2016	Cooper et al., 2008; Fabricius et al., 2012; Rocker et al., 2017	Stafford-Smith & Ormond, 1992	
Mortality	Bessell-Browne et al., 2017b; 2017c; Fabricius et al., 2003; Flores et al., 2012; Humanes et al., 2017a; Jones et al., 2020; Luter et al., 2021; Stafford-Smith, 1993	Bessell-Browne et al., 2017c; Brunner et al., 2021; Chase et al., 2020; Flores et al., 2012; Trapon et al., 2013; Weber et al., 2012	Fabricius et al., 2003	Bessell-Browne et al., 2017b; 2017d; Luter et al., 2021			Humanes et al., 2017a
Multiple	Bainbridge et al., 2018; Brodie et al., 2017a; Cooper et al., 2009; Haynes et al., 2007; Jones et al., 2016; Kroon et al., 2014; Magris & Ban, 2019; Zweifler et al., 2021	Bainbridge et al., 2018; Brodie et al., 2017a; Cooper et al., 2009; Haynes et al., 2007; Jones et al., 2016; Kroon et al., 2014; Magris & Ban, 2019; Waterhouse et al., 2017	Bainbridge et al., 2018; Cooper et al., 2009	Bainbridge et al., 2018; Brodie et al., 2017a; Haynes et al., 2007; Jones et al., 2016			
Other	Le Grand & Fabricius, 2011; Mellin et al., 2019; Sommer et al., 2021	Brunner et al., 2021; Jones et al., 2019; Sommer et al., 2021		Mellin et al., 2019; Petus et al., 2018	MacNeil et al., 2019	Le Grand & Fabricius, 2011	

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Physiology	Anthony, 2006; Anthony & Connolly, 2004; Baird et al., 2021; Bessell-Browne et al., 2017b; 2017c; Cooper et al., 2007; Humanes et al., 2017a; Jones et al., 2020; Luter et al., 2021; Rocker et al., 2019; Sofonia & Anthony, 2008	Bessell-Browne et al., 2017c; Chase et al., 2020; D'Olivo et al., 2013; De'ath & Fabricius, 2011; Duckworth et al., 2017; Philipp & Fabricius, 2003; Weber et al., 2006	Anthony & Fabricius, 2000; Cooper & Fabricius, 2012	Anthony, 2006; Anthony & Connolly, 2004; Anthony & Fabricius, 2000; Bessell-Browne et al., 2017b; 2017d; Cooper & Fabricius, 2012; Cooper & Ulstrup, 2009; D'Olivo et al., 2013; DiPerna et al., 2018; Jones et al., 2021; Luter et al., 2021; Risk & Sammarco, 1991; Strahl et al., 2019	Cooper et al., 2007; 2008; Cooper & Ulstrup, 2009; De'ath & Fabricius, 2011; Rocker et al., 2017; Strahl et al., 2019	Anthony, 2000; Baird et al., 2021; Risk & Sammarco, 1991; Weber et al., 2006	Humanes et al., 2017a
Productivity				Strahl et al., 2019	Strahl et al., 2019		
Reproduction	Bozec et al., 2022; Davidson et al., 2019; Fabricius et al., 2003; Humanes et al., 2017b; Humphrey et al., 2008; Jones et al., 2015; Ricardo et al., 2015; 2016a; 2016b; 2017; 2018; Thompson et al., 2022; Woods et al., 2016	Birrell et al., 2005; Jones et al., 2015; Maida et al., 1994; Ricardo et al., 2017	Fabricius et al., 2003; Ricardo et al., 2018	Jones et al., 2015; Ricardo et al., 2021	Thompson et al., 2022	Humanes et al., 2016; 2017b	
Resilience	McCook et al., 2015						
Symbionts	Cooper et al., 2011						

What are the measured impacts to reefs?

The diversity, function and extent (depth of reef formation) of reefs correspond to gradients in water quality. Reefs with higher sediment, nutrient and chlorophyll concentrations are dominated by the most resilient taxa including *Turbinaria*, Poritidae, Mussiidae, Agariciidae and Faviidae (= Merulinidae), while the more sensitive taxa *Acropora* and *Montipora* are restricted to the uppermost depth (De'ath & Fabricius, 2010; Fabricius et al., 2005; Fabricius & De'ath, 2004; Morgan et al., 2016). There are low densities or complete absence of sensitive species groups, genera and families including octocorals where sediment, nutrient and chlorophyll concentrations are high (De'ath & Fabricius, 2010; Fabricius et al., 2005; Fabricius & De'ath, 2004). The responses are not consistent across species or genera, but there are strong effects on the ratio of abundances of *Acropora* to other corals, and of abundances of coral relative to other benthic reef organisms (De'ath & Fabricius, 2010; Magris & Ban, 2019). Macroalgal abundance can also be enhanced in areas exposed to chronic poor water quality at the expense of corals, especially where there is high nutrient availability (De'ath & Fabricius, 2008; Fabricius et al., 2005; Fabricius et al., 2012; Thompson et al., 2022), and so are the densities of filter-feeding macrobioeroders in living massive *Porites* corals (Le Grand & Fabricius, 2011). Nearshore reefs may also be less functionally diverse, with co-occurring species more similar in their traits compared to coral species from reefs less influenced by river discharge (Sommer et al., 2021). Modelling was also used to determine that 28% of the spatial variation in the community composition of reefs was associated with chronic stressors related to water quality based on a transect from the Mary River in Hervey Bay (Mellin et al., 2019). Even more specifically, coral cover and composition varied with TSS (at 5 m) and fine sediment (at 5 m and 2 m depth) and the proportion of fine-grained sediment on reefs of the Whitsundays (Thompson et al., 2014).

Autotrophic/heterotrophic plasticity is an important trait for species to persist in turbid areas and the composition of communities along spatial gradients in water quality reflects this plasticity (Anthony & Fabricius, 2000; De'ath & Fabricius, 2010; Morgan et al., 2016; Zweifler et al., 2021). For example, heterotrophic richness increased with turbidity and chlorophyll, and the richness of hard corals and phototrophic octocorals decrease along gradients of water quality (De'ath & Fabricius, 2010; Fabricius et al., 2012; Magris & Ban, 2019). Some coral communities including those dominated by soft coral can feed heavily on particulate organic matter and have a net import of energy (Anthony, 1999; Anthony & Fabricius, 2000; Fabricius & Dommisse, 2000). There is systematic spatial variation in a range of other functional traits along water quality gradients. For example corals can have different morphologies, corallite sizes, sedimental removal abilities, development rates and symbiont transition pathways depending on their distance from the mainland and from rivers (Sommer et al., 2021).

Turbid waters can support high levels of coral cover in some locations (McCook et al., 2015; Morgan et al., 2016; Perry et al., 2009), although the lower depth limit of zooxanthellate corals is reduced in turbid environments (Cooper et al., 2007; Morgan et al., 2016; Zweifler et al., 2021). There are also shifts in functional and morphological traits with increasing depth in turbid water settings (Morgan et al., 2016). These include autotrophic/heterotrophic plasticity and morphometric variations that enhance light capture and sediment sloughing (Morgan et al., 2016). Some turbid reefs have persisted with coral cover and growth rates comparable to or exceeding those on midshelf reefs (Browne et al., 2012; Done et al., 2007; Zweifler et al., 2021). Other factors such as disturbance history seemed to affect coral cover more than turbidity (Fabricius et al., 2012).

Temporal variability in coral cover and health is strongly affected by environmental conditions and cumulative pressures (D'Olivo et al., 2013; Kroon et al., 2014; Lam et al., 2018; Thompson et al., 2022; Uthicke et al., 2010). Linking contemporary change in coral reefs to loads of sediments and particulate nutrients is complicated for the reasons described in section 4.1.0 Summary of Study Characteristics. Changes on inshore reefs correspond to elevated discharge and exposure to water quality variables more than midshelf and outer reefs for both contemporary change (Mellin et al., 2019) and long-term change (D'Olivo et al., 2013). For the period 2005 to 2014, decline in coral cover at inshore reefs was strongly associated with environmental drivers (Lam et al., 2018) but the main drivers varied among regions: in the Wet Tropics and Burdekin Natural Resource Management (NRM) regions, change in coral cover was driven by storms and in the Mackay Whitsunday and Fitzroy regions change in coral cover was driven by clay/silt (observed), floods and juvenile corals (Lam et al., 2018). After 2016, cyclones, thermal bleaching, flooding and crown-of-thorns starfish (COTS) all contributed to declining coral cover (Thompson et al., 2022). Therefore, there are regional differences in the manifestation of water quality impacts on coral health and cover that are complicated by regional and local scale cumulative impacts.

Chronic poor water quality and discharge events slow reef recovery following disturbances (Mellin et al., 2019; Roff et al., 2013; Thompson et al., 2022). For example, water quality suppressed the recovery of coral communities (interpreted using the MMP Coral Index) from 2019-2020 to 2020-2021 following disturbances from cyclones, COTS, thermal stress and low salinity flood plumes (Thompson et al., 2022). Southern and central reefs exposed to poor water quality take longer to recover from disturbances including bleaching, and so a 6-17% improvement in water quality would be needed to compensate for bleaching on inshore and midshelf reefs (MacNeil et al., 2019). Coral settlement measured at reefs from 2006-2012 (MMP) demonstrated that water quality and discharge from local rivers has a small influence on rates of coral settlement in the preceding year. Also, turbidity (NTU) affected the pelagic larval phase (Davidson et al., 2019), which is important for reef recovery. Using published information on coral recruitment dynamics and how they are affected by sediments it was estimated that there would be a ~9-month additional recovery time (from an initial 5% coral cover) for every 1 mg L^{-1} increment in time-averaged suspended sediment concentration (eReefs 4 km grid) (Bozec et al., 2022).

Some authors question whether the levels of suspended sediment in the inshore have increased and exceed the tolerance levels for inshore coral species, as they were affected by runoff and resuspension prior to agricultural development (Perry et al., 2008). Furthermore, the modern community composition matches pre-European settlement composition at some sites, with changes linked to sea level rise, but not water quality (Johnson et al., 2017; Perry et al., 2008; 2009;). However, Roff et al (2013) showed distinct peaks in coral mortality at Pelorus Reef in the central GBR with 79.1% of mortality occurring between 1920 and 1955 (Roff et al., 2013). Prior to that was a period of reef stability. These changes were attributed to increasing sediment and nutrient loads following European settlement inhibiting recovery from a range of pressures (Roff et al., 2013). Acclimation of coral to elevated sediment and particulate nutrients in the inshore could occur through physiological adjustments and feeding plasticity in turbidity tolerant species and the mechanisms of impacts and tolerance are described in further detail below. Question 2.3 (Lewis et al., this SCS) delves further into the question of how human activities have influenced ‘anthropogenic’ loads of sediment and particulate nutrients and the resultant changes in water quality at reef locations.

In summary, some reefs have persisted through time with high coral cover and growth rates in highly turbid inshore regions. However, observational and long-term monitoring data from numerous inshore reefs spanning from Cape York to the Fitzroy regions, and their associations with water quality data, provide robust insight into the multitude of ecological and physiological changes in the communities of corals and many other reef-associated organisms along gradients in water quality. Increasing loads of sediments and particulate nutrients are one of the main pressures contributing to changes on inshore coral reefs, especially because they suppress coral recruitment and reef functional diversity, they increase macroalgae, and elevate macrobioeroder densities, and hence reduce reef recovery from multiple disturbances and cumulative impacts (see Question 2.4 Uthicke et al., this SCS).

What are the mechanisms of impact?

Physiological and behavioural studies have been used to unravel the mechanism of impact and mechanisms for tolerance of corals and reef communities to sediments and particulate nutrients. These studies were undertaken both *in situ* and in experimental facilities. The mechanisms of impact that have been described are summarised here as:

- Trophic shifts: Low light or modified light spectrum and elevated heterotrophy are mechanisms for acclimation to low light
- Sedimentation and cleaning
- Coral recruitment
- Disease

Trophic shifts: Low light or modified light reduces photosynthetic rates while elevated heterotrophy is a mechanism for acclimation

Suspended particulate matter changes both the quantity and spectrum of light reaching coral reefs. Light is essential for photosynthesis by the endosymbionts in the coral host (Anthony, 2006; Cooper et al., 2008; Jones et al., 2021; McCook et al., 2015). Experiments have been used to determine the effect of changes in light in isolation or in combination with suspended sediments, to understand the mechanisms of impact caused by particulate matter and to identify light thresholds. A number of these studies, especially recent work (2016 onwards) was aimed at informing dredge management.

Energetic balances are affected by reductions in light. Relatively small increases in particle concentrations are enough to reduce light and cause a shift in some species of corals from autotrophy to heterotrophy, and can lead to an imbalance in the energetic budget and reduce investment into growth, depending on species and depth (Anthony & Fabricius, 2000). Lipids are the principal energy reserves in corals and when exposed to low light, lipid content declines (Jones et al., 2016; Jones et al., 2021; Luter et al., 2021). There is also a reduction in the ratio of storage to structural lipids, reflecting the lower energy gains from photosynthesis (Jones et al., 2020; Luter et al., 2021).

Corals can acclimate to reduced light to some extent, but beyond certain levels or after prolonged exposure they show physiological stress (DiPerna et al., 2018). There may be physiological acclimation to increase light harvesting efficiency with small reductions in light including an increase in symbiont density and pigment concentration (Cooper et al., 2011; Jones et al., 2016; Jones et al., 2020; Rocker et al., 2019) causing corals to darken and increase their light harvesting capacity (Cooper & Fabricius, 2012; Cooper et al., 2007). There may also be an increase in lipid and fatty acid content (Anthony, 2006; Rocker et al., 2019). The rate and amount of acclimation is variable among species, and their acclimation capacity may influence species composition in reefs exposed to changing turbidity regimes (DiPerna et al., 2018). These acclimations enable some inshore corals to tolerate extreme light reduction for 28 days (Luter et al., 2021) compared to corals from midshelf reefs (Jones et al., 2020). With larger reductions in light (more turbid) most coral species become paler, have lower symbiont densities and pigment concentrations and the efficiency of light use declines (e.g., dark yield or quantum yield measured using a pulse amplitude modulated (PAM) fluorometer) (Bessell-Browne et al., 2017b; Jones et al., 2020). In an experimental study, bleaching occurred at 2.7 mol photons m^{-2} d^{-1} leading to a 10% reduction (EC10) after 28 days (Luter et al., 2021) and the EC10 of dark adapted yield (Fv/Fm) occurred at 1.2-1.9 mol photons m^{-2} d^{-1} (Bessell-Browne et al., 2017d). These thresholds indicate suboptimal performance and an early warning sign of partial or full mortality. Partial mortality occurs when corals are exposed to very low light levels or near darkness after just seven days (Bessell-Browne et al., 2017b). There are a range of indicators identified that are sensitive to sublethal stress and could be used for acute monitoring; however the interactive effects of other environmental conditions need to be more thoroughly quantified so that the specificity of their response to light or turbidity can be determined (Cooper et al., 2009).

Therefore, despite some acclimation, corals in areas prone to very high turbidity or subjected to dredge plumes may be at risk from low light levels.

Species that can tolerate turbid conditions may grow at rates comparable to or even faster than those in clearer water. For example, photosynthesis, respiration and calcification rates of *Acropora tenuis* in shallow water (2 m depth) increased along the water quality gradient (as particulates increased) towards the Burdekin River mouth indicating acclimation to the habitat conditions (Strahl et al., 2019). However, it was detrimental to skeletal density (Rocker et al 2017), which concurs with previously proposed mechanisms for lower skeletal density inshore (Risk & Sammarco, 1991). In other cases, *Acropora* growth rates, skeletal density and calcification rates at Middle Reef in Cleveland Bay were comparable to those measured at similar depths on offshore (less turbid) reefs on the GBR, while those in *Montipora* were greater than both clear-water and turbid reefs which also demonstrated acclimation (Browne, 2012). Not all species have the capacity to adjust and tolerate turbidity, hence assemblages change along inshore turbidity gradients in the GBR (Fabricius et al., 2012).

Several factors determine the types and extent of impact on corals by light reduction from particulates (Cooper & Ulstrup, 2009). A change in the light spectrum to mimic turbidity reduces the physiological usable light at a higher total light level than a broad spectrum light reduction (Jones et al., 2021). Experimental testing of turbidity light spectrums induced physiological changes including algal density, pigment content, lipids and small reductions in growth but did not cause any partial mortality (Jones et al., 2021). The simulated impact of anthropogenic loads on symbiont physiology on the five runoff-exposed reefs studied in 2017 was small (Cantin et al., 2021). Models such as eReefs provide a powerful tool to investigate these mechanisms for environmental conditions that have occurred since eReefs was developed (2011) or that have been simulated and need to be interpreted with caution given these constraints (Baird et al., 2021).

Some data exist on light thresholds for reef development and species distribution limits. Cooper et al. (2007) demonstrated that coral reef development in the Whitsunday Islands ceased below thresholds of 6-8% of surface irradiance. Furthermore, Muir et al. (2015) reported a lower light limit for *Acropora* distribution in the GBR at around 5.2 mol photons m^{-2} d^{-1} in winter. On inshore reefs, daily light levels can vary up to four-fold, due to differences in resuspension and cloud cover (Anthony et al., 2004). Despite the ability of corals to acclimatise to variable light, growth rates of two species of *Acropora* were directly related to light availability, in response to both long-term light gradients and to variable light conditions (Noonan et al., 2021). Hence corals accumulated growth with every day of high light, and every day with elevated turbidity reduced their growth potential. Low and variable light also reduced coral recruit survival by facilitating overgrowth with algae, suggesting reductions in reef resilience are possible, but the influence of local contexts (water flow, grazers) needs to be considered and investigated (Noonan et al., 2021).

Settled sediments impact coral health and need to be removed

Corals and reefs are sensitive to sedimentation which causes tissue damage, energetic loss and disrupts coral recruitment (Bainbridge et al., 2018; Flores et al., 2012). Corals can reject settled sediment, but how much remains settled on the corals and their subsequent impact on coral health and survival depends on properties of the particulates, coral morphology, hydrodynamics and ecological interactions with other reef organisms. Fine silt and silt with high loads of particulate nutrients is rejected slowly and causes more damage than carbonate sediment (Duckworth et al., 2017; Fabricius et al., 2003; Weber et al., 2006; Zweifler et al., 2021).

Sediment removal varies among morphologies and species (Anthony & Connolly, 2004; Duckworth et al., 2017; Philipp & Fabricius, 2003) and age of the coral, with younger recruits (9 weeks old) being more sensitive than older recruits (14 weeks) (Brunner et al., 2021). A range of active methods are used to remove sediment and species have varying capability to use them, including mucus production (and mucus sheets in *Porites*) and ciliary transport (Bessell-Browne et al., 2017a; Bessell-

Browne et al., 2017c; Stafford-Smith & Ormond, 1992), tissue expansion of the coenosarc, polyp walls or oral disc (Stafford-Smith & Ormond, 1992) and compartmentalisation of sediment stress to superficial tissues (Philipp & Fabricius, 2003). Three species of coral displayed no polyp contraction at sediment concentrations up to 100 mg L^{-1}; for these species sedimentation at this exposure level alone was unlikely to cause partial morality (Bessell-Browne et al., 2017b).

Mucus laden sediment patches can become trapped in branches, depressions or concave surfaces (Bessell-Browne et al., 2017c; Zweifler et al., 2021), so coral morphology is a passive influence over the amount of sediment retained (Stafford-Smith & Ormond, 1992). Particularly sensitive are corals with relatively small polyps (Philipp & Fabricius, 2003; Stafford-Smith, 1993; Stafford-Smith & Ormond, 1992) and species with massive, flat or foliose morphologies (Duckworth et al., 2017; Philipp & Fabricius, 2003). Morphological characteristics that enhance light capture efficiency (e.g., encrusting), are more susceptible to sedimentation (Jones et al., 2019).

Mutualistic relationships between corals and fish also provide a sediment tolerance mechanism. Damselfish had less sediment in their territory, which was attributed to them actively cleaning or as a byproduct of their activities (Ceccarelli et al., 2005). Colonies with symbiont damselfishes had higher protein levels and chlorophyll (indicative of health) compared to unoccupied corals and had variable yet up to 10-fold less sediment-induced partial mortality (Chase et al., 2020). These results indicate that fish mutualisms may become more important under conditions of high stress (Chase et al., 2020).

There is also an energetic cost to each species of removing sediment that governs whether they are able to survive long-term in turbid or increasingly turbid habitats (Anthony & Connolly, 2004) and if particle feeding compensates for it (Anthony & Fabricius, 2000). Depending on species, corals may display substantial, minor or no sediment ingestion into the mouths (Stafford-Smith & Ormond, 1992). There is also a reduction in sediment removal over time as exposure is repeated (Bessell-Browne et al., 2017c). Furthermore, for the coral species *Acropora millepora* particle feeding rates were higher on inshore reefs compared to those on mid- and outer shelf reefs (Anthony, 2000). This suggests a heterotrophic pre-adaption to high particulate loads, and an ability to compensate for phototrophic deficits to some extent depending on the size of the deficit (e.g., shallow vs deep), and turbidity/light levels (Anthony, 2000). Barnes and Lough (1992) suggested that massive *Porites* would have thicker tissue layers where particulate matter and other food items were not limited, while Fabricius et al. (2012) found that tissue thickness in massive *Porites* declined along water quality gradients towards areas with higher particle loads.

Settled sediment also affects coral health. Sublethal indicators of coral health respond within hours (at higher loads) to days of exposure to settled sediment (Philipp & Fabricius, 2003; Weber et al., 2006). The geochemical properties of sediment, grain size and particulate nutrients associated with the sediment influence the magnitude of response (Bessell-Browne et al., 2017c; Philipp & Fabricius, 2003; Weber et al., 2006). Sublethal stress and risk of partial or full mortality also differs among corals in part due to their sediment rejection capabilities (Bessell-Browne et al., 2017c; Philipp & Fabricius, 2003) and also due to their morphology: branching species are at little risk of smothering and resulting partial mortality (Jones et al., 2019) except at very high (100 mg L^{-1} TSS) and prolonged (12 weeks) levels of exposure (Flores et al., 2012). Microbes mediate the impact of settled particulates on coral tissue, but the organic content of sediment affects how quickly coral tissue is damaged and disease establishes (Weber et al., 2012; Weber et al., 2006). As they settled on coral tissue, respiration rates increased leading to local anoxia and tissue degradation which then leads to harmful levels of hydrogen sulphide that damages adjacent tissues (Weber et al., 2012).

The species, age (recruits vs adults) and morphology-specific capabilities influence the distribution patterns of coral species along water quality gradients. Species with poor ability to remove sediment are restricted to reefs with lower turbidity (Sommer et al., 2021), and coral recruitment is impaired (Fabricius et al., 2005).

Coral recruitment is interrupted by suspended and settled sediments

Coral reproduction and recruitment are life history stages that are sensitive to suspended and settled sediments at levels found in the inshore reefs (McCook et al., 2015; Ricardo et al., 2018; Woods et al., 2016). The reproductive cycle starts with gamete development and release, fertilisation, larval development, settlement and metamorphosis into a sessile polyp (Jones et al., 2015).

Stored lipids in adult corals provide energy reserves to support reproduction (Anthony, 2006). Levels of lipid loss were not statistically different after spawning both inshore and offshore, suggesting similar levels of investment into reproduction in both turbid and clear waters (Anthony, 2006). However, there have been no studies to directly test the effects of turbidity on gametogenesis (Jones et al., 2015).

Fertilisation of gametes is impacted by suspended particulate matter (Woods et al., 2016). Egg-sperm bundles intercepted by sediment have reduced fertilisation success (Ricardo et al., 2016b). In *Acropora tenuis* (Humanes et al., 2016; Ricardo et al., 2018) and in *A. millepora,* fertilisation was reduced by particulates (Humphrey et al., 2008; Ricardo et al., 2015), which was attributed to physical obstruction (Humanes et al., 2016) and to the formation of sperm and clay flocs that sink (Ricardo et al., 2015; 2018;). Therefore, more sperm was needed for fertilisation in the presence of sediments (Ricardo et al., 2015). Fertilisation was inhibited at a threshold concentration (EC10 i.e., 10% reduction) of 2.5 mg L^{-1} at lower sperm concentrations of 104 sperm ml^{-1} but increased EC10 = 54 mg L^{-1} at higher sperm concentrations (Ricardo et al., 2018). This EC10 was exceeded at ~19% of the intervals measured which is approximately once every five years during spawning. Properties of the particulates also affected fertilisation. Fertilisation was reduced by particulate nutrients (Humanes et al., 2016) and was affected more in sediments containing high dissolved nutrients and small sediment grain sizes (Humphrey et al., 2008). *A. tenuis* fertilisation was more sensitive to sediments from Orpheus Reef (mean particle size = 6.7 µm, total organic carbon = 3.76%) than to sediments from Pandora Reef, offshore carbonates and terrigenous sediments of low organic content (Ricardo et al., 2018) but only for siliciclastic and not carbonate sediments (Ricardo et al., 2015).

In the next phase of the reproductive cycle – embryo development – suspended sediments had no effect on successful development (Humphrey et al., 2008; Ricardo et al., 2016a); however 10% of embryos formed negatively buoyant cocoons in sediment treatments (Ricardo et al., 2016a). The follow-on effects were also tested. Embryos were exposed to sediments, nutrients and temperature when they were between 8 and 36 hours old, and the effect of this exposure was tested on various further stages. This pre-exposure did not affect larval survivorship between 36 h and settlement at 5 days (Humanes et al., 2017b).

Settlement of larvae has been the most intensively researched area of coral recruitment. Settlement requires a suitable substratum and there are numerous potential cues for the planulae including the presence of crustose coralline algae (CCA) (Jones et al., 2015; Ricardo et al., 2021) but here the focus is on the effects of particulates. Pre-exposure of embryos to suspended sediment did not affect subsequent settlement after 3 and 5 days (Humanes et al., 2017b). Furthermore, settlement did not appear to be affected by changes in light caused by suspended sediments and turbidity (Ricardo et al., 2021; Ricardo et al., 2017). In contrast to suspended sediments, numerous studies have identified that sediments deposited on settlement surfaces reduce the number of pelagic larvae that settle (Birrell et al., 2005; Fabricius et al., 2003; Humanes et al., 2017b; Maida et al., 1994; Ricardo et al., 2021). Both siliciclastic and carbonate sediments affect settlement (Ricardo et al., 2021) and even thin layers of silt are enough to have an impact (Ricardo et al., 2017). If a clean surface was not available, larvae settled on downward facing surfaces free of sediment (Ricardo et al., 2017). Other environmental factors also affect recruitment including nutrient enrichment (Fabricius et al., 2003; Humanes et al., 2017b), and temperature enhanced this effect highlighting the cumulative effects of particulates in combination with other environmental conditions (Humanes et al., 2017b). Furthermore, bleached CCA caused by recent previous exposure to settled sediments has lower coral settlement rates than those that were not covered in sediment (Ricardo et al., 2017).

In situ observations confirm some of these experimental findings, with settlement on upwards facing settlement plates with sediments up to an order of magnitude lower than downward plates free from sediments (Maida et al., 1994; Ricardo et al., 2021). Interannual and inter-reef variation in recruitment was also observed through long-term monitoring in which turbidity explained a small portion (8-12%) of settlement (Davidson et al., 2019), however that study period had fairly low turbidity (in low discharge years) and greater effects are expected when turbidity is higher (Davidson et al., 2019). By contrast, in a separate field study, survival of laboratory reared *Acropora cytherea* spat was not correlated with the cover of turf algae or sediment on the reef crest or backreef after four weeks of deployment, instead, survival was negatively related to the number of parrotfish feeding scars (Trapon et al., 2013). Furthermore, the types of turf algae (advanced or new) also affected recruitment (Birrell et al., 2005).

Coral settlement may also be suppressed by up to one-third with extreme variation in light spectra, however realistic turbidity- or dredging-dependent changes in light spectra did not affect *A. millepora* settlement (Ricardo et al., 2021). The principal mechanism for particulates to affect settlement is therefore assumed to be by impairing attachment and masking substrate cues including impacts to the health of CCA (Ricardo et al., 2017).

After settlement, both suspended particulates and settled sediments impact juvenile coral growth and survival, as evidenced by many studies (Fabricius et al., 2005). Juvenile corals exposed to four levels of suspended sediments (0-100 mg L^{-1}) and two levels of particulate organic matter (0 and 0.6 mg OC L^{-1} FSW) had reduced growth or survival when exposed to high levels of suspended sediment for 40 days – possibly above what GBR corals typically experience; the organic material had no effect (Humanes et al., 2017a). Another study has shown that the survival of young coral recruits (one month old) is highly sensitive to deposited sediments, especially when organically enriched (Fabricius et al., 2003).

Particulates lead to disease

The current understanding of marine diseases is poor, and very little is known about the environmental controls over disease from the GBR. For example, in Thompson et al. (2014) the disease category 'Sediment damage' on coral colonies was associated with TSS concentration and total discharge. Coral disease *Atramentous necrosis* (AN) was ten times higher in the wet season compared to the dry season and two water quality variables explained most of the variance in disease prevalence – salinity (negative correlation) and particulate organic carbon (positive correlation) (Haapkyla et al., 2011). The incidence of coral disease 'white banding' varied with the proportion of fine-grained sediments on reefs at 5 m, and 'unknown scarring' at both 2 and 5 m, but both were unrelated to water column environmental variables (Thompson et al., 2014).

Where is there evidence of impacts to coral and reefs?

There is evidence that increased loads of sediment and particulate nutrients affect the diversity and abundance and depth of reef development on inshore reefs where gradients in water quality occur, especially in the central GBR (De'ath & Fabricius, 2010; Fabricius et al., 2012). These include some reefs in the Wet Tropics (Fabricius et al., 2005; Fabricius & De'ath, 2004; Thompson et al., 2022), Burdekin (Thompson et al., 2022), Mackay Whitsunday (Cooper et al., 2007) and Fitzroy (Fabricius et al., 2012; Le Grand & Fabricius, 2011) regions. However, the direct influence of sediment and nutrient loads were not easy to identify due to the issues of confounding variables described in 4.1.0 Summary of Study Characteristics. Evidence is instead confirmed through structured epidemiological assessments: effects were strong and ecologically relevant, occurred independently in different populations, agreed with known biological facts of organism responses to increased loads of sediment and particulate nutrients, were consistent with the effects found in other parts of the world, etc. (Fabricius & De'ath, 2004). The inshore MMP coral resilience score (estimated from the change in the Coral Index scores) was reduced in the Wet Tropics, Burdekin and Fitzroy Regions following river discharge from the adjacent catchments which can potentially suppress resilience and recovery from disturbance (Thompson et al., 2022). Therefore, understanding how reefs recover from disturbances and the role of sediments and particulate nutrients in suppressing recovery is a critical next phase of research, which is being addressed through some of the research described above (Mellin et al., 2019), but further work is needed.

There are also turbid-water reefs in the Burdekin region known to have maintained high coral cover in their upper 2 m depth at Paluma Shoals (Morgan et al., 2016; Zweifler et al., 2021) and Middle Reef (Browne, 2012; Browne et al., 2012). These small reefs are found in well-flushed areas which demonstrates that coral reefs can exist in high turbidity conditions in certain environmental settings but are restricted to very shallow non-depositional hydrodynamically favourable conditions.

Macroalgae and microalgae

Impacts to reefs also need to be considered in the context of other benthos including macroalgae (fleshy macroalgae, turf algae and crustose coralline algae) and microalgae.

Studies on the effects of sediments, light and particulate nutrients on algae on coral reefs were biased towards fleshy macroalgae, however crustose coralline algae (CCA), epilithic algal matrix (EAM) and microalgae were also studied (Table 14). The largest number of studies on macroalgae were on their abundance in relation to suspended sediment, settled sediment or water quality in general, with fewer studies on other indicators (Table 15). Turf algae (epilithic algal matrix) and CCA were studied more commonly in relation to settled sediments. There were only seven studies on microalgae, spanning a range of indicators and pressures (Table 14).

Table 14. Type of algae in studies relating to Question 3.2 (some studies are counted twice as they cover more than one type of algae).

Algae	Number of studies
Crustose coralline algae	5
Epilithic algal matrix (turf algae)	7
Fleshy macroalgae	14
Microalgae	4

Table 15. Studies that investigated algae in relation to pressures related to the primary question, also showing the indicator category that was the focus of the question. A reference may be listed in multiple categories.

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Macroalgae							
Abundance	De'ath & Fabricius, 2008; 2010; Fabricius et al., 2012; Smith et al., 2020; Thompson et al., 2022	De'ath & Fabricius, 2011; Schaffelke et al., 2005; Umar et al., 1998			De'ath & Fabricius, 2011; McCook, 1996	Schaffelke et al., 2005	De'ath & Fabricius, 2010; Fabricius et al., 2012
Composition	De'ath & Fabricius, 2008; Hurrey et al., 2013			Hurrey et al., 2013			
Growth		Umar et al., 1998					Schaffelke, 1999
Mortality		Umar et al., 1998					
Multiple	Magris & Ban, 2019	Magris & Ban, 2019					
Physiology							Schaffelke, 1999
Productivity							
Reproduction		Umar et al., 1998					
Size distribution					McCook, 1996		
Epilithic algal matrix							
Abundance		Tebbett & Bellwood, 2020; Tebbett et al., 2018a					
Growth		Goatley & Bellwood, 2013; Tebbett & Bellwood, 2020					
Morphology		Tebbett & Bellwood, 2020					

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Multiple		Brodie et al., 2017a; Waterhouse et al., 2017					
Other		Birrell et al., 2005; Ceccarelli et al., 2005; Goatley & Bellwood, 2013; Tebbett et al., 2018b)					
Physiology		Tebbett et al., 2018a					
Productivity		Tebbett & Bellwood, 2020; Tebbett et al., 2018b					
Crustose coralline algae							
Abundance	Fabricius & De'Ath, 2001; Smith et al., 2020						
Bleaching		Harrington et al., 2005					
Composition	Ricardo et al., 2021						
Mortality				Bessell-Browne et al., 2017d			
Physiology		Harrington et al., 2005		Bessell-Browne et al., 2017d; Ricardo et al., 2021			
Microalgae							
Abundance	Franklin et al., 2018				Gottschalk et al., 2007; Heil et al., 2004	Franklin et al., 2018; Garzon-Garcia et al., 2018	
Composition					Gottschalk et al., 2007		
Growth				King et al., 2022			

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Physiology	Franklin et al., 2018			King et al., 2022		Franklin et al., 2018; Garzon-Garcia et al., 2018	
Productivity	Alongi & McKinnon, 2005; Heil et al., 2004				Heil et al., 2004	McKinnon et al., 2002	

Algae are strongly affected by both bottom up (environmental) and top-down (grazing) drivers and many studies have highlighted the importance of considering them in combination. But here the focus is placed on the impacts from sediments and particulate nutrients. Algae on reefs is also intricately linked to coral reef health (see conceptual model). Therefore, it is very important to consider the changes in algal communities to understand reef health; however, the number of studies addressing this issue is limited.

Fleshy macroalgae

Fleshy macroalgae have important ecological functions on reefs, both as competitors for space with corals and other sensitive benthos, and also because they are productive and diverse and contribute to reef productivity (Schaffelke et al., 2005).

Macroalgal abundance on reefs is highest inshore and monotonically related to spatial patterns in water quality, in particular increasing turbidity and chlorophyll *a* and increased nutrient availability (De'ath & Fabricius, 2010; 2011). This is strongly evident in the central GBR in particular in the Mackay Whitsunday NRM where macroalgae becomes more dominant with increasing turbidity and nutrients (De'ath & Fabricius, 2010; Fabricius et al., 2012). By contrast, the lowest species richness of fleshy macroalgae on the shelf seabed (i.e., inter-reef areas) occurs where there is low irradiance and a high percent mud (<63 µm) based on a GBR-wide analysis from the Great Reef Census (Hurrey et al., 2013).

Sargassum species have been the focus of attention of macroalgae studies that explore the mechanism of responses to sediments and nutrients. The addition of sediments to levels double the natural level (20 mm) significantly reduced recruitment in *Sargassum microphyllum* as well as growth and abundance over 15 months (Umar et al., 1998). Sediments also significantly reduced the rate of thalli regeneration after they were experimentally damaged (Umar et al., 1998). This is consistent with findings from a global analysis in which macroalgae physiology, community abundance, reproduction and recruitment of macroalgae were shown to be sensitive to suspended sediment and sedimentation (Magris & Ban, 2019). In contrast, a threshold level of tolerance was identified of a long-term mean of 0.5-1.0 mg L^{-1} suspended sediment (eReefs spatial predictions), below which macroalgae cover in the GBR declined (Smith et al., 2020), similar to the steep decline in GBR-wide macroalgal cover with increasing Secchi depth, with the highest macroalgal cover found where Secchi depth was <10 m (De'ath & Fabricius, 2010). Indeed, *Sargassum* grows faster and has higher tissue nutrients with a source of particulate nutrients, which was presumed to be remineralised to dissolved nutrient forms (Schaffelke, 1999). These combined results suggest that the impact of particulates may be influenced by other location-specific conditions including light, currents, wave exposure and nutrient supply. Furthermore, *Sargassum* was rapidly grazed on midshelf reefs where it is usually rare (McCook, 1996) and cross-shelf differences in abundance of adult plants were affected more by herbivory than water quality (McCook, 1996), which has implications for interpreting spatial data sets.

Turf algae and epilithic algal matrix (EAM)

Turf algae are important because they are a major benthic cover, occupy dead coral, are stress tolerant, and their productivity supports overall reef productivity (Tebbett & Bellwood, 2020). They may become dominant on reefs as climate change reduces the cover of coral, so it is very important to understand how other stressors may influence them (Tebbett & Bellwood, 2020), and how they influence coral recruitment and recovery (Birrell et al., 2005).

There have been no comprehensive spatial analyses of turf algae diversity and abundance, but through modelling, turf algae on inshore reefs were shown to have lower productivity than on mid and outer shelf reefs due to sediment deposition and loads (Tebbett & Bellwood, 2020).

A number of experimental studies have investigated the effects of sediment. Turf algae (epilithic algal matrix) grew considerably longer with sediments settled on them, which was thought to be a response enabling them to reach light and/or because of nutrient availability associated with sediments (Goatley & Bellwood, 2013). High sediment loads and long turf lengths were associated with large declines in productivity at sediment loads >100–200 g m^{-2} (Tebbett & Bellwood, 2020). In another study, sediment loads negatively affected turf algae through lowering biomass by 63% compared to those with sediments removed (Tebbett et al., 2018a).

Turf algae are also heavily grazed by herbivorous fish, and fish behaviour and feeding also affects turf productivity and abundance, the sediment loads within them and their responses to sediment. Turfs had less sediment in damselfish territories, which was attributed to them actively cleaning or as a by-product of their activities (Ceccarelli et al., 2005). Higher sediment loads dilute the nutritional value of the turfs (Tebbett et al., 2018b). Excluding grazers also results in responses that are similar to the effects of adding sediments by turfs growing longer (Goatley & Bellwood, 2013). Therefore, the distribution of sediments settled on reefs, and their effects on turf algae are also influenced by ecological processes.

Crustose coralline algae

Crustose coralline algae (CCA) are one of the most important and widespread reef-builders in the marine photic zone worldwide and provide important cues for the settlement of coral larvae (Harrington et al., 2004). There are concerningly few studies on CCA given their ecological importance. There were two field studies and three experimental studies identified in this review.

The cover of CCA is strongly and inversely correlated to sediment deposits on reefs and to cross-shelf distance, which incorporates a range of other water quality variables (Fabricius & De'Ath, 2001). In a spatial analysis of reef biota and water quality variables, CCA cover was the most sensitive of all groups to increased suspended sediments (Smith et al., 2020). CCA were also more sensitive to low light treatments than coral and they became darker in low light treatments, and paled and died in the lowest light treatment indicating that light attenuation by suspended sediments may be one of the causes for this pattern (Bessell-Browne et al., 2017d).

CCA are also sensitive to high levels of settled sediment (carbonate). Physiological responses include loss of red pigments (Ricardo et al., 2021) and this was also associated with a decrease in settlement by coral larvae (Ricardo et al., 2021). The coral larvae settled once the CCA had increased their photosynthetic efficiency suggesting that there was a physiological cue of the CCA that were causing the low rates of coral larvae settlement (not a pigment/light spectra one) (Ricardo et al., 2021).

Microalgae – phytoplankton and benthic microalgae

Microalgae (pelagic and benthic) are important because their productivity underpins food webs of freshwater and marine ecosystems.

There are very few studies on benthic microalgae on the GBR in general, and few in relation to pressures from sediment and particulate nutrients. In a transect from the Fitzroy River to Heron Island, benthic productivity was low in the highly turbid (coastal/estuarine) environments compared to the less turbid environments (Heil et al., 2004). This was also found in a transect from Missionary Bay in Hinchinbrook Island to the mainland coast (Alongi & McKinnon, 2005). In both cases this was attributed to light limitation caused by high turbidity.

There are numerous studies on pelagic microalgae (phytoplankton) focused on water quality and correlating spatial and temporal patterns in water quality including chlorophyll *a* (see Question 4.1, Robson et al., this SCS). There are few studies that describe the response of plankton communities to sediments and particulate nutrients from a biological perspective (as opposed to water quality).

Marine phytoplankton increased dark yield (Fv/Fm) when they were exposed during experimental bioassays to sediments from the South Johnstone and the Bowen River catchments, but the increase only occurred in response to ~40% of them (Franklin et al., 2018). Chlorophyll *a* concentration (as a proxy measure for biomass) also increased in ~20% of sediments, but the freshwater communities did not respond as much (6%). It was concluded that the cause of the response was that particulate nutrients adsorbed to sediments dissociated and were transformed to dissolved nutrients (Franklin et al., 2018). Sediments settled and did not directly influence the response and so the marine plankton communities were increasing in response to particulate nutrient availability. Using a similar approach, soil properties were assessed and equations predicting the bioavailability of particulate nutrients from these properties were calculated (Garzon-Garcia et al., 2018). The best equations (based on R^2 and logical selection of parameters) included organic carbon, highlighting the important role of microbial particulate nutrient transformations in driving plankton responses to sediments (Garzon-Garcia et al., 2018).

In McKinnon et al. (2002), marine phytoplankton productivity correlated with particulate nutrients from prawn pond effluent. This also correlated with microbial productivity, which was assumed to facilitate the release of inorganic nutrients from the particulate nutrients (McKinnon et al., 2002) and indicated nutrient limitation.

Pelagic microalgae are light limited nearest to shore in turbid environments, and are the most productive in cross-shelf gradients where light level improves and nutrients are available (Heil et al., 2004). These spatial patterns in chlorophyll *a* and productivity are discussed further in Question 4.1 (Robson et al., this SCS).

There were no citations retrieved using this search criteria on the effects of particulates investigating the important nitrogen fixing blue-green alga *Trichodesmium*.

Microbes and foraminifera

Microbes

Studies on sediment effects on microbes within marine and freshwater environments of the GBR were primarily focused on composition and abundance (Table 16). Foraminifera studies related to the question were also predominantly on composition and growth.

Table 16. Studies that investigated microbes and foraminifera in relation to pressures related to the primary question, also showing the indicator category that was the focus of the question. A reference may be listed in multiple categories.

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Microbes							
Abundance	Franklin et al., 2018				Gottschalk et al., 2007	Alongi, 1990; Franklin et al., 2018; Garzon-Garcia et al., 2018	
Composition	Angly et al., 2016				Angly et al., 2016; Gottschalk et al., 2007; Witt et al., 2012		Witt et al., 2012
Distribution	Kriwy & Uthicke, 2011				McKinnon et al., 2002	McKinnon et al., 2002	
Physiology	Franklin et al., 2018	Weber et al., 2012				Franklin et al., 2018; Garzon-Garcia et al., 2018	
Productivity						Alongi, 1990; Alongi & McKinnon, 2005	
Foraminifera							
Abundance		Johnson et al., 2019					
Bleaching				Prazeres et al., 2016			
Composition	Uthicke & Nobes, 2008; Uthicke et al., 2010; 2012	Johnson et al., 2019	Uthicke et al., 2010				Reymond et al., 2013
Distribution				Nobes et al., 2008			
Growth				Nobes et al., 2008; Prazeres et al., 2016			
Mortality				Nobes et al., 2008			
Other							Reymond et al., 2013
Physiology				Nobes et al., 2008			

Microbes (benthic and pelagic prokaryotes, including archaea bacteria, bacteria, viruses and fungi) are important because they form biofilms on reefs, are productive, drive nutrient transformations and biogeochemical fluxes (McKinnon et al., 2002) and contribute to inducing larval settlement of reef invertebrates.

Microbial activity releases dissolved bioavailable nutrients from particulates promoting phytoplankton productivity which underpins broader ecosystem productivity (Alongi & McKinnon, 2005; Franklin et al., 2018; Garzon-Garcia et al., 2018). Benthic microbial productivity was the highest towards sources of particulate nutrients, such as mangroves (Alongi, 1990) and prawn pond effluent (McKinnon et al., 2002).

The microbial community is affected by gradients in water quality and varies over seasonal cycles with some phyla more likely to occur in the inshore reef (Kriwy & Uthicke, 2011; Witt et al., 2012). Furthermore, reef assemblages are more like riverine communities after high river discharge (Angly et al., 2016). These communities are affected by water quality including particulate nutrients and total suspended solids (Kriwy & Uthicke, 2011; Witt et al., 2012).

A higher prevalence of the microbial coral disease agent *Atramentous necrosis* (AN) was recorded in wet compared to dry seasons, and it was even higher in wet seasons with higher rainfall. Disease abundance was positively correlated with higher particulate organic carbon in the water column (Haapkylä et al., 2011).

Foraminifera

Foraminifera (forams) are important because they are diverse and abundant, and they have been explored as biological indicators of water quality due to their specific ecological requirements, relatively short life (months to years) and because the carbonate tests (exoskeleton) preserve well in the fossil record (summarised in Reymond et al., 2013). Studies typically differentiate between large photosymbiont-bearing benthic foraminifera and the more numerous smaller heterotrophic forams. Some studies have used the ratio of forams with different traits (foram index) as an indicator of water quality (Uthicke & Nobes, 2008; Uthicke et al., 2010).

In reef core sections, assemblages from inner and intermediate inshore reefs in the Mackay Whitsunday region were significantly different at ~55 years old to those older than 150 years (Uthicke et al., 2012), while those on the outer inshore reefs did not vary over the same timeframe - supporting the theory that river discharge drove the changes rather than global or more regional changes (Uthicke et al., 2012). At other inshore reefs (Pandora and Havannah Reef), foraminifera throughout the Holocene were correlated with factors associated with reef shallowing including hydrodynamic energy, light availability and carbonate content, but the timing of changes did not indicate an influence of changes in nutrient and sediment inputs (Johnson et al., 2019). Furthermore, in a separate study of the same reefs using methods to reconstruct paleo environmental conditions (δ^{13}C, C:N ratios), there were indicators of elevated terrestrially derived organic matter on the nearshore reef (Pandora Reef) throughout the 1,000 year record (analysed in 200 year blocks) (Reymond et al., 2013) but there were no signs of change as sediment and nutrient loads increased (Johnson et al., 2019; Reymond et al., 2013). Therefore, water quality appears to be an important influence over forams, but whether they respond to recent increases in sediments and nutrients appears to be location specific.

The abundance of some foram species increased with distance from mainland in the Mackay Whitsunday region, while for other species there was no trend (Nobes et al., 2008). Assemblage traits also varied among regions and reefs with different environmental characteristics (Reymond et al., 2013; Uthicke et al., 2010). Heterotrophic foraminifera were associated with high values of particulates (<63 and 63-250 μm) with high organic carbon content while symbiont species were associated with low turbidity and high inorganic carbon (Uthicke et al., 2010). However, these sediment and water quality gradients together explained less of the assemblage variation (27.7%)

than region did (35%). Similarly, heterotrophic assemblages from inshore Pandora Reef indicate organic matter enrichment associated with terrestrial runoff (C:N >15) (Reymond et al., 2013). The photosymbiont-bearing foraminiferal assemblages from Havannah Reef indicate reduced terrestrially derived organic matter (C:N <10), which could be due to a lower influence of river runoff or a greater level of mixing with oligotrophic water (Reymond et al., 2013).

In Nobes et al., (2008) the cross-shelf changes in assemblage in the inshore did not appear to correlate with benthic light. This was further confirmed by laboratory experiments in which growth rates of two species did not change with light treatments, while for *Heterostegina depressa*, growth was higher in low light compared to high light. Therefore, light was not the main variable driving differences (Nobes et al., 2008). Light levels (photosynthetic and ultraviolet (UV) light) affected foram condition in experiments conducted on forams collected along a cross-shelf gradient in Cape York but the consequences for survivorship depended on the shelf position (Prazeres et al., 2016). Forams from the inner shelf in Cape York were more resistant to variation in light levels than those of mid and outer shelfs, which had lower survivorship under high light levels (Prazeres et al., 2016). However, they all developed lower density shell in the external chambers when under low light irrespective of where they originated from (Prazeres et al., 2016).

Seagrass

There were 45 studies on seagrass relating to the primary question. There are 12 commonly recognised species of seagrass in the GBR (Carter et al., 2021a). The studies related to the primary question were biased towards *Zostera muelleri*, *Halodule uninervis, Halophila decipiens* and *Cymodocea serrulata* (Table 17). Four species only appeared in studies that covered all GBR species and were never the focus of study: *Thalassodendron ciliatum*, *Enhalus acoroides*, *Halophila tricostata*, and *Halophila capricorni*. Most studies focused on the impacts of light, suspended sediments and water quality on seagrass abundance (Table 18).

Table 17. Species of seagrass in studies relating to this question.

Seagrass species	Number of studies
Cymodocea rotundata	1
Cymodocea serrulata	7
Enhalus acoroides	0
Halophila capricorni	0
Halophila decipiens	7
Halophila ovalis	6
Halophila spinulosa	6
Halophila tricostata	0
Halodule uninervis	7
Syringodium isoetifolium	0
Thalassia hemprichii	3
Zostera muelleri (capricorni)	11
All*	4

Not including 12 reviews which generally refer to all species.

Table 18. Studies that investigated seagrass in relation to pressures related to the primary question, also showing the indicator category that was the focus of the question. A citation may be listed in multiple categories.

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Abundance	Campbell & McKenzie, 2004; Collier et al., 2020; Lambert et al., 2021; Lamberta et al., 2019; Petus et al., 2014; Preen & Marsh, 1995; Preen et al., 1995; Turschwell et al., 2021	Benham et al., 2019; McKenzie, 2007; Schaffelke et al., 2005		Adams et al., 2020; Carter et al., 2021a; Chartrand et al., 2016; 2018; Collier et al., 2012a; 2012b; 2016a; 2016b; 2021a; 2021b; McKenzie et al., 2022; Schrameyer et al., 2018; Waycott et al., 2005; Wooldridge, 2017; Wu et al., 2017; York et al., 2015	Carter et al., 2022; Collier et al., 2020; Grech & Coles, 2010; McKenna et al., 2015; McKenzie et al., 2022; Petus et al., 2014; Waycott et al., 2005	Schaffelke et al., 2005; Turschwell et al., 2021	Carter et al., 2021a; Collier et al., 2021b
Composition	Campbell & McKenzie, 2004; Collier et al., 2020; Connolly et al., 2018			Carter et al., 2021a; Collier et al., 2021b; Waycott et al., 2005	Carter et al., 2022; Collier et al., 2020; Connolly et al., 2018; Waycott et al., 2005		Carter et al., 2021a; Collier et al., 2021b
Distribution					Grech & Coles, 2010		
Growth		Benham et al., 2016; 2019		Benham et al., 2016; Collier et al., 2012a; 2016a			
Morphology				Chartrand et al., 2016; Collier et al., 2012a; O'Brien et al., 2018a			
Mortality		Benham et al., 2019		Adams et al., 2020; Collier et al., 2016a			
Multiple	Bainbridge et al., 2018; Brodie et al., 2017a; Hairsine, 2017; Haynes et al., 2007; Magris & Ban, 2019; Waterhouse et al., 2017	Bainbridge et al., 2018; Brodie et al., 2017a; Hairsine, 2017; Haynes et al., 2007; Magris & Ban, 2019		Bainbridge et al., 2018; Brodie et al., 2017a; Haynes et al., 2007			

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Other	Petus et al., 2018			Schrameyer et al., 2018			Petus et al., 2018
Physiology	Brodie et al., 2017b			Adams et al., 2020; Brodie et al., 2017b; Campbell et al., 2007; Chartrand et al., 2018; Pollard & Greenway, 1993			
Reproduction				McKenzie et al., 2022; O'Brien et al., 2018a	McKenzie et al., 2022		
Resilience	Connolly et al., 2018; McCook et al., 2015; O'Brien et al., 2018b			McKenzie et al., 2022; O'Brien et al., 2018a	Connolly et al., 2018; McKenzie et al., 2022		

Seagrasses thrive in inshore areas where they absorb nutrients and there is protection in sheltered bays (Carter et al., 2021a; Grech & Coles, 2010; Schaffelke et al., 2005; Waycott et al., 2005). In the inshore, there is also a high likelihood of exposure to suspended sediment loads from discharge and resuspension where seagrasses predominantly occur (Waterhouse et al., 2017). Unlike reef species, there were limited studies examining the impacts to seagrass based on spatial variation in water quality and seagrass abundance and distribution with few exceptions (Carter et al., 2021a; Collier et al., 2021a) or seagrass and proximity to rivers (Grech & Coles, 2010) at the scale of the GBR.

Seagrass monitoring has been undertaken at a number of locations in the inshore GBR since the 1990s (Carter et al., 2022). Monitoring was conducted by Seagrass-watch (McKenzie et al., 2022) and a co-ordinated ports monitoring program from which some published papers have contributed to this review (Collier et al., 2020; McKenna et al., 2015; York et al., 2015). The ports monitoring program also contributes substantial data towards the 'seagrass composite' dataset that has been applied in numerous publications referred to here (e.g., Carter et al., 2022; Carter et al., 2021b). The inshore seagrass Marine Monitoring Program established in 2005 produces annual peer reviewed reports that track the condition and resilience of seagrass habitats in conjunction with light, temperature and other biological variables. There is no ongoing seagrass monitoring on the midshelf and outer reef and there are considerably less data from Cape York, compared to other NRM regions (Carter et al., 2021b; McKenzie et al., 2022).

There was only one study or monitoring program that met the search criteria that included turbidity, suspended sediments or particulate nutrients measured *in situ* (Campbell & McKenzie, 2004) and none where these parameters were experimentally manipulated to examine seagrass responses. A range of others included sediment loads (Lambert et al., 2021; Lamberta et al., 2019) or modelled relative exposure to turbidity based on water colour (Collier et al., 2020; Petus et al., 2014; Turschwell et al., 2021). Seagrasses do not directly use particulate nutrients and one of the primary known pathways for them and suspended sediments to affect seagrass is through light attenuation (Bainbridge et al., 2018).

What are the measured impacts to seagrass?

Seagrass abundance and extent declines when extreme weather events increase river discharge and increase exposure to turbid water (Campbell & McKenzie, 2004; Carter et al., 2022; Collier et al., 2012b; Lambert et al., 2021; McKenzie et al., 2022; Petus et al., 2018; Waterhouse et al., 2017). While a single event may have substantial immediate impacts in some local contexts (Campbell & McKenzie, 2004; Collier et al., 2012b), consecutive wet seasons and cumulative impacts were identified to cause significant, widespread and more prolonged impacts (Lambert et al., 2021; McKenna et al., 2015; McKenzie et al., 2022). Local conditions affect the impact of declining water quality on seagrass (McKenzie et al., 2022) through some of the mechanisms described in the following section including the influence of low light. The timing is also critical: seagrass may also decline or even completely die-off during the senescent season (Chartrand et al., 2016; York et al., 2015) and therefore if low light occurs during the senescent season or when ephemeral meadows have died back, the impacts may not be as severe (Chartrand et al., 2016; Wu et al., 2017). Dredge-induced turbidity plumes have also been linked to a failure of annual seagrass populations (i.e., deepwater seagrass that re-grows each year) to establish in the following year (York et al., 2015).

Impacts to seagrass follows a relatively predictable sequence with physiological changes occurring within days to weeks, followed by leaf and shoot shedding and growth of new altered tissue, and meadow scale changes, such as species shifts (Collier et al., 2012a; O'Brien et al., 2018a). As indicators, both biomass and percent cover are highly sensitive indicators of water quality (Carter et al., 2022; Chartrand et al., 2016; McKenzie et al., 2022), while shoot density may be less sensitive (Chartrand et al., 2016) because shoots may be retained, but with lower leaf density or modified morphology (e.g., smaller leaves). The extent of seagrass also contracts but more so after prolonged or repeated disturbance (Collier et al., 2012a; McKenna et al., 2015; McKenzie et al., 2022; Petus et al., 2014).

The loss of seagrass affects availability of food for dependant species including dugong and turtle (Preen & Marsh, 1995) and dugong carrying capacity is therefore affected by reductions in seagrass extent and abundance (Brodie et al., 2017b; Wooldridge, 2017). The follow-on effects of habitat loss have not been recorded in the GBR, however, adjacent to it in Hervey Bay, floods and a cyclone in early 1992 led to the loss of more than 1,000 km^2 of seagrass caused by high turbidity and physical disturbance of the sediment (Preen et al., 1995). After 6-8 months, there was a substantial increase in dugong mortality, and a decline in the proportion of dugong calves (Preen & Marsh, 1995).

What are the mechanisms of impact?

Low light or modified light reduces photosynthetic rates

There were a number (24, 56%) of studies that focused on benthic light or light attenuation proxies such as secchi depth (Table 18). These indicators sum the effect of suspended particulate matter on light attenuation and places the emphasis on the mechanism of particulates driving impacts on seagrass (as per coral, page 33, this synthesis). This includes *in situ* light measured at the canopy level, modelled light (e.g., eReefs or satellite), experimental manipulation (Chartrand et al., 2016; Collier et al., 2012a; 2016a), modelling studies and risk assessments (Waterhouse et al., 2017). These studies on light generally do not enable the cause of light reduction (suspended sediments, particulate organic matter, chlorophyll *a* etc.) to be identified, or the source (resuspension or discharge) and in some cases the change in light levels may be exacerbated by clouds.

The light environment where seagrass grows is highly variable (O'Brien et al., 2018a). Decreases in benthic light cause relatively rapid physiological and morphological changes, which are inferred to be acclimation or optimisation of plant performance to the changed conditions (Chartrand et al., 2018; Collier et al., 2012a; O'Brien et al., 2018a; Wu et al., 2017). Improvements in light absorption and utilisation efficiency when light levels decline are seen through increasing pigment concentrations and photosystem II efficiency (Campbell et al., 2007; Chartrand et al., 2018). They are also very sensitive to increasing light levels, with sharp rises in photosynthetic rates as light levels increase (Pollard & Greenway, 1993).

Seagrasses may rely more on stored reserves in the form of sugars and starch to maintain growth and metabolism when there is insufficient light for photosynthesis (Collier et al., 2012a; O'Brien et al., 2018a) and as such the condition and energy reserves leading up to low light events are important (Chartrand et al., 2016; O'Brien et al., 2018a). These reserves eventually deplete and require renewal, and as such, intermittent shading punctuated by ambient levels of light (2 week cycles), have less of an impact (Chartrand et al., 2016). With prolonged depletion of light and low rates of photosynthesis, the carbon imbalances result in the cover of seagrass or biomass declining as shown experimentally (Collier et al., 2012a; 2016a;) and observed in numerous locations in the GBR (Carter et al., 2022; Collier et al., 2016b; McKenna et al., 2015; McKenzie et al., 2022; Petus et al., 2014; York et al., 2015). Seagrass also reduces in extent, particularly near the deeper edge and becomes fragmented and patchy when low light levels are further prolonged or are repeated over multiple years and wet seasons (Lambert et al., 2021; McKenna et al., 2015; McKenzie et al., 2022; Petus et al., 2014).

Tolerance to light reduction and energetic balances are affected by conditions other than light as well (O'Brien et al., 2018a). Carbon accumulation is affected by temperature, including water temperature variability that occurs over seasonal cycles, with higher temperatures enhancing carbon loss when light is low (Adams et al., 2020; Collier et al., 2016a; Pollard & Greenway, 1993). Light reduction during the seagrass senescent season causes a lower level of seagrass loss than during the growing season as water temperature is warming and light levels increase (Chartrand et al., 2016).

Light thresholds are a proxy for water quality guidelines in seagrass habitats, as there are no turbidity, particulate nutrient or chlorophyll guidelines for seagrass. Light thresholds have been developed for short-term light reductions (weeks-months), that can be applied in dredge management plans and for understanding wet season dynamics. These have been developed with a moderate to high level of confidence for *Zostera muelleri*, with lower confidence for a few additional species, and very low confidence for the majority of species owing to the lack of studies (Collier et al., 2016b). Light requirements over seasonal or annual timescales can also be applied for testing the outcomes of management strategies (Brodie et al., 2017b; Collier et al., 2021a; Wooldridge, 2017), but require further refinement, including understanding the effects of multiannual conditions (Lambert et al., 2021) and the effects of local conditions and local acclimation or adaptation.

Changes in the composition, depth and redox potential of sediment affects seagrass

Sediment type and nutrient content has a strong influence on the presence, abundance and condition of seagrass, and the percent of mud (modelled by eReefs) is an important variable for predicting seagrass community composition (Carter et al., 2021a; Waycott et al., 2005). The sediment composition can change following a large discharge event (*sensu*. Campbell & McKenzie, 2004). If there is an increase in the proportion of mud or particulate organic matter, it can alter reducing potential of the sediment, the beneficial microbiome, and lead to intrusion of hydrogen sulphide to roots (Bainbridge et al., 2018). A change in photosynthetic rates, photosynthate release and oxygen diffusion into sediments caused by shading can also affect these processes (Bainbridge et al., 2018; O'Brien et al., 2018a; Schrameyer et al., 2018). In the low nutrient carbonate sediments at Green Island, short-term shading reduced photosynthesis and appeared to reduce exudation, microbial activity and increase the depth of where hydrogen sulphide accumulated, but this is not expected under organic and nutrient enriched conditions (Schrameyer et al., 2018).

An increase in the amount of sediments being deposited can also bury seagrass and prohibit seed germination (Benham et al., 2019; Campbell & McKenzie, 2004), and the impacts can exceed those of low light at extreme levels of burial (>10 cm) (Benham et al., 2016). These processes and their effects on the condition of seagrass have received very little research attention within the GBR, even though the majority of seagrass biomass is in below ground tissues and within sediments (Collier et al., 2021b).

Seagrass resilience is underpinned by feedback processes, resistance strategies and propensity to recover

Many of the seagrass habitats of the GBR are inherently dynamic and prone to cycles of decline and recovery, depending on their exposure to disturbances and the species composition. Seagrass species can be grouped according to their resilience strategies that enable them to either tolerate and resist disturbances (persistent species), recover quickly from them (colonising species), or be able to employ both strategies (opportunistic species) (McKenzie et al., 2022; O'Brien et al., 2018b). The characteristics influencing their resilience strategies include morphological variables, growth and turnover rates and reproductive output (O'Brien et al., 2018b). Tropical seagrass meadows including in the GBR, are commonly dominated by colonising and opportunistic species with a greater reliance on recovery and reproduction (Carter et al., 2021a; McKenzie et al., 2022; Waycott et al., 2005) and in extreme conditions such as deepwater habitats, there is also reliance on transient life history traits (York et al., 2015). Local adaptation of the population by enhancing the number of stress tolerant genotypes may also enhance resilience to flooding based on findings from Moreton Bay following floods in 2011 (Connolly et al., 2018).

In a global analysis, opportunistic species were the most likely to rapidly change (increasing or decreasing) in response to pressures such as turbidity variability, while persistent species tended to change slowly, and colonising species trajectories were not predictable (Turschwell et al., 2021). The Inshore Seagrass MMP incorporates a resilience indicator that includes several features of resilience, and a change in the resilience score provides an indication of trajectory (McKenzie et al., 2022). The resilience indicator also includes an assumption (based on data analysis), that seagrass meadows with persistent species are more stable (McKenzie et al., 2022). However, there are various factors that influence seagrass trajectory and resilience strategies that remain poorly understood globally including the GBR (O'Brien et al., 2018b).

Sedimentation may be enhanced by the presence of seagrass (McKenzie, 2007; O'Brien et al., 2018b). Therefore, decline in cover or biomass and fragmentation of the meadow can breakdown the feedback processes that maintain stable sediments and enhance water clarity (Bainbridge et al., 2018; O'Brien et al., 2018a; 2018b). This could enhance the rate of loss or delay recovery time and increase the environmental improvements needed for recovery, and without this, there may be recalcitrant degradation (O'Brien et al., 2018a). The role of feedbacks has been summarised in review papers (O'Brien et al., 2018a; 2018b), however their importance has not been investigated and thresholds leading to their breakdown have not been observed in the GBR. It is however, essential to know which feedback processes are important in different contexts, such that monitoring and management can be optimised towards them.

The inshore GBR is dominated by opportunistic species that have shown capacity to recover within the same year during the growth season to some extent, especially for colonising rapid growing species such as *Halophila* spp. (York et al., 2015). Full recovery of some opportunistic species (based on percent cover) following major events within five years has been recorded in some locations around Townsville, but protracted recovery has been recorded in other locations (Carter et al., 2022; McKenzie et al., 2022). Land management scenarios improved the extent of suitable seagrass habitat through predicted improvements in benthic light (Collier et al., 2021a). There is insufficient quantitative information that can enable recovery rates to be predicted and to identify limitations to recovery in the GBR, which is essential information needed to identify management interventions that could enhance recovery (O'Brien et al., 2018a; 2018b).

Where is there evidence of impacts to seagrass?

There is evidence of water quality-related seagrass loss from numerous locations in the inshore GBR, particularly in the central and southern inshore from the Wet Tropics to the Burnett Mary NRM regions (Campbell & McKenzie, 2004; McKenzie et al., 2022; Petus et al., 2014; York et al., 2015) and minor declines in Cape York have also been attributed to wet season river discharge (McKenzie et al., 2022). Low light associated with prolonged elevated turbidity caused by extreme weather events, discharge and resuspension are often cited as major contributors to loss. Local, regional and climate factors can also influence vulnerability to water quality declines and recovery from them (Adams et al., 2020; McKenzie et al., 2022) and so they need to be assessed as cumulative pressures (see Question 2.4 Uthicke et al., this SCS).

In summary, the main focus of seagrass studies related to Question 3.2 were studies on light, although there were some studies investigating the impacts to seagrass based on exposure to turbid water (remote sensing water colour) and sediment loads. The abundance of seagrasses are variable but extreme weather and discharge events have been associated with enhanced seagrass loss, and repeated or prolonged events drive the greatest declines, including contraction in their extent. This is most likely due to reductions in light availability caused by suspended particulates and has flow on effects for dependant species including marine megafauna. There has been evidence for water quality-related loss in all NRM regions of the GBR, but to a smaller extent in Cape York.

Non-coral invertebrate reef species

Of the 21 studies on non-coral invertebrates, there were 11 studies with a focus on sponges. Other studies covered a range of organisms, including echinoderms, gastropods, and molluscs (Table 19).

Table 19. Studies that investigated non-coral invertebrate reef species in relation to pressures related to the primary question, also showing the indicator category that was the focus of the question. A reference may be listed in multiple categories.

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Bioeroders							
Abundance	Le Grand & Fabricius, 2011					Le Grand & Fabricius, 2011	
Crustacea							
Mortality			Fabricius & Wolanski, 2000				
Cryptofauna							
Composition		Kramer et al., 2014					
Echinodermata							
Abundance		Fabricius, 1994					
Composition		Fabricius, 1994					
Gastropoda							
Abundance	Catterall et al., 2001	Catterall et al., 2001					
Mollusc							
Growth			Yukihira et al., 2006				
Mortality			Yukihira et al., 2006				
Multiple							
Multiple	Hairsine, 2017; Magris & Ban, 2019	Hairsine, 2017; Magris & Ban, 2019					
Sediment community							
Physiology			Lantz et al., 2017				Lantz et al., 2020

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Productivity			Lantz et al., 2017				
Sponge							
Abundance	Ramsby et al., 2017	Ramsby et al., 2017			Bannister et al., 2010		
Behaviour	Abdul Wahab et al., 2019	Abdul Wahab et al., 2019					
Composition	Ramsby et al., 2017	Ramsby et al., 2017					
Disease		Luter et al., 2012					
Distribution					Bannister et al., 2010		
Growth	Pineda et al., 201)	Pineda et al., 2016; 2017b					
Morphology					Bannister et al., 2010		
Mortality	Abdul Wahab et al., 2019; Luter et al., 2021; Pineda et al., 2016; 2017a	Abdul Wahab et al., 2019; Pineda et al., 2016; 2017a; 2017b		Pineda et al., 2017a	Luter et al., 2021		
Physiology	Bannister et al., 2012; Luter et al., 2021; Strehlow et al., 2017	Pineda et al., 2017b; Strehlow et al., 2017		Luter et al., 2021; Strehlow et al., 2017			
Reproduction	Abdul Wahab et al., 2019	Abdul Wahab et al., 2019			Whalan et al., 2007		
Symbionts	Luter et al., 2021; Pineda et al., 2016	Luter et al., 2012; Pineda et al., 2016			Luter et al., 2021		

Barnacles and gastropods

Coral-dwelling barnacles are crustaceans that build a shell adhered to the coral surface, and their feather like appendages protrude for feeding. Fabricius and Wolanski (2000) demonstrated that barnacles were able to cleanse themselves of deposited sediments at low levels of sedimentation in offshore conditions, but the sticky mud aggregates of inshore sediments caused barnacles to vigorously clean themselves, and they subsequently died (Fabricius & Wolanski, 2000). This pilot study demonstrated that barnacles are sensitive to inshore sediments, but there have been no further quantitative studies on the levels of sedimentation that negatively impact them.

In another study, the Gastropod *Conomurex luhuanus* (previously *Strombus luhanus*) was monitored over 13 years at Heron Island and an effect of dredging of the boat harbour observed. After dredging, there was a progressive density decline coupled with low recruitment at two locations, and a later decline at a third location, followed by a recruitment-driven rebound after a cyclone (Catterall et al., 2001).

Sponges

There were 11 studies on sponges and other non-coral reef invertebrates including *in situ* observational studies and experiments on larvae (2) and adults (0).

Sponges are lower in abundance and have a reduced depth range in inshore areas and this has been attributed to a higher proportion of fine sediments (Abdul Wahab et al., 2019; Bannister et al., 2010; Ramsby et al., 2017). The abundance and depth distribution of the sponge *Rhopaloeides odorabile* increased with distance from the coast (Bannister et al., 2010). The bio-eroding sponge *Cliona orientalis* was also affected by water quality and sediment, occurring less where the percentage of fine sediments exceeded 17% (generally sheltered areas) and changing in abundance in relation to chlorophyll *a* concentrations (Ramsby et al., 2017).

Experimental studies have been used to investigate the mechanisms that may lead to these distributional patterns. High suspended sediment concentrations (250 and 500 mg L^{-1}) led to no or very low growth of ten sponge species and mortality of *Callyspongia confoederata* (Pineda et al., 2016). Growth rates were also negative at suspended sediment concentrations 76 mg L^{-1} in 5 of those species over 28 days (Pineda et al., 2017b). There was also partial mortality and discoloration of tissue caused by higher suspended sediment concentrations after 28 days of exposure, but with only 7 days of exposure and 2 days of sediment being removed there were no visible impacts to the tissue of *Carteriospongia foliascens,* indicating reversible damage over shorter timeframes (Pineda et al., 2017a).

Adult sponges (*Rhopaloeides odorabile*) increased their respiration rates when exposed to clay sediments by 35% but only by 12% when exposed to slightly coarser carbonate sediments. Respiration rates may also decline in response to higher suspended sediments (Pineda et al., 2017b), so it is difficult to generalise about the respiratory responses of sponges. However, a shift in the ratio of storage to structural lipids after 28 days of exposure to suspended sediments, indicates a depletion of energy reserves, caused by suspended sediment exposure (Luter et al., 2021).

The larval stage of sponges is sensitive to sediments. In Abdul Wahab et al. (2019), larval survival of the sponge *Carteriospongia foliascens* was reduced by suspended sediments, with sediments attaching to cilia that led to death of 10% of the larvae at 2.6 mg L^{-1} sediment and 50% of larvae at 17.6 mg L^{-1}. Larval recruitment was also affected by settled sediments and 25 times more likely to be dislodged when there was 3 mg cm^2 sediment compared to 0.3 mg cm^2. In combination these results indicate that not only is sponge recruitment affected by sediments, but high sediments are likely to cause them to be recruited back into the same habitats (Abdul Wahab et al., 2019).

In summary, short-term exposure to high levels of suspended sediment slow growth of sponges, but the mechanisms driving these responses are not clear. Long-term exposure to elevated suspended sediments reduces the abundance and distribution of sponges, which may be influenced by recruitment dynamics.

Fish

There were 21 studies on fish with the majority being experimental approaches (Table 8). Studies on reef fish were biased towards damselfishes (Family Pomacentridae), with 8 of the 11 experimental studies focusing on this family, however a range of species within this family were studied (Table 20). The other three papers studied parrotfish (Scarinae), surgeonfish (Acanthuridae) and roving herbivore communities. Observational studies and reviews did not focus on one species, but the fish community. Studies on fish primarily investigated the effects of suspended sediments on feeding behaviour, recruitment and growth, and the effect of settled sediment on feeding behaviour (Table 21).

Table 20. Genera (and family) of fish in studies relating to this question, studies which include more than one genus are counted multiple times.

Fish	Number of studies
Family: Pomacentridae	
Pomacentrus	4
Dascyllus	2
Chromis	2
Amphiprion	2
Stegastes	1
Acanthochromis	1
Neopomacentrus	1
Family: Pseudochromidae	
Pseudochromis	1
Family: Acanthuridae	
Ctenochaetus	1
Acanthurus	1
Family: Labridae, subfamily Scarinae	
Scarus	1

Abundance and diversity

Fish abundances have been found to correspond to variations in water quality index, calculated using levels of particulate and dissolved nutrients, chlorophyll and suspended solids. Fabricius et al. (2005) identified that the total relative abundance and richness of fish did not change along water quality gradients in two regions, however the abundances of 11 different fish species (including a herbivore, several damselfish and several predatory fishes) systematically varied along the water quality gradients (Fabricius et al., 2005). The mechanisms or historical context relating to these effects were not identified within the study (Fabricius et al., 2005).

Table 21. Studies that investigated fish in relation to pressures related to the primary question, also showing the indicator category that was the focus of the question. A reference may be listed in multiple categories.

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Abundance	Fabricius et al., 2005				Fabricius et al., 2005		
Composition	Fabricius et al., 2005				Fabricius et al., 2005		
Feeding behaviour	Johansen & Jones, 2013; Wenger et al., 2012; 2013	Bellwood & Fulton, 2008; Goatley et al., 2016; Gordon et al., 2016; Tebbett et al., 2017	Gordon et al., 2016				
Growth	Wenger et al., 2012; 2014						
Morphology	Hess et al., 2015						
Mortality	Wenger et al., 2012; 2014						
Multiple	Bainbridge et al., 2018; Brodie et al., 2017a; Magris & Ban, 2019; Waterhouse et al., 2017; Wenger et al., 2015	Bainbridge et al., 2018; Brodie et al., 2017a; Magris & Ban, 2019; Waterhouse et al., 2017; Wenger et al., 2015		Brodie et al., 2017a			
Pathogens	Hess et al., 2015						
Physiology	Wenger et al., 2012						
Reproduction	Wenger et al., 2011; Wenger & McCormick, 2013; Wenger et al., 2014						

Growth, physiology and mortality

The growth of damselfish in their larval and juvenile stages is negatively affected by increased suspended sediments (Brodie et al., 2017a; Waterhouse et al., 2017; Wenger et al., 2015). Juvenile *Acanthochromis polyacanthus* were observed to have significantly decreased growth rates when exposed to increased concentrations of suspended sediments compared to control, however growth rates did not differ significantly between treatments (Wenger et al., 2012). The growth of *Amphiprion percula* also varied between suspended sediment treatments, however the relationships between growth and suspended sediment concentrations were more complex (Wenger et al., 2014). Larvae exposed to low levels of suspended sediments (15 mg L^{-1}) had significantly greater length, mass and standardised mass at metamorphosis compared to those under the control conditions. As suspended sediment concentrations increased, mass and standardised mass decreased, with larvae exposed to the high sediment treatment (45 mg L^{-1}) having significantly lower mass and standardised mass than those exposed to the low sediment treatment (Wenger et al., 2014). These results suggest metamorphosis is delayed in *A. percula* in response to higher suspended sediments, however the mechanisms behind this response were not identified (Wenger et al., 2014).

Body condition of *A. polyacanthus* was also assessed by Wenger et al. (2012), measured by the density of hepatocyte vacuoles, whereby fish exposed to medium and high suspended sediment treatments displayed a significant decline in body condition compared to those exposed to the control and low treatments. Furthermore, the survival of juvenile *A. polyacanthus* was significantly reduced under the high sediment treatments, however no significant variation in survival between the control, low and medium treatments was found (Wenger et al., 2012). In contrast to these findings, mortality of *A. percula* did not differ significantly between treatments (Wenger et al., 2014)

Morphology and pathogens

Increased suspended sediment concentrations have been identified to modify gill tissue and structure of fish larvae (Bainbridge et al., 2018; Wenger et al., 2015). Hess et al. (2015) reported additional cell layers accumulating on the gill epithelium of *A. percula* larvae when exposed to suspended sediment concentrations of 45 mg L^{-1}. The growth of these additional cell layers result in a thicker gill epithelium, increasing the diffusion distance of oxygen between water and the blood, therefore reducing oxygen supply to the larvae (Hess et al., 2015). Mucous production within the gills was found to double with increased suspended sediment, potentially congesting gill lamellae, causing further respiratory stress. Exposure to increased suspended sediments also significantly altered the gill microbiome of *A. percula* larvae, with a shift from ‘healthy’ bacteria found on the gills of individuals in the control, to parasitic bacterial communities on the gills of those exposed to a higher concentration (Hess et al., 2015). These changes in gill morphology and mucous discharge are thought to be mechanisms to protect gill tissues from abrasion by sediment particles.

Recruitment

Suspended sediments can impair visual acuity of fish and detection of chemical cues, limiting the ability of recruiting reef fish to find suitable habitat for settlement (Bainbridge et al., 2018; Wenger et al., 2015). When exposed to increased suspended sediments, damselfish were not able to select their preferred habitat, settling on live coral just as frequently as partially dead and dead corals, whereas under control conditions they showed a strong preference for live corals (Wenger et al., 2011; Wenger & McCormick, 2013). The threshold of suspended sediments impairing visual cues and having an influence on recruitment on *Pomacentrus moluccensis* was identified to be 5 mg L^{-1}, a level which is frequently exceeded (~30%) in central inshore GBR around Townsville (Wenger & McCormick, 2013). Juvenile reef fish also use chemosensory mechanisms such as chemical cues to find suitable habitat to settle, and increased suspended sediments disrupt these chemical cues, reducing the fishes ability to distinguish between live and dead coral (Wenger et al., 2011). These impacts on recruitment are consistent with the findings of a global review by Magris and Ban (2019), whereby recruitment was found to be sensitive to sediments.

The time which it takes reef fish larvae to settle on reefs can significantly affect their chances of survival, as a longer pelagic larval form can have significant implications for recruitment success and mortality (Wenger et al., 2015). When exposed to increased suspended sediment concentrations, the median settlement times of juvenile *A. percula* was slightly longer (12 days) compared to controls (11 days), however the age distribution of juveniles at settlement was highly variable when exposed to suspended sediments, reaching up to 22 days compared to a maximum of 13 days for controls (Wenger et al., 2014).

Foraging and predation

Reduced visibility due to suspended sediments can also affect food acquisition of reef fish, including foraging behaviours and predator-prey interactions, by impairing visual cues necessary for foraging (Bainbridge et al., 2018; Brodie et al., 2017a; Waterhouse et al., 2017; Wenger et al., 2012; 2015). An increase in suspended sediments resulted in the juvenile damselfish *A. polyacanthus* taking a greater amount of time to find food, leading to them consuming less food, which has implications for physiological health and mortality (Wenger et al., 2012). Similarly, Johansen and Jones (2013) noted a reduction in foraging performance of planktivorous damselfish species when exposed to higher turbidity, with attack success significantly declining. The effects of turbidity on predator-prey interactions are more complex. Although predation by *Pseudochromis fuscus* on *Chromis atripectoralis* has been observed to be significantly changed by turbidity levels, the relationship is nonlinear (Wenger et al., 2013). Predation success was significantly greater under the medium turbidity treatment compared to lower success in the control and high turbidity treatment, suggesting an imbalance in the sensitivity of these two species to altered turbidity levels (Wenger et al., 2013).

There is also evidence that increased, or even naturally occurring, sediment loads within the epilithic algal matrix (EAM) can suppress herbivory (Bainbridge et al., 2018; Bellwood & Fulton, 2008; Brodie et al., 2017a; Goatley et al., 2016; Waterhouse et al., 2017; Wenger et al., 2015). A 90% decline in grazing and browsing by herbivores at Orpheus Island was associated with increased sediment loads in turf algae as a result of disturbances (including cyclones and flooding) (Goatley et al., 2016). Experimental reductions of naturally occurring sediment loads also significantly altered feeding rates, with reduced loads resulting in increased feeding rates of roving herbivores and detritivores by 3.8-fold (Bellwood & Fulton, 2008). Similar behaviours were observed in the surgeonfish *Ctenochaetus striatus*, whereby an experimental study found bite rate decreased as a response to increasing sediment loads, however in contrast varying sediment loads had no effect on *Acanthurus nigrofuscus* feeding behaviour (Tebbett et al., 2017).

Additionally, sediment properties also play a role in foraging behaviours, with fish displaying a preference to certain types. Fish are generally deterred from carbonate sediments, the main reason for this is believed to be due to carbon interfering with digestion (Bellwood & Fulton, 2008). Parrotfish have been observed to display a preference towards EAM with fine silicate sediments compared to EAM with coarse carbonate sediments, suggesting that whilst silicates are harder than carbonates, the fine grain size of silicates may reduce their impacts (Gordon et al., 2016). Parrotfish also preferred sediments with high organic loads, indicating that herbivory may be relatively unimpacted by moderate terrigenous sediment inputs (Gordon et al., 2016), however this preference towards higher organic loads was not found to be significant for surgeonfish (Tebbett et al., 2017).

In summary the majority of fish studies related to Question 3.2 were experimental studies, and primarily focused on the effects of suspended sediment concentrations. Increased suspended sediments have a range of impacts on fish throughout larval, juvenile and adult stages of life, including reduced growth, reduced body condition and increased mortality. Sediments also impair the visual and chemical cues used by fish, limiting juvenile success in finding suitable settlement habitat, reducing foraging success and altering predator-prey interactions. Furthermore, these sediments accumulate within the EAM, increasing settled sediment loads which can result in herbivory suppression.

Freshwater ecosystems

Water pollution is considered one of the major threats to GBR catchment wetlands but their impacts are driven by pollutant loads, residence time, wetland area and climate (Adame et al., 2019). Freshwater wetlands are generally affected by pulses of flood water carrying high loads, and then extended exposure to poorly flushed water in the dry season. There are few studies that have assessed the impact of sediments and particulates on freshwater ecosystems adjacent to the GBR, and so most of the evidence is from reviews written for the GBR, but that compile information from Australian and global sources (Adame et al., 2021; Davis et al., 2017).

Aquatic organisms of the GBR are generally able to tolerate short-term exposure to elevated sediments in pulsed runoff (Davis et al., 2017), while chronic turbidity has an impact on streams that are naturally clear such as those of the wet tropics but is less likely to affect rivers such as the Burdekin and Fitzroy that permanently have low photic depths (Davis et al., 2017). The turtle *Elseya irwini* is one species that uses cloacal respiration as an alternate means of oxygen acquisition, and suspended sediment reduces the efficiency of the process and their diving duration under some conditions (Schaffer et al., 2016). Elevated turbidity may influence the diversity of fish species in the Barron River, although many fish species tolerate high turbidity (Davis et al., 2017). Some invertebrate species have shown high levels of resistance to suspended sediments in the short term (Adame et al., 2019) and some invertebrates can rely on alternative senses for searching for prey when water clarity is low (Davis et al., 2017). The effects of sedimentation depend on the flow characteristics of the stream, with upland wet tropics streams more susceptible than those of slow moving streams with high levels of fine sediments in the stream beds (Davis et al., 2017). A change in sediments could impact on egg-laying in fish species (Davis et al., 2017).

There is evidence from around the world that excess nutrients cause excessive growth of algae and aquatic vegetation but these focus predominantly on dissolved nutrients (Adame et al., 2019; Brodie & Mitchell, 2005; Davis et al., 2017). The contribution of particulate nutrients to eutrophication has not been addressed, especially in the GBR. The amount of coarse particulate organic matter (CPOM) collected with each invertebrate sample correlated strongly with associated riparian cover and score (Davis et al., 2015). Results supported the hypothesis that invertebrate assemblages would respond to natural gradients in hydraulic habitat, but not that they would respond to natural gradients in water quality, as they showed no major direct effects of gradients in land-use or anthropogenic changes to water quality (Davis et al., 2015).

Table 22. Studies that investigated wetlands and freshwater ecosystems in relation to pressures related to the primary question, also showing the indicator category that was the focus of the question. A reference may be listed in multiple categories.

Indicator category	Suspended sediment (turbidity)	Sediment (settled)	Particulate organic matter	Light	Water quality	Nutrients	Other
Cyanobacteria (in rivers and dams)							
Abundance	Bormans et al., 2004			Bormans et al., 2004			
Composition	Bormans et al., 2004			Bormans et al., 2004			
Freshwater systems							
Multiple	Davis et al., 2017; Waterhouse et al., 2017						
Other	Schaffer et al., 2016					Adame et al., 2021	
Invertebrates							
Abundance	Adame et al., 2019		Connolly et al., 2016		Adame et al., 2019		
Composition			Connolly et al., 2016				
Diversity	Adame et al., 2019				Adame et al., 2019		
Sediment (in river)							
Abundance	Davis et al., 2015		Davis et al., 2015				
Composition	Davis et al., 2015		Davis et al., 2015				
Wetlands							
Other		Hanson et al., 2021				Brodie & Mitchell, 2005; Hanson et al., 2021	

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

There were 94 new studies for the period 2016 to 2022 and the importance of these findings were described in previous sections. Considerable advancements include:

Coral. Fourteen new studies addressed dredge-relevant influences of sediments and particulate nutrients on corals including:

- Exploring the effects of suspended and settled sediments on coral recruitment (Ricardo et al., 2016a; 2016b; 2017; 2018; 2021).
- Dredge-relevant light levels on sublethal coral physiology (Bessell-Browne et al., 2017b; 2017c; 2017d; Jones et al., 2020; 2021; Luter et al., 2021).
- Sediment clearing (Duckworth et al., 2017).
- Cumulative pressures of which some studies were included in this data extraction (Fisher et al., 2019).

Other coral related studies included:

- Modelling cumulative impacts (Bozec et al., 2022).
- Ecological interactions (Chase et al., 2020).
- Nearshore coral habitats (Morgan et al., 2016; Zweifler et al., 2021).

Sponges. Six new studies with a focus on dredge-relevant influences (Abdul Wahab et al., 2019; Luter et al., 2021; Pineda et al., 2016; 2017a; 2017b; Strehlow et al., 2017).

Seagrass. There were nineteen new seagrass studies including:

- Several seagrass light threshold studies (Adams et al., 2020; Benham et al., 2016; Chartrand et al., 2016; 2018; Collier et al., 2016a; 2016b; 2021a; Schrameyer et al., 2018).
- Seagrass water quality and sediment load studies (Lambert et al., 2019; 2021; Petus et al., 2016; 2018; Wooldridge, 2017).
- Seagrass was also the subject of a number of reviews and meta-analyses (Adame et al., 2021; Bainbridge et al., 2018; Magris & Ban, 2019; O'Brien et al., 2018a; 2018b; Turschwell et al., 2021).
- Data syntheses and seagrass target setting (Carter et al., 2021a; 2022; Collier et al., 2020; 2021b).
- Dredging (Wu et al., 2017).
- Burial (Benham et al., 2019).

Long-term monitoring data. There were several new studies that used maturing long-term monitoring data (Ramsby et al., 2017) (Davidson et al., 2019; Lam et al., 2018; MacNeil et al., 2019; Rocker et al., 2017; Strahl et al., 2019; Thompson et al., 2022).

Reviews. (Bainbridge et al., 2018)

eReefs. Applying eReefs modelling framework to targeted questions (e.g., Baird et al., 2021; Cantin et al., 2021; Woods et al., 2016).

4.1.3 Key conclusions

- **Reef communities.** Increased loads of sediment and particulate nutrients to inshore habitats have persistent impacts on reef composition, leading to greatly compressed depth zonations, reduced depth limit for reef development, and lower coral diversity and suppression of many other sensitive species in favour of macroalgae. High abundance of healthy persistent coral species can be found in the upper 1-3 m water depth in some turbid inshore settings with favourable hydrodynamics. Deeper down, low light levels can cause sublethal stress and partial mortality of corals after only short exposure (days to weeks). Here, communities are typically dominated by turbidity-tolerant species with high levels of heterotrophy and filter feeders, rather than phototrophic taxa. Sediments and particulate nutrients are also suppressing reef recovery from disturbances due to their strong negative effects on coral recruitment including many of the early life stages. Many other sensitive calcifying species such as crustose coralline algae and large benthic photosynthetic foraminifera are also negatively affected by suspended particulates and water quality, through a variety of mechanisms. For sponges, short-term exposure to high levels of suspended sediment affect growth, while long-term exposure reduces their abundance possibly limiting recruitment.

- **Seagrass.** The distribution, abundance and composition of seagrass species are impacted by particulate loads and change in light, which drive declines in abundance and extent and cause shifts in species composition. There is evidence of this in the inshore of all NRM regions at different times, although to a lesser degree in Cape York. Seagrass meadows are dynamic and will often recover with the rate depending on the extent of decline and the local and regional conditions that follow. Protracted recovery has been observed in several locations. Research on the mechanisms driving loss have focused on reductions in light caused by suspended particulate matter, and much less is known about the processes influencing recovery.
- **Fish.** Suspended sediments can affect the growth and time to metamorphosis of juvenile fish, juvenile gill morphology, foraging time, body condition and mortality. Suspended sediments can also interfere with visual cues for juvenile fish to settle into habitat, distinguish between live and dead coral, and settlement time. Settled sediment also interferes with predation and directly or indirectly (through altering algal substrate) affects herbivorous grazing. The number of studies contributing to this evidence is relatively small with only a small number of families investigated and thresholds with adverse impacts requiring refinement.
- **Aquatic ecosystems.** This review highlights a critical knowledge gap on the effects of sediment and particulate nutrients on freshwater wetlands and estuarine wetlands such as mangroves, marshes and supratidal forests in the GBR.

4.1.4 Significance of findings for policy, management and practice

The review, combined with evidence from related questions, identified strong and consistent evidence that increased levels of suspended sediment and particulate nutrients impact on diversity and resilience of GBR ecosystems. Multiple lines of evidence are needed to address this question. The first line of evidence is that river loads of particulates have increased due to human activities (Question 2.3, Lewis et al., this SCS). The second line of evidence is that years with greater sediment loads are associated with prolonged and worse turbidity (Question 3.1, Lewis et al., this SCS), which affects ecosystems through multiple pathways. The third line of evidence is based on the biological responses to higher levels of particulates that show that as they increase, ecosystem state declines as summarised in the previous sections. Reductions in loads could therefore improve the extent, abundance, diversity and health of GBR ecosystems, and their speed to recover from climate related disturbances.

Most field studies were based on spatial associations (responses change along gradients), since causal field experiments exposing marine ecosystems to unnecessary experimental impacts are not desirable. However, the use of an epidemiological matrix in combination with modern statistical analyses is an established tool to attribute ecological changes to their causes (Fabricius & De'ath, 2004). This review has synthesised the comprehensive literature searches to avoid selective use of scientific data and compared field observations with experimental results. It has confirmed the main sets of evidence that ecosystems respond to changes in suspended sediments, particulate nutrients and associated water quality properties:

A. There are many examples of dose–response relationships, which serve as strong evidence for a causal relationship between dose and response.

B. Strength of association is defined by effect size, with many changes many-fold across contrasting water quality conditions.

C. Logical time sequence, indicating that the change did not precede exposure to the disturbance in long-term monitoring and other historical data.

D. Consistency across populations and consistency across regions and with other studies from outside of the GBR.

E. Specificity referring to responses that were known (from published literature) to be caused by runoff, and were unlikely to be caused by another disturbance type (e.g., the Foram index).

F. There was strong agreement with biological facts, as ascertained by comparing the field responses found in observational studies with the results of studies where relationships were directly assessed through manipulative experiments.

However several contextual factors affect these general findings, such as disturbance history of a site including the cumulative impacts from multiple disturbances (described elsewhere) and other local environmental conditions (e.g., local hydrodynamics). The review also identified that there are differences in the amount of evidence for different ecosystems.

There are few studies that quantitatively examine links between sediment and particulate nutrient loads to ecosystem responses and there are several challenges in doing this, including:

- The return period of river discharge events is on the scale of years to decades with large variability in flows and loads.
- Matching the spatial and temporal scale of data on loads and ecological responses including time lags in ecological responses.
- Accounting for cumulative pressures and local-scale conditions and processes.

There are some universal outcomes and recommendations across ecosystems that could facilitate a more nuanced approach to examining risk and improve how management activities are targeted to improve ecological outcomes.

- The composition of particulates, including grain size, sedimentology and particulate nutrient content, has a large influence on most of the ecosystem effects examined (e.g., Bannister et al., 2012; Franklin et al., 2018; Ricardo et al., 2018) and more information is needed on the spatial and temporal distribution of sediments and ecological responses to them.
- Sedimentation, substrate and changes to the substrate are important for seagrass (Benham et al., 2019; Carter et al., 2021a) and reef organisms, especially for influencing settlement (Ricardo et al., 2016b; 2018).
- Timing of sediment and particulate nutrient increases is critical especially for managing the impacts of dredging (Brunner et al., 2021; Chartrand et al., 2016; Humanes et al., 2017b; Wu et al., 2017) and responsiveness to breaches of thresholds can be improved through live data (Luter et al., 2021).
- Incorporating ecological processes (e.g., Bozec et al., 2022), resilience and recovery (MacNeil et al., 2019; McKenzie et al., 2022; Thompson et al., 2022) and function (O'Brien et al., 2018b; Sommer et al., 2021; Turschwell et al., 2021) into risk assessments.
- Cumulative impacts (Brunner et al., 2021; King et al., 2022).

The review also identified a number of other limitations in the current evidence base for the GBR which are highlighted below.

4.1.5 Uncertainties and/or limitations of the evidence

There are several limitations and uncertainties. These include:

- Quantitative synthesis including thresholds of response for the indicators was beyond the scope of this question brief but could also add further insight by summarising ecosystem and species responses over a range of sediment concentrations. This would also enable graphical data presentations e.g., summarising the response of various coral recruitment stages to a range of sediment concentrations.
- The level, duration and frequency of sediments and particulate nutrient exposure needs to be placed in context of those occurring in ecosystems, so that the responses observed can be placed into a realistic context. This is needed to properly assess the risks posed by sediments. A

number of studies do this for the site where the organisms were collected, but compiling that information at the GBR scale and presenting that for all ecosystems was beyond the scope of this review. In the absence of these summary data, this review has also not focused on presenting thresholds.

- There are a number of pertinent elements of this question that are the focus of other SCS questions and so have been excluded from the studies and narrative here. These most relevant questions include:
    - Q2.3 What evidence is there for changes in land-based runoff from pre-development estimates in the Great Barrier Reef? (Lewis et al.)
    - Q2.4 How do water quality and climate change interact to influence the health and resilience of Great Barrier Reef ecosystems? (Uthicke et al.)
    - Q3.1 What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef? (Lewis et al.)
    - 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? (Prosser & Wilkinson)
    - Q4.1 What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef? (Robson et al.)
    - 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? (Diaz-Pulido et al.)
- GBR ecosystems are diverse and complex. There is very little relevant information or long-term monitoring data to inform this question on freshwater and estuarine systems, mangroves, inter-reef habitats, CCA and fauna that are dependent on these habitats (e.g., dugong, turtle, most fish). Similarly, there is a lack of long-term information on the concentrations and properties of suspended and settled sediments and particulate nutrients in most ecosystems except at some inshore reef sites (e.g., Smith et al., 2020).
- Data on nutrient dynamics and the role and influence of these on how particulate nutrients affect GBR ecosystems are especially lacking.
- This question has focused on sediments and particulate nutrients, but the effect of these is influenced by local conditions and cumulative impacts.

4.2 Contextual variables influencing outcomes

There are a large number of variables that influence the effect of sediments and particulate nutrients on ecosystems of the GBR. These include other water quality variables, interactions with climate change (Question 2.4, Uthicke et al., this SCS) spatial and temporal scales and issues of timing and frequency. Some of these are covered in greater deal in other questions and are summarised in Table 23.

Table 23. Summary of contextual variables relevant to Question 3.2.

Contextual variables	Influence on question outcome or relationships as per conceptual model
Mineralogy	The mineralogy and organic content of sediment influences the impacts they have on ecosystems (Bannister et al., 2012; Weber et al., 2012).
Dissolved nutrients and other water quality variables	In numerous studies water quality has an impact through a range of parameters. These may co-vary with sediments and particulate nutrients and so the influence cannot be separated, while in others, co-variates may be removed for statistical analysis but cannot be excluded from having an influence (Connolly et al., 2016). Other water quality variables were also assessed in experiments and acted cumulatively or synergistically (Harrington et al., 2005; King et al., 2022).
Climate change (or climate variability)	Temperature, thermal stress, bleaching and acidification influenced responses to sediment and particulate nutrients. There are numerous

Contextual variables	Influence on question outcome or relationships as per conceptual model
	studies included in this review to examine these interactions but it is addressed more completely in Question 2.4. (e.g., Adams et al., 2020; Brunner et al., 2021; D'Olivo et al., 2013; Haapkyla et al., 2011; Humanes et al., 2016; Lantz et al., 2017; 2020; Roff et al., 2013; Smith et al., 2020).
Chronic and acute exposure to declining water quality	Previous exposure whether chronic or frequent acute exposure can influence the outcomes of an increase in sediment and particulate nutrients. This was not consistent among studies. Chronic exposure to the effects of high turbidity can enhance impacts of acute water quality disturbances e.g., deeper seagrass habitats near their light limit are lost following elevated discharge (Petus et al., 2014), while selection for more turbidity resistant genotypes appears to also provide resilience to extreme events (e.g., Connolly et al., 2018).
Season / timing / duration /frequency	The season and timing of particulate nutrient stress can influence the impacts (Brunner et al., 2021; Chartrand et al., 2016; Wu et al., 2017). The duration of exposure for acute pressures influences the magnitude of the impact (e.g., Collier et al., 2012a; 2016b; Humanes et al., 2017b). The frequency of acute exposure is an important determinant of ecological impacts as observed *in situ* (e.g., Lambert et al., 2021; O'Brien et al., 2018a; Wu et al., 2017). Laboratory experiments have not addressed this.
Trajectories, thresholds, tipping points and feedbacks	Ecological responses to pressures may follow linear responses (Lambert et al., 2021), curvilinear responses reaching saturation (Collier et al., 2016b; Ricardo et al., 2017), asymptotic responses and modal responses with optima at intermediate levels. Distinct tipping points can provide thresholds for use as guidelines (De'ath & Fabricius, 2010; Ricardo et al., 2017). Thresholds can also be derived from linear responses and be determined based on a range of criteria (e.g., sensitivity, confidence) (e.g., Collier et al., 2012b; Petus et al., 2018). Feedback processes contribute to ecological resilience to pressures from particulates (e.g., seagrass canopy slows water velocity, settles sediment and promotes clear water, and if there is seagrass loss, a breakdown in this process accelerates decline (O'Brien et al., 2018a)). They could be an important focus of management targets but there is limited information on this relevant to particulates in the GBR (Kroon et al., 2014).
Region and Year	Some responses vary among region or between years, which probably act as a proxy for other environmental conditions for which there are no data or no data included in analysis (Collier et al., 2021b; McKenzie et al., 2022; Thompson et al., 2022; Uthicke et al., 2010).
Depth	As particulates affect light penetration, depth has an effect on the sensitivity of phototrophic organisms (Anthony & Fabricius, 2000; Carter et al., 2021a; McKenzie et al., 2022; Schrameyer et al., 2018; Strahl et al., 2019; Thompson et al., 2022). Depth of wetlands is also important context (Hanson et al., 2021).
Herbivory	Herbivory can affect primary producers and interact with or have similar consequences as sediment (Goatley & Bellwood, 2013) and parrotfish scars reduce coral larvae survival (Trapon et al., 2013).

4.3 Evidence appraisal

Relevance

The overall relevance of the body of evidence to the question was Moderate (6.0). The relevance of each individual indicator was Moderate (2.3) for relevance of the study approach and reporting of results to the question and-Moderate for spatial (1.8) and temporal relevance (1.6). The categories used for this appraisal are broad, and so some studies may fall within a Low-Moderate, or Moderate-High ranking, but a single number was needed for the evidence appraisal analysis.

Some studies that ranked the highest specifically address and are designed to answer questions on the impacts of sediments (suspended or settled) or particulate nutrients on ecosystems, and further address either mechanisms or the locations for where there is evidence. These include observational studies where statistical models were used to distinguish the effects of particulates, and experimental studies that were focused on sediment or particulate nutrients. There were numerous coral and reef studies in this category, and only one seagrass study.

Moderate ranking for spatial studies included:

- Studies that assessed ecological spatial gradients, temporal variability and/or impacts of gradients in water quality, with water quality data but did not quantitatively investigate the effects of particulates in isolation.
- Studies focused on benthic light that do not specifically investigate the effects of particulates in isolation.
- Studies (observational, experimental and modelling) that were primarily focused on dissolved nutrients or other cumulative pressures (e.g., thermal stress), but included a component of particulates (e.g., a factor in an experiment).
- Studies that were focused on particulates, but the relevance of the treatment levels to those observed in the GBR were not given or they were conducted at sites with low risk of exposure to river discharge or dredging (e.g., midshelf reefs) and where local conditions may influence findings or were conducted with carbonate sediments.
- Reviews that were not focused on the GBR or focused on particulates.

The Low ranked studies were included because they provide some insight into the effects of particulates on ecosystems, but it was not the focus of the study. Studies that ranked Low for relevance included:

- Studies in wetlands and mangroves were not focused on the question of particulates but rather on nutrients, especially dissolved nutrients.
- Studies that included a minor component of sediment or particulate nutrients and provide insight into particulates in ecosystems as important context to the primary question but do not directly address the issue of increasing particulate levels (e.g., analyses that include sediment composition without addressing turbidity or sedimentation).
- Studies that measured variability in indicators that are known to respond to water quality (e.g., coral cover, composition, pigmentation, invertebrate composition) without quantifying what they were responding to. These studies were included in this review because they may provide insight into the spatial and temporal variability of those indicators which adds to the body of evidence for how these indicators vary over time and therefore may help understanding of how they respond to pressures.

The **spatial relevance** of studies was Moderate (1.8). The highest ranked studies were based on GBR-wide datasets, often based on the monitoring programs LTMP or MMP or other broad surveys and included sites in several regions.

Moderately ranked studies included:

- Sites in more than one location/region, with distinctions in the locations and regions studied to provide an indication of how representative the findings were.

- Study organisms that are widely distributed to enhance the generalisability of the findings though many of these also acknowledge the possibility of local acclimation or adaptation that may influence their responses.
- Experiments that used sediments and/or particulate nutrients from multiple catchments, rivers, estuaries or reefs with differences in the composition which provide insight into how generalisable the findings are.
- Experiments that tested responses to multiple treatment levels and dose-response relationships, that can be extrapolated or used to model responses more broadly and if there was not a significant interaction with other conditions tested.
- Studies on the mechanisms of response that can be used to understand ecological responses more broadly.

Low ranked studies included:

- Observational studies at one site or broader location where location-specific conditions are likely to have affected the observations (e.g., organisms from a midshelf reef with limited exposure to sediment).
- Experiments conducted with limited range in treatment levels such as extreme levels, or an observational study over a limited gradient.
- Experiments that tested a limited range of species, sediment levels, or other environmental parameters and there was a significant interaction and so the response clearly depends on other conditions but the number of levels tested do not allow extrapolation.

Temporal relevance was Moderate (1.6) and it was ranked slightly lower than spatial generalisability with numerous studies falling into the Low category. Temporal relevance of study duration is affected by the study organism and ecosystem, the study duration and timing of sampling and the indicators being tested, as some respond very rapidly while others respond slowly. Rapidly responding indicators may need less time to gather information about how they vary; however, rapidly responding indicators may also be highly variable (e.g., physiology). Temporal relevance was ranked the highest if the study used a long-term dataset (MMP or LTMP), used back-dating techniques spanning decades or centuries, or was a study over multiple years and included a range of different conditions especially discharge events. There were only 22 studies (13%) that were ranked High. Moderate ranked studies included those that:

- Included multiple sampling events (e.g., monthly, seasonal) but over a limited number of years (1-2) with a limited range in the conditions.
- Observational studies that included numerous years and conditions, but findings were complex and so generalisation or extrapolation beyond the study period was difficult or responses to particulates were described (qualitatively) but not quantified.
- Experimental studies that were tested over short to moderate timescales (with relevant timescales definitions of short and moderate depending on the indicator and organisms being tested), or with other temporal factors such as repeated dosing.
- Experimental studies that included dose-response relationships or other variables such as seasonally-representative temperature ranges that can enable temporal extrapolation.
- Examined mechanisms of response that enable some temporal generalisation under a range of conditions.

The lowest ranked studies for temporal relevance were the majority of studies (55%) and included:

- Observational studies that assessed a spatial gradient at a single time.
- When the conditions at the time of observations were not known or reported or provide limited generalisability for understanding the effects of increased particulates e.g., a spatial gradient measured multiple times but during relatively dry conditions.
- Examined mechanisms of response or ecological processes under extreme conditions or without any temporal context i.e., without sufficient information on how representative conditions were.

Consistency, Quantity and Diversity

Consistency: Moderate to High. Ecosystems respond to changes in suspended sediments, particulate nutrients and associated water quality properties. The consistency of this finding is High and was demonstrated through many observational and experimental studies. Corals and reefs were the most comprehensively examined and there was strong agreement among studies about the importance of particulates. It is, however, important to note that contextual information is needed to understand which ecosystems and indicators are impacted at any point in time, and the mechanisms driving responses. Therefore, for individual species or species groups, the consistency in responses taking into account the added contextual information is Moderate.

Quantity: Low to Moderate. There were 196 studies. The greatest number were for corals and reefs (Moderate quantity) but there was insufficient information on some regions (e.g., Cape York) and key mechanisms and processes (e.g., life cycle stages and disease). The second largest number of references was on seagrasses (Low to Moderate), but there was only one study that directly assessed suspended particulates in seagrass ecosystems and their impacts and a few that used modelled values (e.g,. water colour), and the majority were on light. There was a limited number of studies on how sediments and particulate nutrients affect fish and other fauna that are closely affected by particulates because of their dependence on benthic habitats and occurrence in the inshore such as turtles and dugongs. There was no information found using the search criteria on mangroves and inter-reef habitats and very limited and low ranked information on freshwater ecosystems. Therefore, the quantity of evidence ranged from Low to Moderate depending on the ecosystem, but was Low for the majority of ecosystems or species groups.

Diversity: High. There were similar numbers of observational and experimental studies depending on ecosystem and species group, with a smaller number of modelling and review studies. There were several additional reviews based on the GBR, or globally, but they were not included because they were older (and superseded) or did not have sufficient GBR content for inclusion.

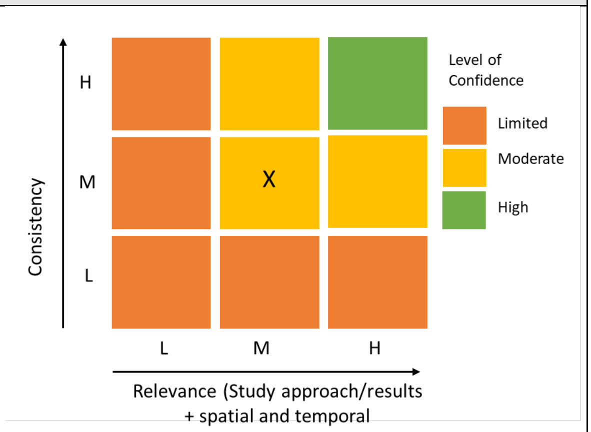
Additional Quality Assurance (Reliability)

There were no reliability issues regarding the internal validity of studies. There were numerous studies with low general relevance, low spatial relevance, and the majority of studies had low temporal relevance. For example, experiments that used very high levels of suspended or settled sediment need to be generalised with caution. Similarly, studies at just one location need to be interpreted with caution. Studies conducted *in situ* are unable to account for all potential confounding factors. Authors generally acknowledged the limitations of the studies and there were no obvious signs of bias. The authors of this review were only able to assess reliability of individual studies within their areas of expertise.

Confidence

The Confidence rating for the primary question, based on the overall relevance rating and consistency was Moderate as shown in Table 24, but varies among ecosystems.

Table 24. Summary of results for the evidence appraisal of the whole body of evidence in addressing Question 3.2 The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency. The final row summarises the additional quality assurance step needed for questions using the SCS Evidence Review method.

Indicator	Rating	Overall measure of Confidence
Relevance (overall)	Moderate	
-To the Question	Moderate	
-Spatial	Moderate	
-Temporal	Moderate	
Consistency	Moderate	
Quantity	Low-Moderate (196 items)	
Diversity	High (40% observational, 39% experimental, 7% modelling, 14% reviews)	
Additional Quality Assurance (Reliability)	Narrative of reliability • Of the 196 studies reviewed, there were no concerns regarding their reliability to address the question. • Authors generally acknowledged the limitations of the studies and there were no obvious signs of bias.	

4.4 Indigenous engagement/participation within the body of evidence

There was one observational study that included Indigenous engagement — the inshore seagrass Marine Monitoring Program — in which Indigenous Rangers and Traditional Owners assist with data collection at Cape York sites but not in other regions (McKenzie et al., 2022). There was one review/workshop that cited Indigenous consultation in the development of the project but not in the workshop itself (McCook et al., 2015).

None of the studies identified any of the authors as Indigenous.

4.5 Knowledge gaps

Data are needed on ecological condition and on water quality in ecosystems. The biggest limitation is a lack of data with long-term monitoring for coral and seagrass, and a complete lack of relevant data for freshwater and estuarine ecosystems. There is inadequate spatial and temporal coverage for answering this question leading to the Low-Moderate rating for spatial and temporal generalisability listed above. There are a number of information gaps that can be addressed to improve how information can be generalised, by focssing on key information gaps and processes as described in Table 25.

Table 25. Summary of knowledge gaps for Question 3.2.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or M&E question to be addressed	Potential outcome or Impact for management if addressed
Differentiation between natural and anthropogenic sediment impacts.	How much of the turbidity and deposited sediments causing an impact to ecosystems are attributed to anthropogenic sources?	Needed to guide management targets.
Condition and trend data over suitable spatial and temporal scales combined with water quality data.	How does the condition and trend of all ecosystems vary and how do	Provide information on ecological impacts, data needed for management prioritisation (e.g.,

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or M&E question to be addressed	Potential outcome or Impact for management if addressed
	sediments and particulate nutrients drive these changes?	catchment management, marine restoration).
Water quality, mineralogy, very fine silts and sedimentation and resuspension processes including the role of biota in influencing these processes – sediment stabilisation, sedimentation.	What is the mineralogy and nutrient content in the water column and sediment and how does this change over time? How much fine silt is there and under what conditions does it increase? How do the concentrations and size classes relate to experimental and observed thresholds (quantitative review)?	How management activities can target ecological processes that enhance sedimentation and stabilisation.
Nutrient uptake, production, transformations and sinks and the role of key species in facilitating these transformations and storages. Nutrient cycling and uptake, filtering through particulate uptake.	How are particulate nutrients used by organisms, how do they drive productivity and what are the sinks (sponges, seagrass, plankton etc.)?	How management activities can target ecological processes that enhance the value of nutrient sinks and processing.
Recruitment and recovery.	How is recruitment in a range of ecosystems and species affected by sediments and particulate nutrients and what are thresholds relevant to these processes?	Management targeted to sensitive life history stages. Better predictions of trajectories especially recovery.
Acclimation and adaptation – differences among populations and the mechanisms enabling acclimation.	How do ecosystems acclimate?	Are there management actions that can facilitate acclimation?
Essential elements for maintaining resilience – feedbacks, tipping points, connectivity, species interactions.	What are the critical thresholds beyond which sediment and particulates should not surpass due to the ecological consequences and costs of returning ecological condition and resilience?	Management activities targeting key processes and sediment and particulate nutrient thresholds.
The impact of realistic conditions (treatment levels, timing, duration, repetition, long-term), and the combined effects of acute and chronic exposure, and how cumulative impacts affect the impact of and recovery of marine and freshwater ecosystems.	Translating experimental work into realistic scenarios including long-term (chronic) effects. Risk assessing the relative contributions of the key stressors/modes of action and their impacts under realistic scenarios.	Realistic scenario testing of impacts, recovery and the influence management actions.
Freshwater and estuarine ecosystems in general – including the influence of flow variability, timing, frequency etc. and how aquatic ecosystem condition influences resilience to particulates.	Condition and trend of freshwater and estuarine ecosystems, impacts of sediment and particulate nutrients on them and information gaps listed throughout this table.	What is the condition of freshwater and estuarine ecosystems, and how can management activities enhance their ecological value.
Inter-reef habitats in general – including invertebrate communities, deepwater seagrass.	What is the condition and trend of inter-reef habitats, and how are they affected by sediments and particulate nutrients and information as listed above such as stabilisation and nutrient processing.	Having information on the condition of inter-reef habitats, incorporating into risk assessments and management prioritisation.

5. Evidence Statement

The synthesis of evidence for **Question 3.2** was based on 196 studies undertaken primarily in the Great Barrier Reef and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (40% observational, 39% experimental, 13% reviews, 7% modelled and 1% meta-analysis) and has a *Moderate* confidence rating (based on *Moderate* to *High* consistency of findings and *Moderate* overall Relevance). There was more evidence for coral reefs and seagrass meadows, and less information on freshwater ecosystems, mangroves and inter-reef habitats, and for habitat-dependant species (e.g., dugong, turtles, invertebrates).

Summary of findings relevant to policy or management action

The measured impacts of increases in the loads of fine sediments and particulate nutrients in the Great Barrier Reef include changes to the presence, abundance, extent, diversity, composition and depth of coral reefs and seagrass meadows, and many of the taxa associated with these habitats such as fish and dugong. Increased fine sediment and particulate nutrient loads affect the quantity and quality of light penetrating the water column, which can negatively affect photosynthetic organisms that depend on adequate light levels for growth and energy supplies (e.g., seagrasses and endosymbionts in corals). Sedimentation, the settling of sediments and particulate nutrients onto surfaces, can also have negative direct effects on a variety of taxa including corals and seagrasses through burial or smothering, increasing the prevalence of disease, causing tissue damage, reducing growth rates and altering microbial communities. Moreover, these direct effects can result in indirect effects on other taxa. There is clear evidence that the loads of sediments exported to the Great Barrier Reef have increased in most basins over the last 170 years, however it is recognised that their influence on ecosystems are superimposed over a gradient of natural variability which complicates the separation of anthropogenic influences. The greatest impacts of fine sediments and particulate nutrients occur in the inshore central and southern Great Barrier Reef (Wet Tropics to Burnett Mary Natural Resource Management regions). Reductions in end-of-catchment loads of fine sediments and particulate nutrients could improve the extent, abundance, diversity and health of Great Barrier Reef ecosystems, particularly inshore areas, and enhance their ability to recover from climate-related disturbances.

Supporting points

- For **coral communities**, increased exposure to sediments and particulate nutrients on inshore habitats has persistent impacts on reef composition. For example, sediments can reduce the abundance of sensitive species and the availability of suitable settlement surfaces, while nutrients can increase the amount of macroalgae on reefs.
- Lower light levels caused by increased suspended particulate matter can impact the spatial extent of coral reefs by limiting where corals can grow. Some turbid inshore locations can support high coral abundances, but these coral communities are typically restricted to depths of 1-3 m and high currents. They are low in species diversity and composed of species that have the ability to cope with turbid conditions (e.g., can switch food sources and self-clean).
- For sponges, short-term exposure to high levels of suspended sediment affects growth, while long-term exposure reduces sponge abundance possibly by limiting recruitment.
- Settled and suspended particulates may negatively affect crustose coralline algae which are important coral settlement substrata, but the number of studies is limited. They may also affect the abundance of large benthic photosynthetic foraminifera. Settled sediment is energetically costly for corals to remove and impedes their recruitment.
- For **seagrass communities**, the distribution, abundance and composition of seagrass species are impacted by particulate loads and changes in light, which drive declines in abundance and extent, and cause shifts in species composition.
- Seagrass meadows are dynamic and will often recover with the rate depending on the extent of decline and the local and regional conditions that follow. Protracted recovery has been observed in several locations.

- Research on the mechanisms driving seagrass loss have focused on reductions in light caused by suspended particulate matter, and much less is known about the processes influencing recovery.
- For **fish communities**, elevated suspended and settled sediments can have physiological and behavioural effects. Sediments can negatively affect growth and time to metamorphosis of fish, alter juvenile gill morphology, reduce body condition and increase mortality. Suspended sediments can also interfere with visual cues that juvenile fish use to settle into habitats, impairing their ability to distinguish between live and dead coral, extend settlement time, and alter feeding patterns such as predation, foraging time and herbivory. Effects have only been investigated for a small number of fish families and thresholds for adverse impacts require refinement.
- This review highlights a critical knowledge gap on the effects of sediment and particulate nutrients on Great Barrier Reef **freshwater wetlands and estuarine wetlands** such as mangroves, saltmarshes and supratidal forests (above the intertidal zone).
- The composition of particulates, including particle size, sedimentology and particulate nutrient content, has a large influence on most of the impacts that have been documented.
- There are multiple lines of evidence supporting cause-effect relationships for increased suspended sediments and biota. This includes a wide range of study types, strong spatial associations between water quality conditions and biotic conditions demonstrated in dose-response relationships, logical time sequences (i.e., ecological changes following increased loads), several cases of high specificity (i.e., impact-specific sensitive indicators), and consistency of responses across populations, across regions and with studies from outside of the Great Barrier Reef. However, several contextual factors affect these relationships such as disturbance history, cumulative impacts from multiple disturbances and other local environmental conditions (e.g., local hydrodynamics).

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 3.2

Theme 3: Sediments and particulate nutrients – catchment to reef

Question 3.2 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?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Catherine Collier	TropWATER, James Cook University	Seagrass, impacts from multiple pressures including water quality and climate change and how to measure and enhance resilience	Lead author	All Sections
2. Aimee Brown	TropWATER, James Cook University	Conservation biology, fish ecology, data synthesis	Contributor	Data extraction, Contributor to all sections
3. Katharina Fabricius	Australian Institute of Marine Science	Ecological processes in coral reefs, and how to maximise potential to recover from acute and chronic disturbances	Contributor	Reef conceptual model, contributor and editor to all sections
4. Stephen Lewis	TropWATER, James Cook University	Geochemist focusing primarily on water quality in the GBR catchment and lagoon including evaluating the sources, transport and risks of various pollutants in freshwater, estuarine and marine ecosystems	Contributor	Reef conceptual model, contributor and editor to all sections particularly on links to Q3.1
5. Guillermo Diaz-Pulido	School of Environment & Science & and Australian Rivers Institute, Griffith University	Macroalgae in coral reef ecosystems, and the influences of human activities and natural processes on algal biology, physiology and ecology, and reef functioning	Contributor	Reef conceptual model, contributor and editor to all sections particularly on links to Q4.2
6. Fernanda Adame	Australian Rivers Institute, Griffith University	Ecosystem services that wetlands provide, such as: carbon sequestration, improvement of water quality, and the protection from tropical storms and flooding	Contributor	Wetlands conceptual model, contributor and editor to all sections