2022 Scientific Consensus Statement

Question 4.2 What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanisms 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

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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

evidence needs, search for and appraise the quality of the evidence, and draw conclusions from the synthesis of this evidence.

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

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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.

the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods[4].

3. **Define the criteria for the eligibility of evidence for the synthesis and conduct searches.** Authors were asked to establish **inclusion and exclusion criteria to define the eligibility of evidence** prior to starting the literature search. The Method recommended conducting a **systematic literature search** in at least **two online academic databases**. Searches were typically restricted to 1990 onwards (unless specified otherwise) following a review of the evidence for the previous (2017) SCS which indicated that this would encompass the majority of the evidence 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.

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

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

We are thankful to Jane Waterhouse (C_2O Consulting), Rob Richards (Evidentiary) and Mari-Carmen Pineda and Katie Sambrook (C_2O Consulting) for guidance with the Evidence Review process and to two anonymous reviewers for valuable feedback. Thanks to Elisa Westmore (CANEGROWERS) and Matthew Leighton (Bundaberg CANEGROWERS) for submitting literature for consideration in this synthesis.

Executive Summary

Question

Question 4.2 What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanisms for those impacts and where is there evidence of this occurring in the Great Barrier Reef?

Background

This question aims to understand the effects of dissolved inorganic nutrients, specifically nitrogen and phosphorus, on the Great Barrier Reef (GBR) ecosystems and builds on the 2017 Scientific Consensus Statement (SCS) on water quality impacts on the GBR. Ecosystems include marine benthic (e.g., coral reefs and seagrass meadows) and planktonic communities and habitats, intertidal mangroves and saltmarshes, and hydrologically connected freshwater wetland systems. Roles of other important nutrients, primarily in primary production, such as iron, silica and carbon (dissolved inorganic carbon – DIC, or dissolved organic carbon – DOC) are not explicitly considered but referred to when relevant. While some dissolved organic nitrogen compounds can be used in micro- and macro-algal nutrition, dissolved inorganic nitrogen (DIN), in particular nitrate and ammonium, are the most important ions for algal and plant growth and therefore are the focus of this review. Mechanisms refer to processes by which dissolved inorganic nitrogen and phosphorus affect the organisms and their ecology (e.g., interactions, competition) as inhabitants of the target ecosystems. These mechanisms can be direct, such as an increase in algal and plant growth due to release of nutrient limitation by nutrient enrichment, or indirect, such as increased macroalgal growth that enhances space competition with corals. The geographic scope of the question is the GBR, including inshore, midshelf and outer reefs, as well as northern, central, and southern sections of the GBR. The review considers peer reviewed literature published from 1990 onwards.

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[5]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Review method was used.
- Search locations were Web of Science and Scopus.
- Search locations included all sections of the GBR, while studies outside the GBR were excluded given the large volume of available literature beyond the GBR and the resources provided for this review. However, when necessary, some evidence was included to provide context to particular concepts (e.g., coral bleaching).
- The search strategy looked for items <great barrier reef> and <nutrients, nitrogen, phosphorus> and <impact, degradation, threat, effect> in the Title, Abstract, and Keywords of the papers. Scopus and the Web of Science returned 358 and 276 records respectively. After combining the outcomes of the two databases, removing duplicates and conducting an initial screening by title and abstract, 227 studies were progressed to second screening. Following second screening which involved reading the full abstract and paper, including references manually added from authors' collections (51), 157 items were incorporated into this synthesis.
- In addition to the evidence appraisal, a further assessment of the reliability of studies was included in the review (e.g., items that were considered relevant in scope but whose methods or approaches were less reliable were noted). Only 7% of studies ranked low in reliability, mainly

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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

because of issues with attribution and evidence inclusion. Overall, the total number of items included (157), was considered an excellent representation of the literature available to address the effects of dissolved inorganic nutrients on GBR ecosystems.

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.
- With a few exceptions, only GBR derived studies were included.
- Only two academic databases were searched.
- Only studies published after 1990 were included.
- Search strategies missed a considerable number of important references (at least 51 refs) which had to be identified using other means (see Section 3 – Search Results). The inclusion of keywords such as 'impact' and 'effect' may partially explain this limitation.

Key Findings

Summary of evidence to 2022

According to the evidence, the measured impacts of dissolved inorganic nutrients on GBR ecosystems include:

- The direct effects of elevated dissolved inorganic nutrients on hard corals are complex, very variable and difficult to generalise, which is not surprising given the high diversity of coral species in the GBR. Despite this variability, direct effects of elevated nutrients include reduced coral calcification, negative impacts on coral reproduction, and potentially lowering thermal tolerance to bleaching.
- The most severe impacts of increased nutrients on corals may be indirect. For instance, elevated nutrient availability on inshore reefs is generally (but not always) positively correlated with increased fleshy macroalgal abundance. High fleshy macroalgae abundance and biomass can reduce coral settlement and recruitment, outcompete corals, reduce coral cover and negatively affect coral calcification. Another indirect effect is the relationship between excess nutrients and increasing phytoplankton food supplies for crown-of-thorns starfish larval stages which can potentially contribute to outbreaks.
- There is a clear gradient of macroalgal abundance across the GBR shelf, with fleshy macroalgal abundance highest in inshore areas and lowest in offshore areas. Nutrient addition does not always enhance macroalgal growth rates or lead to enhanced biomass, therefore it is simplistic to assume that the macroalgal gradient can only be attributed to land-based inputs of nutrients in inshore reefs. The effects of nutrient enrichment need to be considered in combination with other factors, particularly grazing by fish, sedimentation, ocean acidification and warming.
- Evidence is limited for the effects of dissolved inorganic nitrogen and dissolved inorganic phosphorus on crustose coralline algae (CCA) (important for reef building), but available studies show enhanced growth under elevated conditions. The lower abundance of CCA on inshore reefs compared to offshore reefs may be related to increased sediment loads and a reduced seawater calcium carbonate saturation state in inshore reefs.
- Comparing the effects of dissolved inorganic nutrients between and among regions is challenging due to limited spatial data. Reef communities from the Mackay Whitsunday Natural Resource Management region, and to some extent the Burdekin region have been relatively well studied, but there is a significant lack of information from other areas of the GBR.
- There is still debate about whether elevated dissolved inorganic nitrogen raises the susceptibility of corals to thermal stress and contributes to coral bleaching. Computer simulations both support and reject this hypothesis, and severe mass bleaching of corals in 2016 did not show a water quality effect. However, there is mounting evidence from international research groups that supports the hypothesis that nutrient enhancement can reduce thermal bleaching thresholds in corals.

- Crown-of-thorns starfish larval development can benefit from elevated nutrients which can enhance phytoplankton biomass (measured by chlorophyll *a* concentration), but up to a limit as excessive phytoplankton concentrations may reduce larval performance. However, there is evidence that crown-of-thorns starfish larvae can also survive in low nutrient water. Elevated nutrients may exacerbate the incidence or severity of outbreaks, but are likely to be one of several contributing factors along with predator removal and inherent life history traits.
- Evidence suggests that declining water quality (increased nutrients *and* sediment loads combined) contributes to seasonal outbreaks in coral disease in the GBR. However, a direct link between coral disease and dissolved inorganic nutrients has not been demonstrated yet and future studies should specifically address this gap.
- Bioerosion patterns show variable responses in coral reefs across the natural water quality gradient. Inshore reefs have lower rates of total bioerosion relative to midshelf and offshore reefs which typically exhibit high bioerosion rates due to the presence of microborers and increased grazing activity by parrotfish. Higher levels of nutrients and organic matter in inshore and midshelf reefs may explain increased abundance of macroborers potentially leading to increased bioerosion rates. These relationships, however, require further investigation.
- There are strong influences of water quality (combined nutrient availability, sediment loads and light) on species composition of foraminifera assemblages.
- Microbial communities are very responsive to elevated nutrients and thus to gradients of water quality across the GBR. The effects cannot be generalised as benthic and planktonic bacterial communities, and microphytobenthos, are highly variable in species composition but this is a rich target for research to find indicators of water quality.
- Phytoplankton biomass (measured as chlorophyll *a* concentrations) responds positively to nutrient availability. The impact of elevated phytoplankton biomass on coral reefs and seagrass meadows is mostly via reduction of water clarity and consequently reduced light availability for symbiotic corals and seagrasses.
- While elevated nutrients can increase seagrass growth rates and distribution, elevated epiphytic growth has been documented on estuarine seagrasses (possibly from increased nutrients) which can lead to reduction of plant photosynthesis. It is unclear if this condition is contributing to seagrass decline.
- Although elevated nutrients may be beneficial for mangrove growth, they can interact with climate stressors such as drought (low rainfall and low humidity) causing mangrove decline. The few studies available showed that elevated dissolved inorganic nutrients in combination with drought conditions (low rainfall and low humidity) can increase mangrove mortality.
- The direct and indirect effects of increased dissolved inorganic nutrients on freshwater streams and wetlands in the Great Barrier Reef is poorly understood and may vary with differences in landscape characteristics, rainfall, flow regimes, and among ecosystems and organisms.

Recent findings 2016-2022

- Overall, there has been limited new evidence since the 2017 SCS examining the direct or indirect effects of dissolved inorganic N and/or P on GBR ecosystems and organisms. Perhaps this reflects a diversion of scientific attention towards other important areas of environmental concern, including ocean acidification, or the lack of funding supporting projects examining nutrient impacts on the GBR.
- Only one new study focused on impacts of DIN/DIP on coral calcification, which confirmed the negative effects of chronic nutrient enhancement on coral calcification, although it highlighted that pulse nutrient additions may be beneficial to corals. Two correlational studies examined the gradient of water quality and the relationship with benthic communities, and one experiment addressed effects on macroalgae, emphasising the high variability in algal responses.
- Manipulative experiments and a review paper added to the unsolved problem of the role of nutrient runoff as a cause of COTS outbreaks in the GBR, with mixed support for this hypothesis. A recent study using regression analyses suggested that water quality can only explain a proportion of the COTS outbreaks.

- Our understanding of the relationship between microbial communities and nutrient runoff has improved considerably since the 2017 SCS, possibly because of the advancement in, and access to, molecular tools (e.g., 16S rRNA gene amplicon sequencing). However, there is still a lack of manipulative experiments directly testing the effects of dissolved inorganic nutrients on microbes.
- The hypothesis that increased terrestrial DIN loading lowers the thermal bleaching thresholds in corals in the GBR is not settled and further experimental evidence specifically from the GBR is needed.
- There has been limited progress since the 2017 SCS in our understanding of how seagrass meadows and mangrove forests respond to excess nutrients in the GBR. Although the Marine Monitoring Program (MMP) seagrass results have shown that some estuarine habitats have high loads of epiphytic algae, there is no trend of an ecosystem-state shift away from seagrass-dominated towards macro- or microalgae-dominated benthos. Further, there is no evidence in the GBR that nutrient enrichment has favoured algal blooms in estuarine wetlands, which could smother mangrove pneumatophores and seedlings and result in the shift of primary production from a plant to an algae-dominated system, as implied in the 2017 SCS. Mortality of nutrient enriched coastal wetland vegetation may be exacerbated during extreme droughts, although research evidence is limited. There is no research data on effects of nutrient enrichment on saltmarsh communities in the GBR.
- Very limited information has arisen since the 2017 SCS regarding the effects of excess nutrients on freshwater streams and wetlands. This review, however, has further uncovered the urgent need to investigate whether increased dissolved inorganic nutrients have led or can lead to excessive algal growth and subsequent eutrophication, which could then affect invertebrate and fish fauna by reducing light and suitable substrate and by promoting ammonia toxicity and hypoxia. While all those responses have been suggested as water-quality stressors there is no evidence that supports widespread eutrophication in GBR catchments.

Significance for policy, practice, and research

Nutrients are critically important for the overall condition of the GBR. Particular levels of nutrients are required to maintain the health of the GBR and component ecosystems, but *overall*, it is clear that an excess of nutrients is detrimental. Therefore, controlling nutrient runoff from agriculture, aquaculture and populated areas should remain a priority and such controls should be developed specifically for each basin and considered (and weighed up) in the mix of policy approaches for a healthy GBR ecosystem.

For macroalgae, it is increasingly important that the effects of nutrient enrichment are considered in combination with effects of other factors, particularly grazing by fish, sedimentation, and importantly, ocean acidification and warming. For example, there is emerging evidence that tests the strength of some of our previous understanding of the influence of nutrient concentrations on the distribution of macroalgal abundance across the GBR continental shelf. Elevated CO_2 concentrations are higher in inshore reefs, and CO_2 is emerging as a major factor involved in enhanced macroalgal production, but empirical research is needed. Key areas of uncertainty are the interactions between water quality and climate change stressors, including ocean acidification and warming.

There is a clear gradient of macroalgal abundance across the GBR shelf, with fleshy macroalgal abundance increasing from outer to inshore reefs, positively correlated with elevated nutrient concentrations. Since fleshy macroalgae can inhibit coral recovery by reducing coral settlement and recruitment, and outcompeting corals, high macroalgal growth rates and biomass accumulation is a concern for GBR management. However, high macroalgal abundance in inshore reefs may well be a natural phenomenon, and there is still debate as to whether macroalgal dominance has been exacerbated by anthropogenic nutrient addition, with herbivory (or lack of in inshore areas) being a potential major driver. Clearly, disturbances such as bleaching, cyclones and COTS kill corals and free up space available for algal colonisation, contributing to enhanced macroalgal abundance. Filamentous algal turfs rapidly colonise available substrate, but herbivores rapidly consume algal production. Observed increased macroalgal abundance is therefore not just due to increased nutrient availability, but a consequence of complex interactions with other stressors and factors. The risks of nutrient enrichment promoting macroalgal overgrowth of corals will be most significant under low herbivory regimes, such as areas where herbivores are naturally scarce, for instance inshore reefs.

Higher taxonomic resolution in macroalgae (in all functional levels, fleshy, CCA, and algal turfs) can help identify effects on this group.

Macroalgal removal is now being considered as a strategy to manage excess algal accumulations on reefs.

Lack of studies on the impacts of DIN on mangroves and freshwater wetlands (and none for saltmarshes) should be addressed urgently.

Key uncertainties and/or limitations

There are a number of issues where there is still considerable uncertainty about the relationship between elevated dissolved inorganic nutrients and ecological impacts. For example, several hypotheses postulated about the causes of COTS outbreaks in the GBR have not been resolved yet. Several studies support the important role of nutrient runoff as a contributing factor to increased COTS larval development, via increased microalgal biomass (an important food for planktonic larvae) in response to nutrient enrichment. However, there is some evidence indicating that larvae can also do well under limited nutrient availability (see COTS section below, and Question 4.3, Caballes et al., this SCS). Therefore, the role of nutrient enrichment in COTS outbreak dynamics remains unresolved. Also, there is still limited information and considerable uncertainty around the potential role of nutrient enrichment in increasing the susceptibility of corals to thermal stress and consequent coral bleaching (see also Question 2.4, Uthicke et al., this SCS). There are also uncertainties about the interactions between elevated nutrients, high CO_2 (ocean acidification) and other stressors on ecosystems. In particular, the impact of combined elevated nutrients and CO_2 enrichment needs further study. Assessing spatial patterns at regional scales is difficult due to limited spatial data, and although there is important information from the Whitsundays region, ecosystems in the northern sections of the GBR have been poorly examined with regard to the impacts of dissolved inorganic nutrients.

Evidence appraisal

Relevance

We reviewed 157 studies, and the overall relevance of the body of evidence to the question was rated as Moderate (6.4). The relevance of each individual indicator was rated as Moderate (2.1) for the relevance of the study approach and reporting of results to the question, Moderate for spatial relevance (2.2), and Moderate for temporal relevance (2.1). Of the 157 articles included, 39% had a High score for overall relevance to the question, and this moderate proportion means that many studies did not explicitly address the question or addressed it indirectly, or were designed to address other points mentioning the effects of nutrients tangentially. 32% (50) had a High spatial relevance score, indicating that some studies represented the ecosystems/organisms of interest across the large extension of the GBR well, while the majority of the studies were focused on only an individual or few localities. A moderate proportion of studies 34% had a High temporal relevance score, indicating most studies were conducted using relatively small temporal scales (e.g., days or weeks), while few considered multi-year studies.

Consistency, Quantity and Diversity

Consistency: Medium to Low. There is large variability of findings regarding the question being addressed, and this reflects the complexity in processes, and diversity of the organisms that inhabit the GBR’s ecosystems. Even within the same taxonomic group and one that is generally understood to respond positively to nutrient enhancement (such as macroalgae), there are considerable discrepancies in the outcomes, with studies demonstrating positive, neutral or negative effects of nutrients on algal processes. Quantity: 157 studies were reviewed specifically addressing the GBR since 1990. Based on the authors experience and knowledge of the potential total available pool of evidence to answer the question, it is considered that 157 studies are an excellent representative sample of this pool. Diversity:

High diversity of studies. Of the 157 papers examined, 43% were observational studies (including natural experiments along the gradient of water quality across the GBR continental shelf), 30% were manipulative experiments, and 15% were reviews/summaries. The remaining 12% of papers were modelling and theoretical.

Additional Quality Assurance (Reliability)

Of the 157 studies considered in this review, 93% of the studies did not raise any concerns regarding the reliability of the study. This indicates that overall, studies are well designed, well replicated, and contain adequate controls to contrast with experimental treatments. The remaining 7% of the studies raised some reliability concerns (some potential risk of bias). In the majority of cases this was due to limitations of the study in providing distinctions between the impacts of alternative factors such as sedimentation, organic nutrient supply, herbivory, etc., or based comparisons on limited data. Two studies also presented some inconsistencies between trends in the data and the conclusion reached in the paper. In one instance, we were unable to assess the reliability of the study as authors were unfamiliar with the methods employed in the modelling exercise.

Confidence

Confidence is Moderate based on Medium to Low consistency and Moderate Relevance. This Moderate confidence reflects the large variability in responses of the different processes and organisms included in conceptual models. For example, responses of phytoplankton to nutrient enrichment are clear, but responses of other primary producers are variable (e.g., seaweeds), or even positive (seagrasses). Important components of models, such as coral bleaching and COTS outbreak responses to enhanced nutrients, are also controversial. Responses of GBR organisms such as corals and CCA to inorganic nutrients are also mixed.

1. Background

The ecosystems and organisms of the Great Barrier Reef (GBR) face considerable threats from declining water quality, a fact that was well established in the 2017 Scientific Consensus Statement (SCS) (e.g., Schaffelke et al., 2017) and previous iterations. One of the key components of water quality is the availability of dissolved inorganic nitrogen and phosphorus. The availability of particulate inorganic nutrients and organic nutrients, sediment deposition, reduced water clarity and presence and quantities of pesticides and herbicides are also critically important constituents of the quality of GBR waters. Understanding the independent (and combined) effects of dissolved inorganic nutrients is important as these nutrients are major components of fertilisers that are added to crops along the Queensland coast. These nutrients, or their excess, are washed off the crops and aquaculture and urban systems during rain and via rivers (runoff) and have the potential to pollute GBR ecosystems. Better knowledge on the type of impacts of inorganic nutrients on GBR ecosystems, and the mechanisms by which these impacts operate, will allow a better understanding of the problem, giving managers, practitioners and policy makers the knowledge needed to address and mitigate the excess of nutrients (and their sources) affecting the GBR. Governments have directed important resources to programs aimed at improving the quality of the water flowing from the catchment area to the GBR to reduce the effects of nutrients on the GBR, and it is vital to identify if relevant policies and programs are justified, and whether those measures have had a positive impact on the ecosystems. Effective and adaptive management of the impacts of dissolved inorganic nutrients is critically important for the conservation of the GBR.

1.1 Question

Primary question	**Q4.2** What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanisms for those impacts and where is there evidence of this occurring in the Great Barrier Reef?

This question aims to understand the effects of dissolved inorganic nutrients, specifically nitrogen and phosphorus, on the Great Barrier Reef World Heritage Area (GBRWHA). The area includes marine (coral, seagrass, pelagic, benthic, and planktonic communities), estuarine (estuaries, mangroves, saltmarshes), and freshwater (freshwater wetlands) systems. However, given that most available studies have been conducted in coral reefs and seagrass meadows, this review will focus predominantly on these habitats and include effects on other systems when available evidence exists. Other nutrients such as iron, silica and carbon (dissolved inorganic carbon – DIC, or dissolved organic carbon – DOC) will not be considered but will be referred to when relevant. While some dissolved organic nitrogen (DIN) compounds (such as amino acids) can be used in algal nutrition, DIN, in particular nitrate and ammonium, are the most important ions for algal growth and therefore the focus of this review.

Mechanisms refer to processes by which DIN and dissolved inorganic phosphorus (DIP) affect organisms (e.g., biology, physiology, growth) and their ecology (e.g., interactions, competition) as inhabitants of the target ecosystems. These mechanisms/processes can be direct, such as an increase in algal growth due to release of nutrient limitation by seawater nutrient enrichment, or indirect, such as increased macroalgal growth that increases space competition with corals. The last component of the question is interpreted as identifying geographic localities or regions in the GBR where these impacts and mechanisms have been documented.

Several questions in the 2022 Scientific Consensus Statement focus on other important aspects of nutrients in the GBR. Question 4.1 (Robson et al.) deals with the spatial and temporal distribution of nutrients in the GBR, Question 4.5 (Burford et al.) addresses the loss of nutrients to the GBR, while Question 4.6 (Thorburn et al.) focuses on management practices for reducing dissolved nutrient losses from the GBR catchment area.

The review focuses on literature published from 1990 onwards and GBR-derived studies.

1.2 Conceptual diagram

Figure 1 illustrates the potential impacts of dissolved inorganic nitrogen (DIN) and phosphorus (DIP), predominantly from rivers and runoff, on GBR organisms and ecosystems, and the proposed mechanisms/processes by which nutrients impact organisms, their ecology and key ecosystem components/attributes. DIN and DIP may directly enhance nutrient uptake in seagrasses, phytoplankton and benthic algae potentially enhancing algal growth causing algal blooms. Algal blooms may influence GBR ecosystems, for example causing coral decline, influencing COTS outbreaks, causing reduced reef accretion, increased coral bleaching and increased disease.

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	**Q2.4** How do water quality and climate change interact to influence the health and resilience of the Great Barrier Reef ecosystems? **Q3.2** What are the measured impacts of increased sediment and particulate nutrient loads on Great Barrier Reef ecosystems, what are the mechanisms for those impacts and where is there evidence of this occurring in the Great Barrier Reef? **Q4.1** What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef? **Q4.3** What are the key drivers of the population outbreaks of crown-of-thorns starfish (COTS) in the Great Barrier Reef, and what is the evidence for the contribution of nutrients from land-runoff to these outbreaks? **Q5.1** What is the spatial and temporal distribution of pesticides across Great Barrier Reef ecosystems, what evidence is there for pesticide risk and what are the (potential or observed) ecological impacts in these ecosystems?

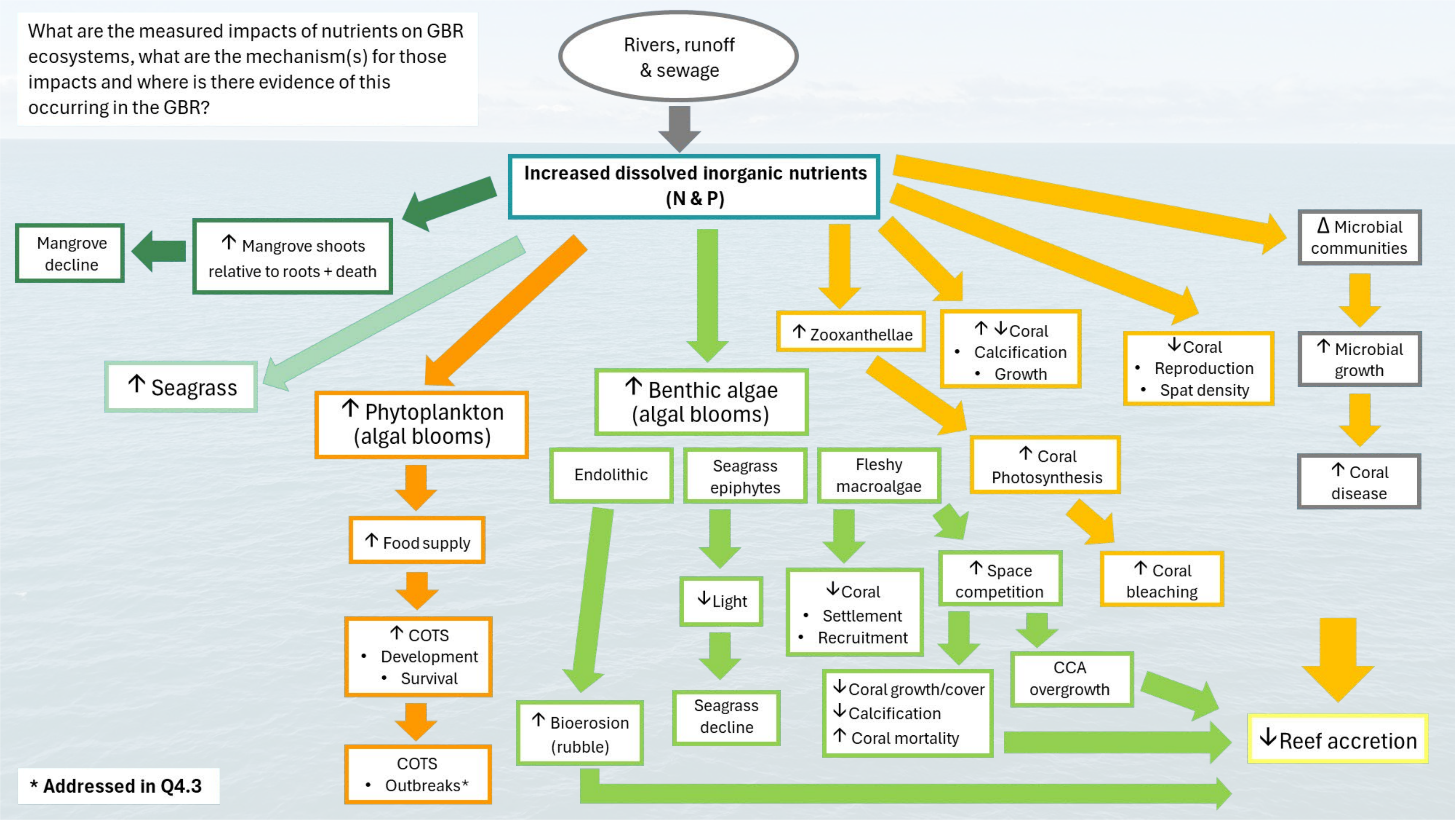

Figure 1. Conceptual diagram illustrating the potential impacts of dissolved inorganic nitrogen (DIN) and phosphorus (DIP), predominantly from rivers and runoff, on GBR organisms and ecosystems, and the proposed mechanisms/processes by which nutrients impact organisms, their ecology and key ecosystems components/attributes. The different coloured boxes refer to different ecological groups, e.g., dark green for mangroves, pale green for seagrass, green for benthic algae, etc. Arrows within boxes indicate a generalised direction of the response of that group to nutrient enrichment. Influences of nutrients on COTS are addressed in Question 4.3 (Caballes et al., this SCS).

2. Method

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

2.1 Primary question elements and description

The primary question is: ***What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanisms for those impacts and where is there evidence of this occurring in the Great Barrier Reef?***

S/PICO frameworks (Subject/Population, Exposure/Intervention, Comparator, Outcome) can be used to break down the different elements of a question and help to define and refine the search process. The S/PICO structure is the most commonly used structure in formal evidence synthesis methods[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 primary question elements for Question 4.2.

Question S/PICO elements	Question term	Description
Subject/ Population	GBR ecosystems	The GBR ecosystems include coral reefs, seagrass meadows, estuaries, mangroves and other saline and freshwater wetlands and refers to the biological communities and the abiotic factors influencing those communities. A biological community refers to the association of interacting species inhabiting a defined area. Attributes of the ecosystem and community will include organism traits (e.g., rates of photosynthesis, growth, recruitment, calcification), or community traits (e.g., species richness, diversity, dominance, species composition). Species interactions such as herbivory, symbiosis and predation, are also important aspects of a community and will be considered when relevant and when information is available. The review focuses on coral reefs and seagrass meadows because most available evidence comes from these systems. It will also consider estuaries, mangroves, and freshwater wetlands where relevant evidence is available.

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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
Intervention, exposure & qualifiers	Nutrients	Nutrients refer to dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP). The focus in this review will be land-based inputs of nutrients to the GBR. DIN and DIP are readily available for uptake by microscopic or macroscopic organisms, mainly algae. While some dissolved organic nitrogen (DON) compounds (such as amino acids) and dissolved organic phosphorus (DOP) can be used in algal nutrition, DIN (in particular nitrate and ammonium) and DIP (phosphate) are the most important ions for algal growth and therefore are the focus of this review. Further, DON and DOP require surface algal enzymes and/or microbial communities to remineralise these compounds to inorganic ions for algal uptake and growth.
Comparator		(Not relevant)
Outcome & outcome qualifiers	Measured impacts of nutrients	Measured impacts refer to when an attribute of the ecosystem (e.g., organism trait, being a physiological or vital rate, or community trait such as diversity, productivity, etc.) has been measured (or quantified) in response to the effect of increased availability of DIN and/or DIP. It also considers the spatial context of the impacts, particularly identifying the region/location where the effects have occurred. Mechanisms refer to processes or pathways by which DIN and DIP affect organisms, communities and more broadly the ecosystem. The mechanisms can be direct (e.g., nutrients directly enhance algal growth and cause algal blooms), or indirect (e.g., when macroalgal growth enhances space competition with corals, or algal blooms induce hypoxia in benthic communities).

Table 2.Definitions for terms used in Question 4.2.

Definitions	
Nutrients	Nutrients refer to inorganic nitrogen (N) dissolved in seawater (DIN), and inorganic phosphorus (P) dissolved in seawater (DIP). Dissolved nitrogen includes nitrate (NO^-_3), nitrite (NO^-_2) and ammonium (NH_4). DIP includes phosphates (PO_4). While some dissolved organic nitrogen compounds (such as amino acids) and dissolved organic phosphorus can be used in algal nutrition, DIN, in particular nitrate and ammonium, and DIP, such as phosphates are the most important ions for algal growth and therefore are the focus of this review.
GBR ecosystems	The GBR ecosystems include coral reefs, seagrass meadows, estuaries, mangroves and freshwater wetlands and refer to the biological communities and the abiotic factors influencing these communities. A biological community refers to the association of interacting species inhabiting a defined area.
Mechanisms	Mechanisms refer to processes or pathways by which DIN and DIP affect the organisms, the communities and more broadly the ecosystems. The mechanisms can be direct, for example N and P directly enhance algal growth and cause algal blooms, or indirect, for example nutrients contribute to coral decline by enhancing algal competition.

2.2 Search and eligibility

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

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

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

a) Search locations

Searches were performed on:

- Web of Science (WoS)
- Scopus

b) Search terms

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

Table 3. Search terms for S/PICO elements of Question 4.2.

Question element	Search terms
Subject/Population	Great Barrier Reef
Exposure or Intervention	Nutrient, nitrogen, nitrate, nitrite, phosphate, phosphorus, eutrophication, runoff
Comparator	(Not relevant)
Outcome	Algal blooms, algal growth, competition, coral bleaching.

c) Search strings

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

Table 4. Search strings used for electronic searches for Question 4.2.

Search strings
Web of Science: ((TI=("Great Barrier Reef")) OR AB=("Great Barrier Reef")) OR AK=("Great Barrier Reef") AND (((((((TI=(nitr*)) OR AB=(nitr*)) OR AK=(nitr*)) OR TI=(phosph*)) OR AB=(phosph*)) OR AK=(phosph*)) OR TI=(nutrient*)) OR AB=(nutrient*)) OR AK=(nutrient*) AND ((((((((((TI=(impact)) OR AB=(impact)) OR AK=(impact)) OR TI=(degradation)) OR AB=(degradation)) OR AK=(degradation)) OR TI=(threat)) OR AB=(threat)) OR AK=(threat)) OR TI=(effect)) OR AB=(effect)) OR AK=(effect) = 276 records (as per Feb 2023).
Scopus: (TITLE-ABS-KEY ("great barrier reef") AND TITLE-ABS-KEY (nutrient* OR nitr* OR phosph*) AND TITLE-ABS-KEY (impact OR degradation OR threat OR effect)) = 358 records (as per Feb 2023).

Note: *The authors assume Great Barrier Reef includes ALL ecosystems required for inclusion in the SCS, including coral reefs, seagrass meadows, estuaries, and freshwater wetlands. Preliminary searches were conducted for individual ecosystems and was found to be resource intensive and provided limited additional benefit to the search outputs.*

d) Inclusion and exclusion criteria

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

Table 5. Inclusion and exclusion criteria for Question 4.2 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	Great Barrier Reef. Searches were not restricted by ecosystem so in principle this should include all systems.	Papers that do not relate to the GBR (Exclusion Criteria 4).
Exposure or Intervention	Nitr* (to include nitrogen, nitrate, nitrite) Phosph* (to include phosphorus, phosphate) Nutrient* (includes nutrients, and nutrient) impact OR degradation OR threat OR effect	Exclusion Criteria 1: No direct information on biological communities. Exclusion Criteria 2: Only water quality data included. Exclusion Criteria 3: Does not answer the question of nutrient impacts.
Comparator	(Not relevant)	
Outcome	Unspecified, to include all ecosystem and organism attributes, metrics, mechanisms, processes, etc.	None
Language	English	Non-English studies
Study type	All types (experimental, laboratory, descriptive, modelling, review, etc.).	None
Accessibility to Authors	Includes items accessible to authors via institutional access, e.g., Scopus, WoS, ResearchGate, Google Scholar, etc.	Some evidence items were not accessible to authors and therefore were excluded from the analysis. Only applicable to two items). (Exclusion Criteria 5)

3. Search Results

A total of 634 studies was identified through online searches for peer reviewed and published literature. Fifty-one studies were identified manually through expert contact and personal collections, which represented 22% of the total evidence. 157 studies were eligible for inclusion in the synthesis of evidence (Table 6) (Figure 2). Two studies were not accessible.

Using the same keywords and search strings, the Web of Science search yielded less records (276) than Scopus (358). Both records were combined, and duplicates were eliminated from the database.

Some important references were not picked up by any of the searches, including studies in coral reefs, mangroves, and freshwater ecosystems. One study was a global assessment of nutrient impacts on mangroves but did not have the word "Great Barrier Reef" in the paper, while others did not have the word "impact OR degradation OR threat OR effect" despite directly addressing nutrient impacts from the GBR in the context of reef degradation. These papers were retrieved manually.

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

Date (d//m/y)	Search strings	Sources	
A) Academic databases		Web of Science	Scopus
10/02/2023	((TI=("Great Barrier Reef")) OR AB=("Great Barrier Reef")) OR AK=("Great Barrier Reef") AND ((((((((TI=(nitr*)) OR AB=(nitr*)) OR AK=(nitr*)) OR TI=(phosph*)) OR AB=(phosph*)) OR AK=(phosph*)) OR TI=(nutrient*)) OR AB=(nutrient*)) OR AK=(nutrient*) AND (((((((((((TI=(impact)) OR AB=(impact)) OR AK=(impact)) OR TI=(degradation)) OR AB=(degradation)) OR AK=(degradation)) OR TI=(threat)) OR AB=(threat)) OR AK=(threat)) OR TI=(effect)) OR AB=(effect)) OR AK=(effect) = 276 records	*122 of 276*	
10/02/2023	(TITLE-ABS-KEY ("great barrier reef") AND TITLE-ABS-KEY (nutrient* OR nitr* OR phosph*) AND TITLE-ABS-KEY (impact OR degradation OR threat OR effect)) = 358 records		*151 of 358*
B) Search engines (e.g. Google Scholar)			
	n/a		
	Total items online searches	***183 (78 %)***	
C) Manual search			
Date/time	Source	Number of items added	
	References provided by co-authors, some cited as key papers in other publications, and authors personal collections.	*50*	
28/07/2023	*Literature suggested by Reviewers*	*1*	
	Total items manual searches	***51 (22 %)***	

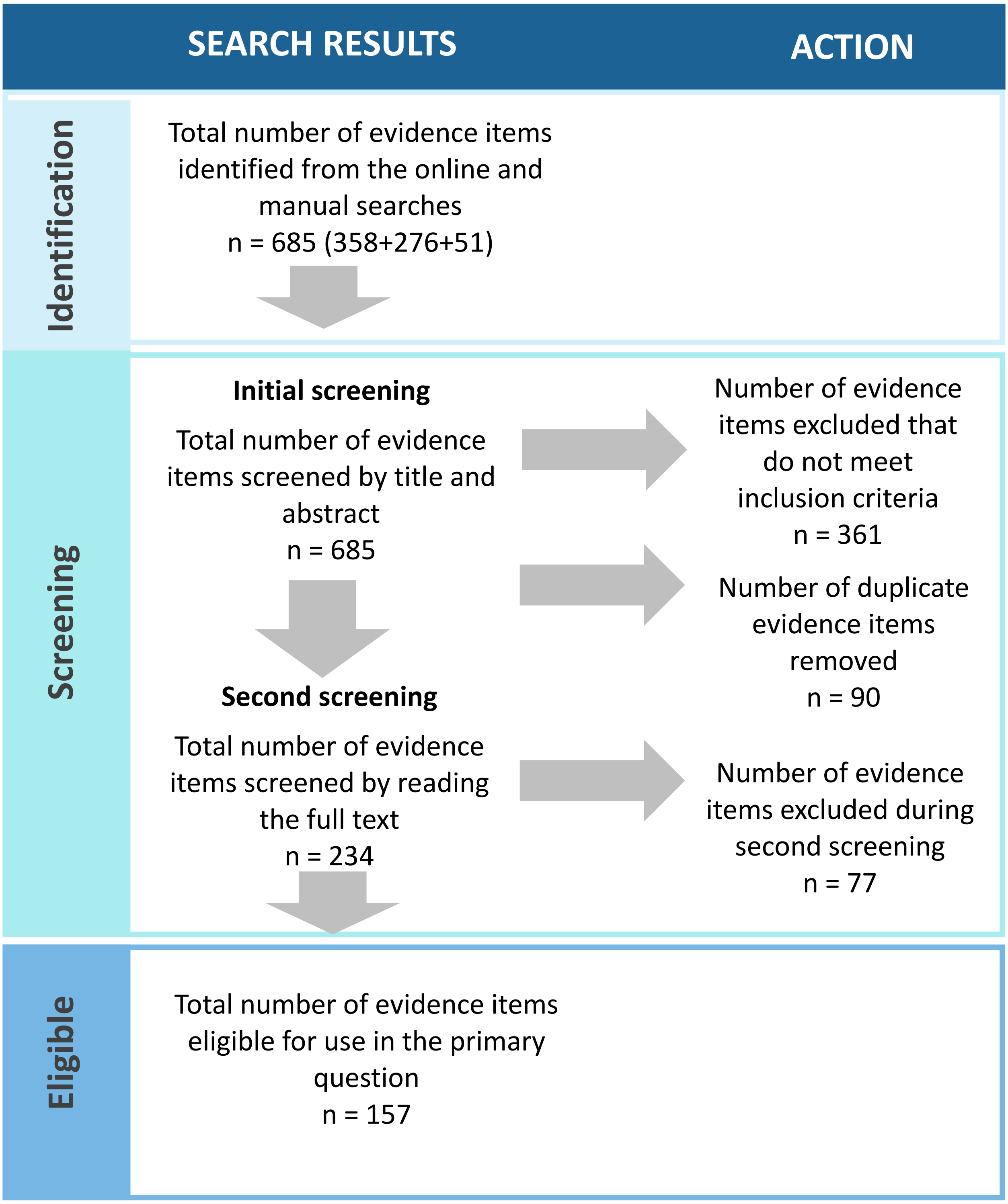


Figure 2. Flow chart of results of screening and assessing all search results for Question 4.2.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

Searches across two online databases of peer reviewed literature (Scopus and Web of Science) identified 183 studies addressing directly or indirectly the impacts of dissolved inorganic nutrients on GBR ecosystems and/or organisms. In addition, 51 studies were added manually through expert contact and author's knowledge. After a second screening process, 157 studies with exclusive spatial focus on the GBR and spanning 1990 to 2022 were eligible to be included as the body of evidence (Table 7). As expected, most studies focused mainly on coral reefs (107 items, 71%), or on coral reefs combined with other ecosystems (e.g., combined reefs and seagrasses, 6 items, 4%). The second most studied system is the coastal (pelagic) marine environment (15, 10%), which for ease of communication encompasses water column environments (including phytoplankton communities) from the inshore to the outer reefs. Few studies are dedicated exclusively to, or included, seagrass meadows (10 items, 6%) and even a lower number focused on mangroves, estuaries, saltmarsh wetlands and freshwater communities (19 items, 12%, Table 7).

Studies reviewed were classified as primary studies (including experimental, whether manipulative or natural, observational, palaeoecological and modelling), secondary studies (reviews), or combined (e.g., experimental/modelling, observational/review studies). Of the 157 studies included in our synthesis, 46 used manipulative experimental methods, or had a manipulative aspect, explicitly testing a hypothesis, and generally with an overall robust experimental design. Of the 46 experiments, 42 examined the direct effect of nutrient addition, with 17 (41%) testing the independent *and* combined effects of both DIN and DIP, and 3 testing the effects of DIN only compared with one study simply testing DIP effects (Table 9). Manipulative experiments are highly valuable as they provide a key direct test of the effects of dissolved inorganic nutrients on GBR ecosystems and/or organisms. These studies however are not always applicable across a range of spatial and temporal scales, nor incorporate the multiple and complex interactions occurring in the natural environment. There were 38 studies that have primarily used an observational approach via direct measurements with often broad applicability across the GBR but providing combined (usually indiscernible) impacts of different water quality factors, not only inorganic nutrients, but also organic nutrients, sediments, DOC. Four of those observational studies have a palaeoecological focus offering historical context and critical information on water quality gradients and ecosystems status pre- and post-European settlement. Further, 30 studies were identified as natural experiments with most of them largely linking the spatial water quality gradient from upstream to downstream within the catchment or from inshore, mid to offshore reefs, with variations in attributes of organisms, assemblages and communities. A total of 20 studies used modelling, or included modelling elements, as the primary method to evaluate the impacts of nutrients on GBR ecosystems and/or organisms. Some of these studies combined observational and modelling methods (8) and the majority comprised important water quality and biological datasets across broad spatial and temporal scales and often explained how the data were used to constrain the models and what assumptions were incorporated. Reviews, including conceptual approaches, were also an important component of the evidence with 26 papers in total. While these studies usually cover a broad range of factors, organisms and areas and provide good summaries of the current state of knowledge, they usually lack empirical evidence or new data limiting the ability to disentangle the effects of nutrients from other water quality parameters. Only one commentary study was included but has limited application to this review.

Table 7. Summary of the body of evidence considered in this review detailing the type of study or combination of them across relevant ecosystems.

Study type	Ecosystem										Total
	Coral reef	Seagrass Coral reef	Seagrass	Seagrass Coral reef Coastal marine	Coastal marine	Mangrove Seagrass Coral reef	Mangrove	Estuary	Freshwater	Wetland	
Manipulative experiment	39		3				1		2		45
Manipulative experiment / modelling	1										1
Modelling	8										8
Modelling / conceptual	1										1
Modelling / observational	6				2						8
Modelling / meta-analysis	1										1
Natural experiment	17		1		3			1	3	1	26
Natural experiment / manipulative experiment	2										2
Observational	17	1	3		6		1	2	3		33
Observational / palaeoecological	2									1	3
Observational / review	2										2
Review	7	1	3	1	4	2			3	1	22
Review / modelling	1	1									2
Natural experiment / palaeoecological / observational	2										2
Commentary	1										1
Total	107	3	10	1	15	2	2	3	11	3	157

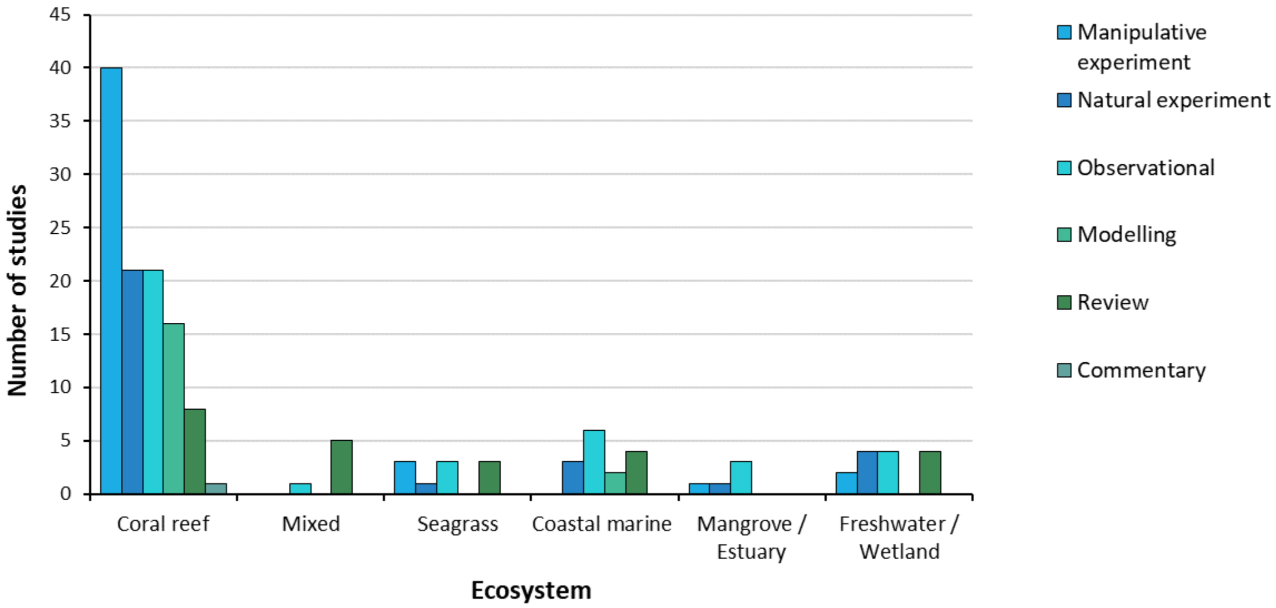


Figure 3. Summary of the body of evidence considered in this review summarised by the primary type of study across relevant ecosystems. Values are percentages (from actual values from Table 8 below).

Table 8. Summary of the body of evidence considered in this review summarised by the primary type of study across relevant ecosystems.

Study type	Coral Reef	Mixed	Seagrass	Coastal marine	Mangrove / Estuary	Freshwater / Wetland	Total
Manipulative experiment	40 (25%)		3 (2%)		1 (1%)	2 (1%)	46 (29%)
Natural experiment	21 (13%)		1 (1%)	3 (2%)	1 (1%)	4 (3%)	30 (19%)
Observational	21 (13%)	1 (1%)	3 (2%)	6 (4%)	3 (2%)	4 (3%)	38 (24%)
Modelling	16 (10%)			2 (1%)			18 (11%)
Review	8 (5%)	5 (3%)	3 (2%)	4 (3%)		4 (3%)	24 (15%)
Commentary	1 (1%)						1 (1%)
Total per ecosystem	107 (68%)	6 (4%)	10 (%6)	15 (10%)	5 (3%)	14 (9%)	157 (100%)

4.1.1 Summary of evidence to 2022

This section provides a summary of the evidence of the impacts of elevated nutrients on the GBR grouped by ecosystems, including coral reefs, seagrass meadows, mangroves, and freshwater wetlands. Given the complexity of coral reef ecosystems and diversity of organisms inhabiting this system, the evidence for coral reefs is grouped by themes that have historically been considered important in the context of nutrient enhancement (e.g., macroalgae versus coral dominance) and/or have a high influence on ecosystem condition (e.g., coral bleaching, crown-of-thorns starfish (COTS)). These themes will also discuss processes and mechanisms by which nutrients directly or indirectly influence the ecosystems.

1. Coral reefs

Seventy percent of the items assessed correspond to studies in coral reef ecosystems, and the majority investigate impacts of nutrients on individual organisms (such as hard corals, benthic macroalgae, foraminifera and COTS) or address the influence of the gradient in nutrient concentrations from inshore to outer reefs on changes in dominance of fleshy macroalgae and hard corals. Five items addressed the relatively recently established link between coral bleaching susceptivity and nutrient enhancement, while 12 papers address the nutrient enrichment hypothesis for COTS outbreaks (explored fully in Question 4.3, Caballes et al., this SCS).

Table 9. Summary of the number of experimental studies and type of nutrient added to examine the direct effects of dissolved inorganic nutrients on organisms and ecosystems in the GBR. DIN: dissolved inorganic nitrogen; DIP: dissolved inorganic phosphorus.

Type of nutrient added experimentally	Number of studies (%)
Plant fertiliser (e.g., Osmocote®), guano, or organic nutrients	8 (19%)
DIN only (as nitrate)	3 (7%)
DIP only	1 (2%)
DIN and DIP tested independently, not combined	3 (7%)
DIN and DIP tested independently and in combination	17 (41%)
DIN and DIP tested in combination, not independently	10 (24%)
Total number of manipulative studies	42 (100%)

Fleshy macroalgae versus coral abundance & diversity

There is marked variation in abundance and species composition of fleshy upright macroalgae (or seaweeds) and hard corals across the continental shelf. High fleshy macroalgal abundance and low coral cover generally occurs in inshore reefs, while midshelf and outer reefs are usually characterised by low fleshy macroalgal biomass and moderate to high cover and species diversity of corals and crustose coralline algae (CCA) (De'ath & Fabricius, 2010; Diaz-Pulido et al., 2016; Fabricius & De'ath, 2004; Fabricius et al., 2005; 2023; McCook et al., 2000; Smith et al., 2020; Thompson et al., 2023; Van Woesik et al., 1999) (Table 10). There is strong correlative (observational) evidence that this gradient in community structure and composition relates to a gradient in water quality from inshore to outer reefs, with reefs exposed to high nutrient availability from land-based nutrient runoff having high fleshy macroalgal abundance (Table 10). The inshore reef Marine Monitoring Program (MMP) (Thompson et al., 2023) has also identified positive correlations between fleshy macroalgal cover and chlorophyll *a* (Chl-*a*), a proxy for response to nutrient availability. High macroalgal biomass on reefs generally has negative effects on corals, particularly via increased space competition (McCook et al., 2001). The gradient in macroalgal abundance and coral community structure is also regulated by a variety of other environmental factors and processes, in particular by intense fish grazing (Russ & McCook, 1999), low sedimentation rates, high water clarity and high irradiance (see also Question 3.2, Collier et al., this SCS) in outer reefs (Fabricius & De'ath, 2004; Fabricius et al., 2005), tidal range (Fabricius et al., 2023) and saturation state of aragonite with respect to seawater (Diaz-Pulido et al., 2016; Fabricius et al., 2023; Smith et al., 2020). Macroalgal dynamics are also influenced by the availability of hard substrate, and it is well known that dead coral skeletons (e.g., following bleaching, cyclones, COTS outbreaks) are rapidly colonised by macroalgae (algal turfs, fleshy and CCA; Diaz-Pulido et al., 2007). Therefore, macroalgal abundance at a particular point in time is the result of complex interactions between ecological processes and cannot only be attributed to increased nutrients (e.g., Done et al., 2007).

Table 10. Summary table of all studies considered in this review that examined the effects of dissolved inorganic nutrients on macroalgal abundance. Studies are grouped by study type, including natural experiments or correlational studies, manipulative experiments, modelling, and reviews (only two review examples included). When macroalgae type was not specified in the paper, it is listed as fleshy macroalgae. CCA: Crustose coralline algae. Field and lab refer to experiments conducted in the field and laboratory respectively. Omega: saturation state of aragonite with respect to seawater.

Study type	Region / location	Macroalgal type	Comment / outcome
Natural experiment / correlations			
McCook, 1996	Water quality gradient, central GBR	*Sargassum*	Algae transplanted from inshore to midshelf reefs were viable, suggesting the cross-shelf difference is not due to nutrients but to differences in herbivory.

Study type	Region / location	Macroalgal type	Comment / outcome
Russ & McCook, 1999	Water quality gradient, central GBR	Algal turfs	Algal production was higher in outer than inshore reefs; nutrient conditions do not directly explain spatial patterns of algal abundance across the shelf.
Van Woesik et al., 1999	Water quality gradient, Whitsunday region	Fleshy macroalgae	Increased macroalgal cover positively correlated with Chl-*a*.
McCook, 2001	Inshore reefs, Central GBR	Algal turfs	Algal-coral competition did not vary along a gradient of water quality, algae were not more successful competitors in more eutrophic conditions.
Fabricius & De'ath, 2004	Water quality gradient, Princess Charlotte Bay and Wet Tropics)	Fleshy macroalgae	Increasing macroalgal cover and decreasing octocoral biodiversity related with elevated nutrients.
Fabricius et al., 2005	Water quality gradient	Macroalgae, CCA	Shift in macroalgal abundance attributed to nutrients.
Ceccarelli et al., 2020	Inshore reefs, Central GBR	Fleshy macroalgae	Chl-*a* strong predictor of macroalgal cover at some, but not all reefs.
Cheal et al., 2010	Inshore reefs, Central GBR	*Lobophora*	No evidence that nutrients explain macroalgal blooms, while fish communities were strongly associated with the coral to macroalgal phase shift.
Diaz-Pulido et al., 2016	Water quality gradient, Lizard Island region	Fleshy macroalgae	Carbon uptake physiology in macroalgae vary across the gradient, with outer reef species having higher proportion of CO_2 only species.
Thompson et al., 2023	Inshore reefs, GBR wide	Fleshy macroalgae	Macroalgal cover was positively related to Chl-*a* (& total suspended sediments (TSS)) at 2 m, while coral cover was negatively related to Chl-*a* (& TSS). Reef recovery was negatively related to discharge from rivers.
Manipulative experiment (nutrient additions)			
Larkum & Koop, 1997	Outer reef, One Tree Island (field, ENCORE)	Algal turfs (epilithic algae)	N, P, or N+P addition had no effect on growth or primary production (oxygen exchange) of the epilithic algal community.
Koop et al., 2001	Outer reef, One Tree Island (field, ENCORE)	Algal turfs (epilithic algae), CCA	Nutrient enrichment had no effects on epilithic algal productivity and only observed minor increases in larger macroalgae. No effects on coralline algae.
Schaffelke & Klumpp, 1998a	Inshore reefs, (lab)	*Sargassum*	Enhanced nutrients increased *Sargassum* growth, but higher concentrations also resulted in reduced growth rates.
Schaffelke & Klumpp, 1998b	Inshore reefs, central GBR (field)	*Sargassum*	Short-term nutrient pulses (as short as 1 h) enhanced *Sargassum* photosynthesis and growth.
Jompa & McCook, 2002	Inshore reefs, Orpheus Island (field)	*Lobophora*	Nutrient addition increased coral tissue mortality but only when herbivores were removed and when *Lobophora* was present.
Diaz-Pulido & McCook, 2003	Midshelf reefs, Rib reef (field)	*Sargassum* &	Elevated nutrients enhanced *Lobophora* but not *Sargassum* growth; but effects were minor compared to those of grazing. Functional responses identified.

Study type	Region / location	Macroalgal type	Comment / outcome
		Lobophora recruits	
Diaz-Pulido & McCook, 2005	Inshore reefs, Central GBR (lab)	*Sargassum*	Nutrient enrichment reduced vegetative and reproductive biomass.
Reef et al., 2012	Outer reef, Heron Island (lab)	*Laurencia, Sargassum, Caulerpa*	N & P enrichment increased photosynthetic performance but not growth.
Bender et al., 2014	Outer reef, Heron Island (lab)	*Chnoospora*	Nutrient enrichment did not affect growth rates.
Bender-Champ et al., 2017	Outer reef, Heron Island (lab)	*Turbinaria, Chnoospora, Laurencia*	Nutrient enhancement did not enhance growth rates; however, mortality was increased under high nutrients in *Laurencia*.
Chazottes et al., 2017	Outer reef, One Tree Island (field, ENCORE)	CCA	Nutrient enrichment enhanced microbioerosion (likely due to endolithic algae) and accretion rates of CCA growing on blocks, possibly encouraged fish grazing.
Modelling studies			
De'ath & Fabricius, 2010	Across water quality gradient	Fleshy macroalgae	Macroalgal biomass increased with increasing Chl-*a*, but stronger correlations with decreasing water clarity.
McCook et al., 2000	Across water quality gradient	Fleshy macroalgae	Eutrophication reduces the ability of corals to recover from disturbances by altering coral recruitment success due to competition with fleshy macroalgae.
Smith et al., 2020	Across water quality gradient	Coralline algae, macroalgae	Inconclusive / inconsistent relationship between CCA and fleshy macroalgal cover with Chl-*a* & stronger responses to omega, high CO_2 may promote fleshy macroalgae.
Fabricius et al., 2023	Across water quality gradient	Macroalgae (excl turfs)	Macroalgae increased from offshore to inshore reefs (opposite for corals & CCA) and best predictor was tidal range, omega & Secchi depth, while Chl-*a* & DIN were of lower importance.
Reviews (examples)			
McCook, 1999	Across water quality gradient	Fleshy macroalgae	Nutrient enrichment is unlikely to lead to phase shifts simply by enhancing algal growth rates hence allowing coral overgrowth unless herbivory is low.
Bell et al., 2007	Outer reef, One Tree Island	Fleshy macroalgae	Attributed increased macroalgal abundance to ENCORE experiments, but no direct proof.

Manipulative, nutrient enrichment experiments in the GBR have shown variable effects on macroalgal growth rates. In **inshore reefs**, nutrient additions (particularly N) have shown increased growth rates of fleshy macroalgae, such as *Sargassum* spp. and *Lobophora* (evidence summarised in Table 10; also Schaffelke (1999) for addition of particulate organic matter). However, there is also evidence that excess nutrient additions (e.g., >5 µM ammonium combined with >0.5 µM phosphate) may be harmful for *Sargassum* growth (Schaffelke & Klumpp,1998a) and reproduction (Diaz-Pulido & McCook, 2005). Field and lab studies using fleshy macroalgae from **outer reefs** have shown that nutrient enrichment does not necessarily increase macroalgal growth rates or biomass accumulation (Bender-Champ et al., 2017; Bender et al., 2014; Koop et al., 2001; Larkum & Koop, 1997) (Table 10). Recent evidence from Heron Island showed that nutrient enhancement had no effect on the growth rates of three very common tropical macroalgae species, and in fact, mortality in one of the algal species was increased under high nutrients. This is not consistent with the accepted notion that nutrients universally favour macroalgal growth rates causing macroalgal blooms in the GBR and reveals high variation in responses of macroalgal groups/species to nutrient enrichment (Bender-Champ et al., 2017; Lovelock, 2020). It therefore seems that addition of nutrients does not always enhance macroalgal growth rates or lead to enhanced biomass accumulation, and it is simplistic to assume that the macroalgal biomass gradient can only be attributed to nutrient pollution in inshore reefs. There is strong evidence that grazing (mainly by herbivorous fish) controls fleshy macroalgal biomass accumulation in midshelf and outer reefs (Diaz-Pulido & McCook, 2003; Hoey & Bellwood, 2010; Jompa & McCook, 2002; McCook 1996; 1999; Wismer et al., 2009), and transplant experiments of macroalgae from inshore to outer reefs show that macroalgae are able to grow as healthily in outer reefs as in inshore reefs (McCook, 1996). This suggests that in reefs with low water nutrient concentrations (i.e., midshelf and outer reefs, compared to inshore reefs), fleshy macroalgae are able to obtain the nutrients required for growth (McCook, 1996) and that the low fleshy macroalgal biomass in the outer reefs is more due to intense grazing rather than lack of nutrients. Experimental and modelling evidence suggests that nutrient effects on macroalgal growth only lead to competitive effects on adult corals when herbivory is insufficient to consume excess algal growth (Jompa & McCook, 2002; McCook et al., 2000). **The risks of nutrient enrichment promoting macroalgal overgrowth of corals will be most significant under low herbivory regimes (McCook, 1999; also discussion in Shenton et al., 2010), such as areas where herbivores are naturally scarce, such as inshore reefs (Wismer et al., 2009)**.

Recent evidence published since the 2017 SCS (Schaffelke et al., 2017) confirms the pattern of distribution of fleshy macroalgae and coral abundance across the water quality gradient (Fabricius et al., 2023; Smith et al., 2020). Also, new evidence emerged that the gradient in macroalgal abundance can also be explained by other environmental variables, such as tidal range, Secchi depth and importantly, is inversely correlated with saturation state of calcium carbonate with respect to seawater (Ω, omega, which is related to carbon dioxide (CO_2) availability in seawater). This suggests that increasing seawater CO_2 (and related ocean acidification) may contribute to promoting fleshy macroalgal growth in the GBR (Fabricius et al., 2023; Smith et al., 2020). Further, a study on macroalgal physiology (Diaz-Pulido et al., 2016) showed that the strategy of dissolved inorganic carbon use in macroalgae from the GBR varies across the gradient of water quality, with outer reef macroalgae having proportionally more species using CO_2, and because CO_2-only user macroalgae are more responsive to increased seawater CO_2 and ocean acidification (OA), reef slopes of outer reefs can be potentially more vulnerable to the impacts of OA. The interactions between water quality and carbon dioxide (CO_2) enrichment (and ocean acidification) on macroalgal ecology in the GBR is an emerging area of research which needs more investigation (Diaz-Pulido et al., 2016; Fabricius et al., 2023; Smith et al., 2020).

Crustose coralline algae and dissolved inorganic nutrients

The effects of dissolved inorganic nutrients on crustose coralline algae (CCA) are poorly understood in the GBR. There is a clear pattern of increased CCA abundance along the water quality gradient across the continental shelf, with low CCA cover in inshore reefs and high CCA cover in shallow outer reefs (Dean et al., 2015; Diaz-Pulido et al., 2016; Fabricius & De'ath, 2001; Fabricius et al., 2023; Smith et al., 2020; Wismer et al., 2009). The sedimentary environment (i.e., sedimentation rates, sediment type) has been generally identified as the major environmental factor affecting the cross-shelf distribution of CCA (Fabricius & De'ath, 2001). High wave energy and to a lesser extent high fish grazing rates in the outer reefs have also been associated with higher CCA abundance in these areas compared to inshore environments (Wismer et al., 2009). Recent correlative studies have demonstrated a positive relationship between CCA cover and calcium carbonate saturation state of seawater (Smith et al., 2020). Importantly, in the context of this review, we identified only one study as part of the ENCORE experiment in One Tree Island in the southern GBR (Chazottes et al., 2017) that experimentally tested the effect of nutrient enrichment on CCA accretion rates (obtained from crust thickness and surface area measurements). Chazottes et al. (2017) found a 24% increase in accretion rates of CCA under elevated nutrients (DIN and DIP combined) and suggested that this increase may have been (indirectly) facilitated by increased fish grazing (feeding on endolithic algae). This proposed mechanism, however, requires careful examination because fish grazing may also remove CCA tissue (both calcium carbonate and biomass) with potential negative effects on CCA accretion rates. It is also possible that enhanced nutrient concentrations accelerated CCA growth, suggesting CCA were nutrient limited in this environment. Using the same ENCORE experiment, Koop et al. (2001) did not find any negative effects of nutrient additions on coralline algae. The evidence for the effects of dissolved inorganic nutrients on CCA from non-GBR areas is contrasting, with studies demonstrating negative (Belliveau & Paul, 2002; Björk et al., 1995; Schubert et al., 2019) and positive (Smith et al., 2001; Tanaka et al., 2017) effects on CCA growth and calcification, as well as complex interactions between nutrients, herbivory and fleshy macroalgae (Diaz-Pulido et al., 2007; Smith et al., 2001). Further studies are needed to determine the direct and indirect effects of DIN and DIP on the growth and ecology of CCA in the GBR, and particularly how DIN and DIP enrichment interact with sediment runoff and other local (e.g., pesticides; Harrington et al., 2005) and global stressors (e.g., warming and acidification; Diaz-Pulido et al., 2012; Smith et al., 2020). Understanding the effects of the different water quality components on CCA along and across the GBR would be important given the critical contribution of CCA to reef cementation, framework consolidation and accretion (Cornwall et al., 2023), reef resilience by inducing coral larval settlement (Abdul Wahab et al., 2023), and their role as a settlement cue, habitat and food source for juvenile COTS (Babcock et al., 2016; Doll et al., 2023).

Increased coral bleaching susceptibility

Increased terrestrial dissolved inorganic nitrogen (DIN) loading has been **associated with a lowering of thermal bleaching thresholds in corals in the GBR** (Wooldridge, 2009; Wooldridge & Done, 2009; Wooldridge et al., 2012). Zooxanthellae, as any other algae, generally benefit from enhanced DIN (that is because it releases the endosymbiotic algae from N limitation), which may promote excessive zooxanthellae growth and division rates (e.g., Bucher & Harrison, 2018) and a similar response has also found in GBR giant clams (Ambariyanto & Hoegh-Guldberg, 1997). Proliferation of endosymbiont populations increases the likelihood of CO_2 becoming a limiting internal substrate during periods of high photosynthesis, causing symbionts to retain photosynthates, and disrupting the stability and functioning of the coral-zooxanthellae endosymbiosis (Wooldridge, 2009; 2020). Further modelling (Wooldridge, 2020) proposed that excess nutrients that permit increased zooxanthellae densities beyond an optimum range are linked with seawater chlorophyll *a* >0.45 $\mu g \cdot L^{-1}$, and Wooldridge (2009) argue that this **Chl-*a* threshold correlated with enhanced bleaching** sensitivity during the 1998 and 2002 mass bleaching events. Experimental studies in the GBR by Fabricius et al. (2013) found that enhanced DIN (specifically nitrate) did not alter bleaching responses in two *Acropora* and *Montipora* corals, but corals exposed to high *organically enriched treatments* experienced significantly greater reductions in fluorescence yields and lower survival compared to control corals. Therefore inorganic nutrients had little influence on bleaching, results supported by recent experimental evidence from Cantin et al. (2021) (although Cantin et al. is an institutional report, not a journal publication). Recent studies from non-GBR localities have advanced the mechanistic understanding of the pathways by which enhanced DIN (Wiedenmann et al., 2013) or elevated DOC (Pogoreutz et al., 2017; Rädecker et al., 2015; 2021) increase the susceptibility of corals to temperature- and light-induced bleaching. **However, the experimental, lab or field evidence of these mechanisms is still very limited in the GBR (Cantin et al., 2021; Fabricius et al., 2013) and this represents an important knowledge gap (refer also to Question 2.4, Uthicke et al., this SCS)**.

Baird et al. (2021a) indirectly tested the hypothesis proposed by Wooldridge (Wooldridge, 2009; Wooldridge & Done, 2009) that increased DIN levels increase the susceptibility of corals to temperature-induced bleaching in the GBR. Baird et al. (2021a) conducted computer simulations using the eReefs platform showing a small, even negligible, effect of river-derived anthropogenic loads (of nutrients and sediments) on reactive oxygen stress build-up (used as an indicator of bleaching) in five sites chosen for their relatively high potential exposure to rivers. The model suggested that nutrient (and sediment) loads did not significantly change the severity of coral bleaching on the GBR in 2017 (although the river discharge may have been low for that period of time). Similarly, Hughes et al. (2017) and Cantin et al. (2021) concluded that hundreds of individual reefs were severely bleached in 2016 irrespective of their inshore–offshore differences in water quality in the GBR.

Therefore, despite the mechanistic and conceptual explanations about the influence of DIN loads on the reduction of the temperature threshold of coral bleaching in the GBR, the observational evidence using bleaching data and eReefs, as well as the limited manipulative experimental evidence, does not provide support to this hypothesis. This continues to be an area of considerable debate (Cantin et al., 2021; Wooldridge, 2020) (also Question 2.4, Uthicke et al., this SCS). **Further laboratory and field manipulative experiments are** critical to provide support or dispute the link between the theory and direct observations regarding the effects of DIN and coral bleaching.

COTS outbreaks

Crown-of-thorns starfish (COTS) outbreaks are one of the most important causes of coral cover loss and consequently reef degradation in the GBR (De'ath et al., 2012). Question 4.3 (Caballes et al., this SCS) comprehensively addresses the key drivers of population outbreaks. In this section, we focus specifically on the evidence for the links between dissolved inorganic nutrients and COTS outbreaks, particularly the impacts on COTS early life stages. This link is encapsulated in the **'nutrient hypothesis'** (Brodie, 1992) similar to the 'terrestrial runoff hypothesis' from (Birkeland, 1982), which proposes that elevated nutrient loads discharged from the land cause phytoplankton blooms in coastal waters during the starfish larval period, and since larvae feed on phytoplankton, increased microalgal blooms are suggested to favour larval survival, settlement success and juvenile survival.

Twelve studies (10% of the total studies assessed here) were included in the analysis and six of them **directly tested the effects of increased food availability** (or phytoplankton concentrations, as proxies for nutrient concentrations) on several stages of COTS larval development including settlement. Most studies demonstrated that higher phytoplankton concentrations (biomass or cell numbers) enhanced larval traits (e.g., expedited larval development, increased survival) (Fabricius et al., 2010; Pratchett et al., 2017a; Uthicke et al., 2015; Wolfe et al., 2015), with most studies showing greatest larval development at intermediate food levels. Both experimental (Fabricius et al., 2010; Pratchett et al., 2017a; Wolfe et al., 2015) and review studies (Brodie et al., 2017) **provide support for the enhanced nutrients hypothesis, but up to a limit as excessive algal concentrations may reduce larval performance**. Importantly, however, Wolfe et al. (2017) found that under low nutrient/oligotrophic conditions typical of many GBR reefs (0.1 µg Chl-*a* L^{-1}), COTS larvae are also able to successfully settle to the benthos, suggesting that high larval survival occurs across a broad range of nutrient levels, even below levels posited by the enhanced nutrients hypothesis (>2 µg Chl-*a* L^{-1}) (Fabricius et al., 2010). Further, new evidence is now available on the sensitivity of COTS larvae to low salinity which may be interpreted as opposing the nutrient enrichment hypothesis as a cause of COTS outbreaks (Clements et al., 2022). Different levels of phytoplankton biomass offered as food (as proxy for nutrient availability) did not have an effect on COTS larvae and did not affect the direction of the effects of salinity on COTS (Clements et al., 2022); results (Clements et al., 2022; Wolfe et al., 2017) that are **inconsistent with the enhanced nutrients hypothesis** and consistent with the alternative hypothesis of larval resilience that dictates that outbreaks do not necessarily require eutrophic conditions and associated increased levels of phytoplankton. A recent study using regression analyses provided a better understanding of the potential causes of the spatial distributions of COTS outbreaks in the GBR, indicating that nutrients, or more precisely chlorophyll *a* concentration, explains 12.6% of COTS prevalence, flood plume exposure explains 13.0% of COTS presence, while larval connectivity explains 22.7% (Matthews et al., 2020) (further details in Question 4.3, Caballes et al., this SCS). Despite most papers supporting the nutrient hypothesis, there are also examples where COTS larvae settle successfully under low nutrient levels. **Therefore, the extent of the role of nutrient enrichment in COTS outbreak dynamics still requires further resolution**.

An important point to consider is that none of the studies identified in the literature searches have considered the direct impacts of nutrient enrichment on COTS larval development, since most studies have done so indirectly using a range of algal biomass indicators as proxies for nutrient concentrations. In fact, when other variables associated with terrestrial runoff (such as lower salinity) have been tested on COTS larval development, there were detrimental effects on the larvae (Clements et al., 2022). **It would be important to test if the early life history stages of this invertebrate are, like corals, very sensitive to elevated nutrient concentrations**.

Direct negative effects on corals

The direct effects of elevated dissolved inorganic nutrients on hard corals **are complex, very variable and difficult to generalise**, which is not surprising given the more than 450 species of Scleractinia corals present in the GBR (Bridge et al., 2012; DeVantier et al., 2006; Wallace, 2019). As pointed out by Fabricius et al. (2013), it is important to remember that reef building corals need some nutrients, therefore nutrient availability can be beneficial for corals, but *excess* nutrient loads can be a stress factor. Fabricius (2005; 2011) reviewed and synthesised information on the effects of nutrients on corals (although not specifically for the GBR) and indicated that most studies show that high levels of DIN and DIP can cause significant physiological changes in corals, but do not kill or greatly harm individual coral colonies (see also Nalley et al., 2023). Forty-one **studies directly or indirectly addressed the effects of nutrients on GBR corals**. The seminal nutrient experiments conducted in the field in the mid-1990s as part of the ENCORE (Enrichment of Nutrient on a Coral Reef Experiment) program (Hoegh-Guldberg et al., 2004; Koop et al., 2001), showed that a variety of biological and physiological processes of the corals were initially not affected (with the exception of coral reproduction), likely because nutrients were rapidly taken up by the reef communities, or overall low nutrient loading (Hoegh-Guldberg & Williamson, 1999). However, elevated dosing of nutrients to ecologically unrealistic levels (e.g., 11–32 µm ammonia, 2.4–5.1 µmol phosphate) for an additional year, did negatively affect a variety of coral processes, including increased mortality in *Pocillopora* corals (Koop et al., 2001), and change in secondary metabolites in soft corals (Fleury et al., 2000; 2004).

Overall, the ENCORE studies and more recent experiments have shown that **coral reproduction is a very sensitive process affected by nutrient enrichment**. Ward and Harrison (2000) found corals exposed to elevated nitrogen concentrations produced significantly smaller and fewer eggs and contained less testicular material than control corals. Reduced settlement of *Acropora longicyathus* was also observed under elevated N and P treatments (Ward & Harrison, 1997). A more recent study by Humanes et al. (2016), showed that *Acropora* exposed to elevated nutrients suffered a reduction in fertilisation, particularly when combined with temperature stress. **However, even in the sensitive process of coral reproduction, outcomes are not universal.** For example, Humphrey et al. (2008) did not find a direct effect of nutrient enrichment on coral fertilisation in a GBR coral, unless nutrients were combined with sediments, when a negative effect was manifested.

A decline in coral calcification has also been associated with enhanced nutrient availability (e.g., Fabricius, 2005). For example, the ENCORE experiments found that although elevated DIP increased coral linear extension, skeletal density was reduced, potentially making corals more prone to breakage (Koop et al., 2001; Rocker et al., 2017) along a gradient in water quality. Increased shell extension but reduced shell weight has also been observed in giant clams (Braley et al., 1992). New evidence confirms the negative effects of excessive nutrient addition (N, P) on coral physiological processes, specifically reducing calcification rates in *Acropora intermedia* (van der Zande et al., 2021), however this new evidence also noted that short-term pulses of nutrients may actually be beneficial for corals (van der Zande et al., 2021), supporting earlier findings that moderate nitrogen concentrations may benefit coral reef calcification (McMahon & Santos, 2017; McMahon et al., 2013; but see Shaw et al., 2012). D'Olivo et al. (2013) conducted a natural experiment investigating the influence of water quality on coral calcification and found a long-term decline in calcification for the inshore GBR, and attributed this decline to the persistent ongoing effects of nutrient loads from wet season river discharges (also D'Olivo et al., 2015). On the other hand, Strahl et al. (2019) found that the photosynthesis of *Acropora tenuis* did not respond negatively to declining water quality. However, as in other correlative studies conducted along a gradient of water quality (e.g., Jupiter et al., 2008), it is not possible to tease apart the effects of DIN supply from those of sedimentation, salinity, light, etc. A historical study on the recovery of coral reef assemblages in the central GBR (Roff et al., 2013) suggested that increased sediment fluxes and nutrient loading from modern agricultural practices were associated with the lack of recovery in *Acropora* assemblages (e.g., via coral recruitment impairment), however, it is difficult to attribute causality to nutrient enrichment given the combined effect of the stressors.

Coral diseases have also been associated with enhanced nutrient availability in coastal waters of the GBR. Haapkylä et al. (2011) found a direct correlation between summer outbreaks of atramentous necrosis disease in corals and environmental parameters related with water quality, in particular particulate organic carbon, which is strongly autocorrelated with Chl-*a* and dissolved inorganic nutrients. Lower salinity may also reduce coral immune responses, and/or increased virulence of pathogen(s) causing the disease. **A direct link between coral disease and dissolved nutrients cannot yet be demonstrated** and future studies should specifically address this gap, although it is clear that overall, declining water quality (particularly low salinity and concentrations of particulate organic carbon) clearly facilitates seasonal outbreaks in coral disease in the GBR (Haapkylä et al., 2011).

Increased bioerosion

Bioerosion refers to the biological mediation of carbonate removal (whether corals, crustose coralline algae or the reef framework) by microborers (e.g., endolithic algae), macroborers (sponges, bivalves, worms) and grazers (fishes and sea urchins), and is a critical process influencing reef carbonate budgets and reef accretion rates (Brown et al., 2021; Tribollet & Golubic, 2005; Wolfe et al., 2020). One of the few studies identified by this review was conducted at One Tree Island (**outer reef**) and showed that rates of microbioerosion (presumably by endolithic algae including cyanobacteria and Chlorophyta, and fungi (Chazottes et al., 2002) and grazing on dead substrates were increased by direct enrichment of inorganic nutrients (combined DIN and DIP) compared to control conditions (Chazottes et al., 2017). Increased microborer abundance in response to increased nutrient levels may have led to an increase in fish grazing (Chazottes et al., 2017). Correlational studies however show that microbioerosion is apparently inhibited by high sedimentation rates in **inshore reefs** (Hutchings et al., 2005;Tribollet & Golubic, 2005), although the evidence comes from only one reef transect in the northern Wet Tropics. Changes in the microborer community and its bioerosion rates on giant clam shells were not clearly related to nutrient enrichment in **outer reefs** (Vogel et al., 2000). Bioerosion patterns across the natural water quality gradient in the GBR show variable responses. **Inshore reefs** have lower rates of total bioerosion relative to mid and outer reefs, and **outer reefs** exhibit high bioerosion rates primarily due to microborers and increased grazing activity by parrotfish (Hutchings et al., 2005; Tribollet & Golubic, 2005). High internal macroerosion is found in **inshore and midshelf corals** compared to **outer reefs** (Risk et al., 1995).

While the limited evidence presented does not fully clarify the role of nutrients on bioerosion processes and communities nor the mechanisms involved, it provides two main premises that need to be further investigated: 1) higher levels of nutrients and organic matter in inshore and midshelf reefs may explain increased abundance of macroborers hence increasing bioerosion rates; 2) increased nutrient levels in outer reefs may stimulate endolithic algal growth in turn enhancing parrotfish grazing and hence increasing bioerosion rates (Chazottes et al., 2017).

Microbial communities, microphytobenthos and benthic foraminifera from coral reef environments

Sixteen studies investigating the influences of elevated dissolved inorganic nutrients on microbial communities in coral reef systems were identified from the literature searches and personal databases. The studies included benthic foraminifera, microphytobenthos, and planktonic and benthic microbial communities, and there was a good spread of natural experiments/observational studies and manipulative experiments (Table 11).

The influences of DIN on these communities or organisms were highly variable. For example, nutrient enrichment experiments decreased growth rates of some benthic foraminifera (Reymond et al., 2011) and caused increased bleaching in symbiont-bearing foraminifera (Prazeres et al., 2016), while no effects were documented on others (Uthicke & Altenrath, 2010). A palaeoecological study (Johnson et al., 2019) on benthic foraminifera from the central GBR suggested that the change observed in species composition of foraminifera assemblages may have been driven by changes in hydrodynamic energy, light availability and the carbonate content of reef-matrix sediments during reef shallowing towards sea level rather than nutrient and sediment inputs. **This study adds to the debate around whether coral reef condition represents a natural state, or whether it is attributable to intensifying disturbances induced by human activities, including eutrophication, sedimentation, etc.** (see also discussion in Perry et al., 2008; Ridd et al., 2011). Similarly, addition of nutrients in lab experiments had contrasting effects on microbial communities. For instance, some recorded a reduction of primary production at elevated nitrate concentrations (Witt et al., 2012), or an increase in primary production (Uthicke & Klumpp, 1998), while others documented strong resilience in microbial communities associated with a reef sponge (Simister et al., 2012).

A series of studies have examined the change in community composition along water quality gradients in the GBR, and overall they have found strong influences of water quality on species composition of foraminifera assemblages (Uthicke & Nobes, 2008; Uthicke et al., 2012), benthic dinoflagellates (Skinner et al., 2013), and planktonic microbial communities (Angly et al., 2016; Frade et al., 2020). As for other GBR organisms, there is variability in the microbial responses to nutrient availability, and there are examples showing that microbial communities associated with a reef sponge are strongly resilient to nutrient enrichment (Simister et al., 2012), supporting the notion that sponges are resistant to moderate nutrient enrichment (Ramsby et al., 2020). The comprehensive meta-analysis and modelling study by Frade et al. (2020) clearly demonstrated the sensitivity of planktonic bacterial communities to changes in water quality parameters, with a trend of reduced richness and diversity of bacterial communities associated with increased terrestrial input nearshore and more diverse and rich bacterial communities under more oligotrophic oceanic conditions in offshore reefs. **Although the microbial patterns correlated with nutrient gradients, it is important to remember that DIN concentrations are also autocorrelated with other water quality parameters including sediments, DON, DIC, DOC, etc., therefore conclusive evidence of direct effects of DIN on microbes needs careful consideration**.

Table 11. Summary table of all studies considered in this review that examined the effects of dissolved inorganic nutrients on microorganisms (excluding phytoplankton). Microorganisms were grouped into benthic categories such as microphytobenthos (e.g., microscopic algae, biofilms), benthic foraminifera (forams), and benthic dinoflagellates or planktonic groups (e.g., planktonic microbial communities). Studies are grouped by study type, including natural experiments or correlational, manipulative experiments, and modelling. Field and lab mean experiment conducted in the field and laboratory respectively.

Study type	Region/ location	Community type / organism	Comment / outcome
Natural experiments / correlations			
Uthicke, 2006	Water quality gradient, Whitsundays, central GBR	Microphytobenthos	Photosynthetic efficiency did not vary along the water quality gradient.
Schueth & Frank, 2008	Low Isles Reef and Heron Island	Benthic foraminifera	Community composition was similar between two reefs differing in water quality (but no data provided), suggesting no effects of water quality on coral populations.
Uthicke & Nobes, 2008	Water quality gradient, Whitsundays, GBR wide	Benthic foraminifera	Abundance of symbiont-bearing forams was negatively correlated with Chl-*a*, and FORAM index (of spp. composition) varies across the water quality gradient.
Uthicke et al., 2012	Water quality gradient, Whitsundays, central GBR	Benthic foraminifera	Forams vary across the water quality gradient (heterotrophic versus symbiont-bearing further away from the coast); youngest assemblages differed from pre-development.
Skinner et al., 2013	Water quality gradient, Northern GBR	Benthic dinoflagellates (epiphytic)	Abundance of ciguatera causing dinoflagellates was positively correlated with DIN concentrations and there is evidence of recent dinoflagellates community shifts.
Angly et al., 2016	Tully River mouth	Planktonic microbial communities	Microbial communities strongly influenced by seasonal river discharge, but link with nutrients is inconclusive.

Study type	Region/ location	Community type / organism	Comment / outcome
Johnson et al., 2019	Paluma reefs, central GBR	Benthic foraminifera (fossils)	No evidence of change in modern foram assemblages relative to pre-development, but identified transitions associated with sea level change.
Glasl et al., 2021	Magnetic Island, central GBR	Microbial communities (epiphytic)	Some bacteria positively / negatively correlated with water quality parameters including ammonium, PO_4, DOC and causality cannot be established.
Manipulative experiment (nutrient additions)			
Uthicke & Klumpp, 1998	Great Palm Island, Central GBR	Microphytobenthos	NH_4 enrichment (via holothurians (sea cucumber) excretions) enhanced primary production (10 to 12%). Other nutrients may have also altered algal responses.
Albert et al., 2005	Hardy Reef, central GBR (field)	Benthic cyanobacteria (*Lyngbya*)	Photosynthesis was enhanced by guano (mostly iron, P and organic C) suggesting that guano is related with cyanobacteria blooms at this reef.
Uthicke & Altenrath, 2010	Whitsundays, central GBR (field)	Benthic foraminifera (two spp.)	No effect of nutrient enrichment on growth, but lower growth close to shore (difficult to disentangle effects of DIN from sediments, light, or DON).
Reymond et al., 2011	Whitsundays, central GBR (lab, AIMS)	Benthic foraminifera (*Marginopora. vertebralis*)	Nutrient enrichment decreased growth rate of a symbiont-bearing foram, and growth was lower in sites closer to the river mouth (high N & P).
Witt et al., 2012	Central GBR (lab, AIMS)	Benthic microbial communities	Nitrate enrichment at high levels reduced biofilm productivity, and this depended on temperature & light; no effects on Chl-*a* but more diatoms in high nitrate.
Simister et al., 2012	Orpheus Island, central GBR	Benthic microbial communities (on sponges)	Nutrient enrichment did not alter microbial community composition or functionality and had no adverse effects on the sponge.
Prazeres et al., 2016	Lizard Island, northern GBR	Benthic foraminifera (*Amphistegina lobifera*)	Nitrate additions had stronger negative effects (e.g., bleaching) on forams from mid and outer shelfs than inshore sites (which were more resilient).
Modelling studies			
Frade et al., 2020	Water quality gradient, GBR wide	Planktonic microbial communities	Bacterial communities strongly correlated with water quality (including nutrients), with inshore reefs having lower diversity compared to outer shelf reefs.

2. Impacts on phytoplankton (and potential effects on reefs and seagrasses)

Nearly 30% of the items assessed dealt directly or indirectly with the effects of dissolved inorganic nutrients (N and P) on phytoplankton, specifically on levels of chlorophyll *a* (Chl-*a*). The link between elevated dissolved inorganic nutrients and Chl-*a* is well established (Bainbridge et al., 2012; Baird et al., 2021a; 2021b; Bell, 1992; Brodie et al., 2007; 2011, Devlin et al., 2012; 2015; Franklin et al., 2018; Gabric et al., 1990; Petus et al., 2014; Schaffelke et al., 2012; Wooldridge et al., 2006), and will not be considered in detail here (see Question 4.1, Robson et al., this SCS). Intense and extensive phytoplankton blooms following the discharge of nutrient-rich river flood waters have been documented in many regions of the GBR, particularly in the central and southern inshore areas of the GBR (Brodie et al., 2011; Gabric & Bell, 1993), but also in the northern GBR (e.g., Princess Charlotte Bay;

(Howley et al., 2018). The evidence shows that nutrients are rapidly taken up by phytoplankton and converted to organic matter, with the relative abundances of dissolved nutrient species strongly indicating N limitation of new phytoplankton formation (Franklin et al., 2018; Furnas et al., 2005; McKinnon et al., 2013). Furnas et al. (2005) and McKinnon et al. (2013) indicated that increased nutrient availability can induce rapid changes in the composition of phytoplankton communities in the GBR lagoon (provided there is sufficient light availability), from a picoplankton-dominated system to one dominated by diatoms and dinoflagellates (Furnas et al., 2005). McKinnon et al. (2013) also noted that *Trichodesmium*, a nitrogen-fixing cyanobacterium forms episodic blooms and may be an important source of new N to the GBR. **The hypothesis by Bell (Bell, 2021; Bell et al., 1999) that *Trichodesmium* population density/abundances have resulted from increases in river borne nutrients that would promote N fixation (e.g., phosphorus, iron and dissolved organic matter) still needs experimental validation**, although phosphate enrichment did not affect rates of N_2 fixation by diazotrophic bacterioplankton (Hewson et al., 2007). Phytoplankton biomass is very responsive to reef processes, including oceanic upwelling (McKinnon et al., 2013), coral spawning (Eyre et al., 2008; Wild et al., 2008), and aerial dust deposition (Shaw et al., 2008). Given the rapid uptake of DIN by planktonic microalgae, indices of plankton biomass such as chlorophyll are better indicators of change and effects of water quality than dissolved inorganic nutrient concentrations (Furnas et al., 2011; Schaffelke et al., 2012).

The impact of elevated phytoplankton on coral reefs and seagrass meadows is mostly via reduction of water clarity and consequently light availability for symbiotic corals, seagrasses and other benthic marine plants (see Schaffelke et al., 2017). Specifically isolating the impacts of nutrients on phytoplankton followed by algal blooms and subsequent light reduction, from impacts of light reduction caused by sediments (or changes in salinity, DOC, etc.) associated with discharges of nutrient-rich river flood waters, is outside the scope of this review. A recent modelling study (Baird et al., 2021b), found that catchment load reductions including a decrease in chlorophyll concentration enhanced biomass of one seagrass (*Zostera*), but caused reductions in *Halophila*. Complex interactions between nutrient dynamics, light penetration, and nutrient uptake by seagrass roots from sediment porewaters were considered in the model, yet there is little direct experimental evidence documenting the effects of microalgal bloom-induced light reductions on these systems (but see Question 3.2, Collier et al., this SCS for discussion).

3. Seagrass meadows

The peer reviewed literature search revealed very few studies addressing directly or indirectly the impacts of dissolved inorganic nutrient enrichment on seagrass and seagrass ecosystems in the GBR, with only 15 papers retrieved, and an additional paper identified using authors personal collection. Of those, three were review/descriptive studies (Carruthers et al., 2002; Lee Long et al., 2000; Waycott et al., 2005), two were correlational studies (Lambert et al., 2019; Mellors et al., 2005), and two were manipulative experiments directly testing the effects of nutrient enrichment on seagrass (Ow et al., 2016; Udy et al., 1999). Three marine monitoring programs focused on seagrasses and provide valuable information on the status of the ecosystem and potential nutrient impacts (Collier et al., 2014; Mackay et al., 2010; McKenzie et al., 2021). Several general reviews on water quality impacts on GBR ecosystems have also touched marginally on the effects of dissolved inorganic nutrients on seagrasses, but these provide limited empirical evidence (Brodie et al., 2012a; 2019; Haynes & Michalek-Wagner, 2000; Haynes et al., 2007).

Overall, there is no evidence that nutrient enrichment (N or P) has had a direct negative effect on seagrass growth and distribution in the GBR (Carruthers et al., 2002; Waycott et al., 2005). In fact, one of the two nutrient addition experiments, conducted in the field in Green Island, showed that increases in growth rate and tissue nutrient content of *Halodule uninervis* and *Syringodium isoetifolium* occurred in response to elevated sediment N. Addition of P did not elicit any effect on these species suggesting N, rather than P, is the primary limiting nutrient for growth of seagrass in carbonate sediments (Udy et al., 1999). Furthermore, using aerial photographs from 1936 to 1994, Udy et al. (1999) suggested that an increase in the seagrass distribution and biomass at Green Island over that period was caused by an increase in nutrient availability. A nitrate addition experiment conducted in the laboratory at Lizard Island (Ow et al., 2016), however did not enhance growth in *Halodule uninervis* or *Thalassia hemprichii*, therefore the universality of the effects of nutrients on growth cannot be established. It is worth mentioning that Ow et al. (2016) indicated that *Thalassia* grew 50% less in the laboratory compared to the field, so there may be some experimental constraints that limit these comparisons. These two experimental studies support the overall notion that nutrient additions do not have a direct negative effect on seagrasses.

Leaf tissue nutrient analyses showed that some seagrass species act as 'nutrient sponges' as plants growing in locations with higher porewater nutrients have higher tissue nutrients (Mellors et al., 2005), however, recent laboratory experiments did not support the generalisation of these findings (e.g., *H. uninervis*; Ow et al., 2016). Historical comparisons of seagrass tissue nutrients in the central GBR suggest that the N and P content of seagrass leaves has increased since the 1970s, reflecting changing land use practices, also suggesting that seagrasses can be used as potential bioindicators of increased nutrient availability (Mellors et al., 2005). Recent monitoring programs of seagrass condition in the GBR have questioned the use of seagrass tissue nutrient ratios (C:N) as an indicator of water quality due to inconsistent responses to water quality variables, perhaps reflecting the complexity of influences and the dynamic nature of seagrass meadows in the GBR (McKenzie et al., 2021).

Increased epiphytic algal growth in response to nutrient enhancement has been documented in seagrass from non-GBR ecosystems causing detrimental effects on seagrasses (e.g., via reducing light availability and/or increasing grazing on epiphytes and leaves; Botany Bay NSW, Cockburn Sound WA; Jiménez-Ramos et al., 2018; Ralph et al., 2006). Although Carruthers et al. (2002) and McKenzie et al. (2023) observed that seagrass meadows influenced by fresh water (i.e., river estuary habitats) have higher loadings of micro and macro-algal epiphytes than other Queensland seagrass habitats, and the recent seagrass monitoring program in the GBR reporting increased epiphyte loads at some locations in the GBR (but not all) (McKenzie et al., 2023), there is no direct indication of effects of epiphytic algal growth on seagrass meadows. Lambert et al. (2019) documented the long-term dynamics of seagrass meadows, describing the declines in biomass and area of both subtidal and intertidal seagrasses following high flows and loads from the Burdekin River and subsequent recovery time. Subtidal seagrasses appeared more sensitive to changes in catchment discharges than intertidal seagrass meadows, however, the study does not allow for a direct attribution of the change in condition to elevated nutrients *per se* as these occur in conjunction with sediment loads.

4. Mangroves

Very few studies have examined the impacts of elevated nutrients on mangrove ecosystems in the GBR catchment area. McKinnon et al. (2002) recorded increased Chl-*a* when effluent from shrimp farms was discharged to estuarine waters associated with mangroves in the northern wet tropics, suggesting that phytoplankton is quite responsive to nutrient addition in these systems (Trott et al., 2004). The experiments by Lovelock et al. (2009) demonstrate that the potential increase in mangrove growth in response to coastal nutrient enrichment is offset by the costs of decreased resilience due to mortality during drought events. The study included two sites in the GBR catchment area, Port Douglas (with *Avicennia marina* trees) and Hinchinbrook Island (*Rhizophora lamarckii* and *Ceriops tagal*) and found enhanced mortality of mangrove trees at sites that had been experimentally enriched with nutrients and at sites where high sediment salinity was coincident with low rainfall and low humidity (i.e., drought). Tree mortality also occurred in unfertilised trees in landward (as opposed to fringe forests) scrub forests, where hypersaline soils developed at sites with low annual rainfall, and this pattern was exacerbated by the addition of N fertiliser, but not P fertiliser. The mechanisms explaining the higher mortality with increased soil water salinity and nutrient enrichment were related to nutrient enrichment favouring growth of shoots relative to roots, thus enhancing growth rates but increasing vulnerability to environmental stresses that adversely affect plant-water relations. A second study (Duke et al., 2005) also related with mangrove diebacks attributed the mortality and poor health of mangrove trees of *A. marina* in the Mackay estuaries to concentrations of herbicides (diuron) in sediments, but did not find a relationship with soil nutrients (N or P). However, it is worth noting that sites where the highest mortality occurred had high levels of chlorophyll *a* (Duke et al., 2005), a well-known indicator of excess of nutrients (Devlin et al., 2015). Therefore, it seems that elevated nutrients may have also been implicated in the mangrove dieback in the region, although this needs further study. Although elevated nutrients may favour growth and other attributes of mangroves, they can clearly interact with climate stressors especially drought and contribute to mangrove decline.

5. Freshwater wetlands

Freshwater streams and wetlands, including floodplains, receive large pollutant loads from farming runoff primarily during the wet season (Davis et al., 2017). They also vary greatly across GBR catchments with some experiencing fewer intensive modifications while others are characterised by extensive development, particularly on coastal lowlands. The review papers considered in our evidence analysis have suggested that increased nutrients resulting from intensive land use in the GBR catchment area have led to water quality deterioration with negative impacts on freshwater streams and wetlands (Adame et al., 2019; Arthington et al., 2020; Davis et al., 2017; Pearson et al., 2021; Tsatsaros et al., 2013). However, these studies do not provide empirical information to clarify the influence of elevated nutrients on these ecosystems. In fact, the direct effects of elevated dissolved inorganic nutrients on freshwater ecosystems and/or organisms have received considerably less research attention than in marine systems. The studies included in the synthesis below refer only to empirical findings and to the effects of reduced water quality as in many instances it is not possible to differentiate the roles of dissolved inorganic nutrients from those of dissolved organic nutrients or sediments (and/or pesticides), perhaps a consequence of the correlational nature of most studies considered.

Invasive aquatic plants have expanded in distribution and there may be increased levels of algae and microalgae when the health of wetlands and freshwater streams declines. This can be associated with poor water quality but other factors such as flow also influence habitat quality and the responses of aquatic plants (Tibby et al., 2019). Invasive aquatic plants have, for instance, expanded in a highly impacted wetland of the Burdekin floodplain and the dominance of epiphytic diatom taxa indicated an ecological phase shift (Tibby et al., 2019). This contemporary and palaeoecological study determined the relative contributions of different stressors on wetland degradation including increased sedimentation rates due to extensive grazing and hydrological alterations associated with irrigated agriculture. In a second study, a diatom community index declined with elevated nutrients and total suspended solids compared with reference sites for 14 GBR catchment sites (Wood et al., 2019). The index was sensitive to changes in water quality over two successive wet seasons indicating changes in diatom composition following exposure to pollutants and recovery during the dry season when exposure was low.

Macrophyte metrics including cover, richness, and assemblage structure, were not associated with water quality gradients in the Mulgrave-Russell basin of the Wet Tropics, likely because variations in water quality metrics throughout the study area were relatively slight (Mackay et al., 2010). The region is characterised by a narrow coastal plain and therefore streams of the region are potentially receiving fewer agricultural runoff inputs under baseflow conditions than other eastern Queensland streams with larger catchment areas. The highest nutrient loads are transported by flood flows (Brodie & Mitchell, 2005). Nonetheless, TN and TP concentrations exceeded guidelines for upland (TN/TP) and lowland (TP only) streams (EPA, 2006). However, elevated TN and TP levels were not associated with excessive submerged macrophyte growth in the Mulgrave-Russell basin (Mackay et al., 2010). While declines in the health of forest streams associated with changes from unicellular algae to filamentous green algae and macrophytes were linked to nutrient enrichment (Bunn et al., 1998; 1999), further evidence is required to unequivocally attribute causality to nutrient enrichment due to compounding effects of extensive clearing of riparian vegetation and light increase. The limited spatial representativity of these studies conducted only in the Johnstone River in the Wet Tropics with no data on water quality (Bunn et al., 1998; 1999) do not allow generalisations of the responses to nutrient enrichment. **Understanding the effects of nutrient enrichment from agricultural runoff in forest streams requires urgent attention and systematic assessment across the GBR catchment area**.

Bainbridge et al. (2009) found elevated nitrate concentrations in streams draining sugarcane on the Tully–Murray floodplain, indicating fertiliser export from intensive agriculture. Pearson et al. (2013) recorded strong downstream gradients in water quality (dissolved oxygen, conductivity, pH, temperature, DON and transparency), habitat measures (plant species richness, exotic plant species richness, riparian condition, macrophyte cover, litter cover) and herbicide concentrations (diuron and hexazinone) in the Tully–Murray lagoons in the Wet Tropics. However, the abundance and diversity of benthic macroinvertebrate assemblages in floodplain lagoons displayed no indication of severe stress from water quality factors, possibly because anthropogenic chemicals did not reach threshold levels that would be of major concern to lagoon biota. Nevertheless, there was a gradient of response by individual invertebrate taxa and assemblages to a land use gradient, suggesting that a composite threshold had been crossed (Pearson et al., 2013). Seasonal cyclicity of assemblages was clear in several lagoons, but temporal variation was not strong (Pearson et al., 2013). A broad scale study across eight areas of the GBR catchment found that stream invertebrate assemblages reflect land use disturbances influenced by habitat, water quality, other factors and interactions (Pearson et al., 2019). While this study included water quality as a disturbance predictor, only conductivity and pH parameters were considered and the effects of nutrients were expected to be indirect (i.e., mediated by microbial or plant productivity). Connolly and Pearson (2013) showed that nutrient enrichment of a heterotrophic stream altered leaf-litter nutritional quality and the physiological condition of shredder invertebrates via the microbial pathway. Supplements of phosphorus, but not nitrogen, enhanced leaf breakdown, microbial growth and growth of invertebrate larvae.

Native fish assemblages of the Tully-Murray lagoons varied considerably along the land use gradient described by Pearson et al. (2013). Major water quality correlates of fish assemblage structure were minimum pH, minimum conductivity, maximum dissolved oxygen (DO), chlorophyll *a,* DON, and the herbicide hexazinone (all negative); and maximum and minimum transparency (positive) (Arthington et al., 2020). These water quality variables represent gradients of human influence from the agricultural land use that has occurred in the catchment (Pearson et al., 2013). Kyambul, Raccanello’s and Boongaray lagoons were particularly influenced by concentrations of DON, DO and herbicides. The clearest pattern of differentiation of fish assemblage structure was related to distance of the lagoons from the coast, position on the floodplain and habitat structure (Arthington et al., 2015). Although these lagoons are surrounded by intensive agriculture, especially sugarcane farms, they seem to be in good ecological condition, largely because of retention of some riparian vegetation, and frequent flushing by high stream flows.

Despite differences in landscape characteristics, rainfall, flow regimes, and the spatial and temporal scales of studies, and the not entirely consistent responses of ecosystems and organisms across the reviewed studies, overall, they suggest that moderate water quality gradients, associated with agriculture, frequent flushing by high stream flows and the retention of some riparian vegetation are fundamental elements to mitigate negative water-quality impacts on freshwater streams and lowland wetland systems of the GBR. Further empirical work is critical to understand the particular effects of inorganic nutrients on freshwater organisms and ecosystems, including effects of seasonal variability of rainfall and runoff on water quality gradients and concentrations, whether N and P eutrophication are occurring, and the mechanisms involved in organismal and ecosystem response.

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

Overall, there has been limited new evidence since the last SCS (Schaffelke et al., 2017) examining the direct or indirect effects of DIN or DIP on GBR ecosystems and organisms. Perhaps this reflects a diversion of scientific attention towards other important areas of concern, including ocean acidification, or perhaps the lack of funding supporting these types of studies. Only one new study focused on impacts of DIN/DIP on coral calcification (van der Zande et al., 2021), two on the gradient of water quality and relationship to reef communities (Fabricius et al., 2023; Smith et al., 2020), and one experimental study on macroalgae emphasising the high variability in algal responses. Manipulative experiments (Pratchett et al., 2017a) and a review paper (Brodie et al., 2017) added to the unsolved problem of the role of nutrient runoff in COTS outbreaks in the GBR, with variable support for the role of enhanced nutrients. A recent study using regression analyses (Matthews et al., 2020) suggested that water quality can only explain a proportion of the COTS outbreaks (further details in Question 4.3, Caballes et al., this SCS). Understanding of the relationship between microbial communities and nutrient runoff has improved considerably since the last SCS, possibly because of the advancement in, and access to molecular methods (e.g., 16S rRNA gene amplicon sequencing). However, there is still a lack of manipulative experiments directly testing the effects of dissolved inorganic nutrient on microbes. The hypothesis that increased terrestrial dissolved inorganic nitrogen loading lowers the thermal bleaching thresholds in corals in the GBR is not settled and further experimental evidence specifically from the GBR is needed.

There has been limited progress in understanding how seagrass meadows and mangrove forest respond to excess nutrients in the GBR. There is no evidence of an ecosystem state shift away from seagrass-dominated towards macro- or microalgae-dominated benthos. Further, there is no evidence in the GBR that nutrient enrichment has favoured algal blooms in estuarine wetlands, which could smother pneumatophores and seedlings and result in the shift of primary production from a plant to an algae-dominated system, as implied in an earlier SCS (Schaffelke et al., 2017). Mortality of nutrient enriched coastal wetlands may be exacerbated with extreme droughts, although research is limited. There is no research on effects of nutrient enrichment on saltmarsh communities in the GBR.

Very limited information has arisen since the 2017 SCS regarding the effects of excess nutrients on freshwater streams and lowland wetlands. This review, however, has further uncovered the urgent need to investigate whether increased dissolved inorganic nutrients have led or can lead to excessive algal growth and subsequent eutrophication, which could then affect freshwater invertebrate and fish fauna by reducing light and suitable substrate and by promoting ammonia toxicity and hypoxia. While all those responses have been suggested as water-quality stressors there is no evidence that supports widespread eutrophication in the freshwater ecosystems of GBR catchments. A different process proposed by Pearson et al. (2019) is that the effects of nutrients on freshwater invertebrates may be indirect, mediated by microbial or plant productivity (nutrient concentrations were not recorded in their study), rather than direct effects that reduce invertebrate richness.

4.1.3 Key conclusions

- The direct effects of elevated dissolved inorganic nutrients on hard corals are complex, very variable and difficult to generalise, which is not surprising given the high diversity of coral species in the GBR. Despite this variability, direct effects of elevated nutrients include reduced coral calcification, negative impacts on coral reproduction, and potentially lowering thermal tolerance to bleaching.
- The most severe impacts of increased nutrients on corals may be indirect. For instance, elevated nutrient availability on inshore reefs is generally (but not always) positively correlated with increased fleshy macroalgal abundance. High fleshy macroalgae abundance and biomass can reduce coral settlement and recruitment, outcompete corals, reduce coral cover and negatively affect coral calcification. Another indirect effect is the relationship between excess nutrients and increasing phytoplankton food supplies for crown-of-thorns starfish larval stages which can potentially contribute to outbreaks.
- In the GBR, dissolved inorganic nutrient availability typically decreases from inshore to offshore areas with the highest concentrations found between Cooktown and Gladstone in waters influenced by river plumes.
- Macroalgal abundance follows a clear gradient across the GBR shelf, with fleshy macroalgal abundance highest in inshore areas and lowest in offshore areas. Nutrient addition does not always enhance macroalgal growth rates or lead to enhanced biomass, therefore it is simplistic to assume that the macroalgal gradient can only be attributed to land-based inputs of nutrients in inshore reefs. The effects of nutrient enrichment need to be considered in combination with other factors, particularly grazing by fish, sedimentation, ocean acidification and warming.
- There is still debate about whether elevated dissolved inorganic nitrogen raises the susceptibility of corals to thermal stress and contributes to coral bleaching. Computer simulations both support and reject this hypothesis, and severe mass bleaching of corals in 2016 did not show a water quality effect. However, there is mounting evidence from international research groups that supports the hypothesis that nutrient enhancement can reduce thermal bleaching thresholds in corals.
- Crown-of-thorns starfish larval development can benefit from elevated nutrients which can enhance phytoplankton biomass (measured by chlorophyll a concentration), but up to a limit as excessive phytoplankton concentrations may reduce larval performance. However, there is evidence that crown-of-thorns starfish larvae can also survive in low nutrient water. Elevated

nutrients may exacerbate the incidence or severity of outbreaks, but are likely to be one of several contributing factors along with predator removal and inherent life history traits.

- Evidence suggests that declining water quality (increased nutrients *and* sediment loads combined) contributes to seasonal outbreaks in coral disease in the GBR. However, a direct link between coral disease and dissolved inorganic nutrients has not been demonstrated yet and future studies should specifically address this gap.
- Bioerosion patterns show variable responses in coral reefs across the natural water quality gradient. Inshore reefs have lower rates of total bioerosion relative to midshelf and offshore reefs which typically exhibit high bioerosion rates due to the presence of microborers and increased grazing activity by parrotfish. Higher levels of nutrients and organic matter in inshore and midshelf reefs may explain increased abundance of macroborers potentially leading to increased bioerosion rates. These relationships, however, require further investigation.
- There are strong influences of water quality (combined nutrient availability, sediment loads and light) on species composition of foraminifera assemblages.
- Microbial communities are very responsive to elevated nutrients and thus to gradients of water quality across the GBR. The effects cannot be generalised as benthic and planktonic bacterial communities, and microphytobenthos, are highly variable in species composition but this is a rich target for research to find indicators of water quality.
- Phytoplankton biomass (measured as chlorophyll a concentrations) responds positively to nutrient availability. The impact of elevated phytoplankton biomass on coral reefs and seagrass meadows is mostly via reduction of water clarity and consequently reduced light availability for symbiotic corals and seagrasses.
- While elevated nutrients can increase seagrass growth rates and distribution, elevated epiphytic growth has been documented on estuarine seagrasses (possibly from increased nutrients) which can lead to reduction of plant photosynthesis. It is unclear if this condition is contributing to seagrass decline.
- Although elevated nutrients may be beneficial for mangrove growth, they can interact with climate stressors such as drought (low rainfall and low humidity) causing mangrove decline. The few studies available showed that elevated dissolved inorganic nutrients in combination with drought conditions (low rainfall and low humidity) can increase mangrove mortality.
- The direct and indirect effects of increased dissolved inorganic nutrients on freshwater streams and wetlands in the Great Barrier Reef is poorly understood and may vary with differences in landscape characteristics, rainfall, flow regimes, and among ecosystems and organisms.

4.1.4 Significance of findings for policy, management and practice

Nutrients are critically important for the overall condition of the GBR. Some levels of nutrients are required for the health of the GBR and component ecosystems, but overall, it is clear that excess of nutrients is detrimental. Therefore, controlling nutrient runoff from agriculture, aquaculture and populated areas should remain a priority and such controls should be developed specifically for each basin and considered (and weighed up) in the mix of policy approaches for a healthy GBR ecosystem.

For macroalgae, it is increasingly important that the effects of nutrient enrichment are considered in combination with effects of other factors, particularly grazing by fish, sedimentation, and importantly, ocean acidification and warming (e.g., Thompson et al., 2020). For example, there is emerging evidence (Fabricius et al., 2023; Smith et al., 2020) that tests the strength of some of our previous understanding of the influence of nutrient concentrations on the distribution of macroalgal abundance across the GBR continental shelf. Elevated CO_2 concentrations are higher in inshore reefs, and CO_2 is emerging as a major factor involved in enhanced macroalgal production, but empirical research is needed. Key areas of uncertainty are the interactions between water quality and climate change stressors, including ocean acidification and warming.

There is a clear gradient of macroalgal abundance across the GBR shelf, with fleshy macroalgal abundance increasing from outer to inshore reefs (De'ath & Fabricius, 2010; Diaz-Pulido et al., 2016; McCook, 1996; 1999; Wismer et al., 2009), and with fleshy macroalgal abundance positively correlated with elevated nutrient concentrations. Since fleshy macroalgae can inhibit coral recovery by reducing coral settlement and recruitment, and outcompeting corals (Diaz-Pulido et al., 2010; McCook et al., 2001), high macroalgal growth rates and biomass accumulation is a concern for reef management. However, high macroalgal abundance in inshore reefs may well be a natural phenomenon, and there is still debate as to whether macroalgal dominance has been exacerbated by anthropogenic nutrient addition, with herbivory (or lack of in inshore areas) being a potential major driver (McCook, 1999; Wismer et al., 2009). Clearly, disturbances such as bleaching, cyclones and COTS kill corals and free up space available for algal colonisation, contributing to enhanced macroalgal abundance. Filamentous algal turfs rapidly colonise available substrate, but herbivores rapidly consume algal production. Observed increased macroalgal abundance is therefore not just due to increased nutrient availability but a consequence of complex interactions with other stressors and factors. The risks of nutrient enrichment promoting macroalgal overgrowth of corals will be most significant under low herbivory regimes, for instance in areas where herbivores are naturally scarce, such as inshore reefs.

Higher taxonomic resolution in macroalgae (in all functional levels, fleshy, crustose coralline algae, algal turfs) can help identify effects on this group.

Macroalgal removal is now being considered as a strategy to manage excess algal accumulations on reefs.

Lack of studies on the impacts of DIN on mangroves and freshwater wetlands (and none for saltmarshes) should be addressed urgently.

4.1.5 Uncertainties and/or limitations of the evidence

- There are a number of issues where there is still considerable uncertainty about the relationship between elevated dissolved inorganic nutrients and ecological impacts. For example, several hypotheses postulated about the causes of COTS outbreaks in the GBR have not been resolved yet. Most studies support the important role of nutrient enrichment as cause of increased COTS larval development, by increased microalgal biomass (an important food for planktonic larvae) in response to nutrient enrichment. However, there is also some evidence indicating that larvae do well under limited nutrient availability (see Question 4.3, Caballes et al., this SCS), therefore, the role of nutrient enrichment in COTS outbreak dynamics remains unresolved (Pratchett et al., 2017b; Thompson et al., 2023). Also, there is still considerable uncertainty about, and lack of information on, the potential role of nutrient enrichment in increasing the susceptibility of corals to thermal stress and consequent coral bleaching (see also Question 2.4, Uthicke et al., this SCS). There are also uncertainties about the interactions between elevated nutrients, high CO_2 (ocean acidification) and other stressors on the ecosystems. In particular, the impact of elevated nutrients and CO_2 enrichment needs further study.
- Although there is information addressing the differences in reef communities across the continental shelf (i.e., inshore versus outer reefs) in relation to water quality, assessing spatial patterns at regional scales is difficult due to limited spatial data. The Whitsundays region and to some extent the central section of the GBR have been relatively well studied but there is a significant lack of information from the northern section of the GBR.
- As stated earlier, important areas of uncertainty are the interactions between water quality (i.e., increased nutrients, sediment loads and pesticides) and climate change stressors (including ocean warming and acidification). There is an important need to differentiate between the effects of human-induced (including those induced by warming) stressors from natural disturbances in the GBR’s catchment area, coastal and marine systems.
- Limitation of the rapid review method employed to carry out this Evidence Review. A very ambitious project given the time and funding limitations. Properly assessing the literature requires quality time. e.g., on average 1 hour per paper, 200 papers examined equates to 200 hours, that is 27 days dedicated only to extracting the evidence. Meetings, emailing and writing took time from the more detailed evaluation of evidence. The search strategy missed a considerable number of important references (about 40 herein), which had to be identified using other means, as noted in Section 3 – Search Results. For example, adding the words

impact OR *degradation* OR *threat* OR *effect* clearly reduced the number of items included, perhaps a necessary process, but with implications for missing important items.

4.2 Contextual variables influencing outcomes

Table 12. Summary of contextual variables for Question 4.2.

Contextual variables	Influence on question outcome or relationships
Ocean warming and acidification	Warming and acidification influence the responses of some macroalgae, corals and foraminifera to elevated nutrients, e.g., Question 2.4, Uthicke et al., this SCS but also (Bender et al., 2014; Bender-Champ et al., 2017; Humanes et al., 2016; Ow et al., 2016; Wolff et al., 2018).
Drought	Nutrients interact with drought to exacerbate mangrove mortality (Lovelock et al., 2009).
Herbivory	Critically important process determining the accumulation of macroalgal biomass on reefs (Diaz-Pulido & McCook, 2003; Jompa & McCook, 2002; Russ & McCook, 1999).
Timing	Nutrient inputs from terrestrial runoff largely occur during the wet season and also coincide with higher temperature (bleaching), COTS spawning and combined influences with other inputs such as reduced light from sediment inputs (which can also be caused by increased algal growth from nutrient enrichment) (Brodie et al., 2017).
Location	The proximity of the reef to the mainland varies along the coast from the northern to southern sections of the GBR, therefore reef location may influence the responses of organisms and ecosystems to nutrient enrichment (De'ath & Fabricius, 2010). Also, different adjacent land use in the north versus the south influences ecosystem responses, with less developed areas in the northern section. Distance from mainland and consequent changes in water quality, nutrients, sediments etc. across the GBR shelf will also influence the responses to nutrient enrichment.

4.3 Evidence appraisal

Relevance

We reviewed 157 studies, and the relevance of the overall body of evidence was Moderate (6.4). The relevance of each individual indicator was Moderate (2.1 out of 3.0) for the relevance of the study approach and reporting of results to the question, Moderate for spatial relevance (2.2), and Moderate for temporal relevance (2.1).

Of the 157 articles included in the review of the measured impacts of nutrients on GBR ecosystems, 39% (62 of 157) were given a High score for overall relevance to the question, and this relatively moderate value means that many studies did not explicitly address the question, many only indirectly answered the question, or were designed to address other points mentioning the effects of nutrients in a tangential manner. 32% (50 of 154) had a High spatial relevance score, indicating that many of the studies were focused on only an individual reef or few reefs, while few encompassed the large extension of the GBR. A relatively small proportion of studies (34%, 44 of 129) had a High temporal relevance score, indicating most studies were conducted using relatively small temporal scales, e.g., days or weeks, while few considered multi-year studies, and this is understandable given the complexities of conducting long-term research in coastal and marine ecosystems.

Consistency, Quantity and Diversity

Consistency: Medium to Low. There is large variability of findings regarding the question being addressed, and this reflects the complexity in processes, and diversity of the organisms that inhabit the

GBR. Even within the same taxonomic group and one that is generally understood to respond positively to nutrient enhancement such as macroalgae, there are considerable discrepancies in the outcomes, with studies demonstrating positive, neutral or negative effects of nutrients on algal processes.

Quantity: 157 studies were reviewed specifically addressing the GBR since 1990. Based on the authors experience and knowledge of the potential total available pool of evidence to answer the question, it is considered that 157 studies are an excellent representative sample of this pool.

Diversity: High diversity of studies. Of the 157 papers examined, 43% were observational studies (including natural experiments along the gradient of water quality across the GBR continental shelf), 30% manipulative experiments, and 15% reviews/summaries. The remaining 12% papers were modelling and theoretical.

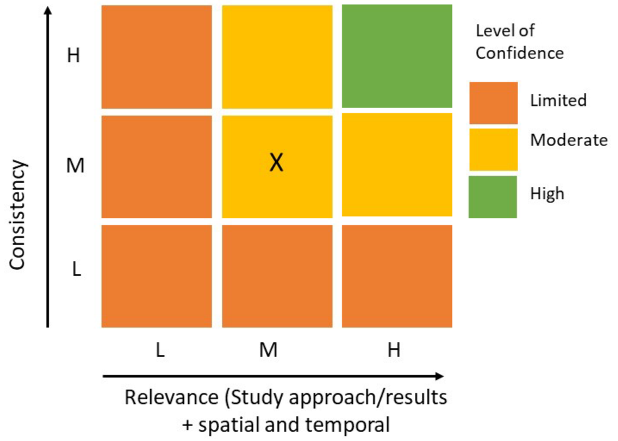
Additional Quality Assurance (Reliability)

Of the 157 studies considered in this review, 93% of the studies did not raise any concerns regarding the reliability of the study. This indicates that overall, studies are well designed, well replicated, and contain adequate controls to contrast with experimental treatments. In the case of review papers which by their nature do not have experimental controls, these types of studies provided informative and generally comprehensive summaries of previous studies. The remaining 7% of the studies had some reliability concerns, and in the majority of the cases this was due to the study providing limited distinction between the impacts of alternative factors such as sedimentation, organic nutrients supply, herbivory, etc. Two reviews (Bell, 1991; 2007), for instance, provided very limited evidence to support a status of eutrophication to the GBR, and evidence was based on a single nutrient threshold concentration (e.g., PO_4 and chlorophyll), which is inadequate given the variabilities in concentrations of nutrients in the GBR, the complexities in processes involved in nutrient uptake, processing, remineralisation, and sources (e.g., sources are varied, including anthropogenic runoff, but also natural due to guano, decomposition or organic matter e.g., due to coral spawning, N recycling, etc.). Further, higher concentrations of PO_4 recorded from the Low Isles in 1977 compared to values from 1928 were used to argue that the GBR lagoon is eutrophic, this is an overstatement coming from very limited data (Bell, 1991). Two additional studies also presented some inconsistencies between trends presented in the data and the conclusion reached in the paper (Fleury et al., 2004; Vogel et al., 2000). In one instance, we were unable to assess the reliability of the study as authors were unfamiliar with the methods employed in the modelling exercise (Wooldridge & Brodie, 2015).

Confidence

The overall Confidence level of the body of evidence is Moderate based on Medium to Low consistency and Moderate Relevance (Table 12). This Moderate confidence reflects the large variability in responses of the different processes and organisms included in conceptual models, for example, responses of phytoplankton to nutrient enrichment is clear, but responses of other primary producers is variable (e.g., seaweeds), or even positive (seagrasses). Important components of the model such as coral bleaching and COTS outbreak responses to enhanced nutrients are also controversial, although more inclined towards links between these processes and nutrient enhancement. Responses are also mixed on important GBR organisms, such as corals and CCA.

Table 13. Summary of results for the evidence appraisal of the whole body of evidence in addressing the question. The overall measure of Confidence was rated as Moderate, as it reflects the large variability in responses of different ecosystem processes and organisms assessed and is represented by a matrix encompassing overall relevance and consistency rated as Moderate. 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 (6.4)	
-To the Question	Moderate	
-Spatial	Moderate	
-Temporal	Moderate	
Consistency	Moderate-Low	
Quantity	High (157 studies in total)	
Diversity	High (43% observational, including natural experiments, and 29% manipulative experiments)	
Additional QA (Reliability)	• Only 11 studies (7%) raised some concerns regarding their reliability. • The common causes of reliability concerns/biases occurred when a single threshold/value was used as an indicator of eutrophication processes or to derive major conclusions, or when a hypothesis was supported or rejected but the sampling size and/or high variability could have led to statistical errors. • Studies raising reliability concerns were identified during the synthesis stage, with less emphasis being placed on those findings.	

4.4 Indigenous engagement/participation within the body of evidence

There was no evidence of Indigenous engagement within the body of evidence.

4.5 Knowledge gaps

Table 14. Summary of knowledge gaps for Question 4.2.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
Distinctions between the effects of dissolved inorganic nutrients from those of sediments and particulates nutrients, including role of DOC.	What are the independent and combined effects of different nutrients in the GBR and what is the role of sediments in driving these differences?	Better understanding of effects and better linkages to fertiliser reductions.
Roles of elevated CO_2 in driving responses of	What are the effects of ocean acidification on macroalgae and how are these responses	Understanding the impact of CO_2 emissions on macroalgal

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
macroalgae to nutrient enrichment.	modulated by nutrient enrichment?	abundance and coral reef decline.
Direct effects of DIN and DIP on crustose coralline algae (CCA) and interactions with other water quality components (e.g., sediments) and global change.	How do CCA respond to nutrient enrichment? Is addition of DIN and DIP deleterious for CCA calcification? How does nutrient enrichment interact with ocean acidification and warming?	Better understanding of nutrient effects on reef cementation, accretion and growth in the context of global change.
Lack of knowledge on the influence of taxonomic resolution in identification of trends and responses of macroalgae to stressors. Currently, macroalgae are treated as a single group but there are >600 spp. (e.g., Fabricius et al., 2023).	Variability in responses to environmental conditions in the GBR: are trends in water quality impacts species specific?	Use of a selected group of species as indicators to better identify and predict environmental change.
Relationship between coral disease and dissolved inorganic nutrients cannot yet be demonstrated.	Does enhancement of DIN/DIP induce coral disease?	Coral disease is a critical indicator of coral health.
Direct impacts of nutrient enrichment on COTS larvae, not only of food requirements.	What are the direct effects of elevated nutrients (independent/ or in combination with those of phytoplankton biomass / food supply) on COTS larval development? What is the sensitivity of early life stage of COTS to elevated DIN and DIP?	Better understanding of the causes of COTS outbreaks in the GBR.
Experimental/empirical validation of the role of elevated inorganic nutrients on coral bleaching, beyond modelling studies (limited lab studies).	Can results from computer simulations on the effects of DIN on bleaching susceptibility be validated in the field?	Understanding of interactions between local and global stressors on coral bleaching.
Nutrient sinks and sources, including biological processing and nutrient sinks in biomass and sediments.	Where does DIN and DIP go? How do ecological processes and ecosystem health influence nutrient sinks and nutrient release?	Management prioritisation to maximise nutrient sinks including Blue Carbon.
Knowledge of nutrient impacts on seagrass epiphytes, macroalgae and the role of top-down processes (grazing) in controlling nutrient-driven overgrowth.	Does increased DIN, DIP favour seagrass epiphytes with consequent negative effects on seagrasses?	Better understanding of indirect effects of nutrients on seagrass ecosystems.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
Interactions between nutrient supply, phytoplankton (Chl-*a*), particulates, and light impacts.	Does nutrient enrichment affect seagrasses (or other benthic systems) via decreased light induced by high phytoplankton biomass?	Understanding of interactions between stressors associate with seagrass decline.
Interactive effects of climate stressors with nutrient pollution on mangroves and diebacks.	Does nutrient pollution exacerbate negative impacts of drought and pesticides on mangrove mortality?	Better understanding of causes of diebacks in mangroves.
Overall knowledge of direct and indirect effects of dissolved inorganic nutrients on freshwater streams and wetlands, at all levels.	How does nutrient enrichment directly and indirectly affect key attributes and biota of freshwater wetlands? What are the interactions of these with other human stressors?	Understand nutrient impacts on critical freshwater ecosystems of the GBR catchment area.
Seasonal variability and the influence of rainfall and runoff on nutrient concentrations and freshwater wetlands; determine whether eutrophication is occurring across the GBR catchment area, and the mechanisms involved in ecological responses.	How does seasonal rainfall interact with potential eutrophication in freshwater wetlands?	Understand nutrient impacts on critical freshwater ecosystems of the GBR catchment area.
Limited knowledge of eutrophication on carbonate bioerosion and reef accretion and reef cementation.	Can outcomes from ENCORE on bioerosion be extrapolated to other GBR sites? What are the direct and indirect (e.g., grazing) impacts of elevated nutrients on carbonate accretion, bioerosion, reef cementation?	Understanding of the effects of nutrient pollution on reef growth and better predictions for understanding climate change effects (e.g., sea level rise) on coral reefs.

5. Evidence Statement

The synthesis of the evidence for **Question 4.2** was based on 157 studies undertaken primarily in the Great Barrier Reef and published between 1990 and 2023. The synthesis includes a *High* diversity of study types (43% observational including natural experiments, 29% manipulative experiments, 15% reviews, 12% modelling and 1% commentary), and has a *Moderate* confidence rating (based on *Moderate to Low* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

In the Great Barrier Reef, dissolved inorganic nutrient availability typically decreases from inshore to offshore areas with the highest concentrations found between Cooktown and Gladstone in waters influenced by river plumes. Dissolved inorganic nutrients are critically important for the overall health and condition of Great Barrier Reef ecosystems but if they occur in excessive amounts, nutrients can have a detrimental effect. The most severe impacts of increased nutrients on corals may be indirect. For instance, elevated nutrient availability on inshore reefs is generally (but not always) positively correlated with increased fleshy macroalgal abundance. High fleshy macroalgae abundance and biomass can reduce coral settlement and recruitment, outcompete corals, reduce coral cover and negatively affect coral calcification. Another indirect effect is the relationship between excess nutrients and increasing phytoplankton food supplies for crown-of-thorns starfish larval stages which can potentially contribute to outbreaks. Direct effects of elevated nutrients include reduced coral calcification, negative impacts on coral reproduction, and potentially lowering thermal tolerance to bleaching. Links between elevated nutrients and other impacts such as coral disease, microbioerosion and microbial communities are variable between studies and locations and require further investigation. There is no clear evidence of direct negative impacts of increased dissolved inorganic nutrients on seagrass ecosystems, and although elevated nutrients may be beneficial for mangrove growth, they can interact with climate stressors such as drought (low rainfall and low humidity) causing mangrove decline. There is limited evidence of the impact of dissolved inorganic nutrients on Great Barrier Reef wetland ecosystems. Regional and basin-specific management of nutrient runoff from the Great Barrier Reef catchment area should remain a priority to support inshore marine ecosystems.

Supporting points

- Macroalgal abundance follows a clear gradient across the Great Barrier Reef shelf, with fleshy macroalgal abundance highest in inshore areas and lowest in offshore areas. Nutrient addition does not always enhance macroalgal growth rates or lead to enhanced biomass, therefore it is simplistic to assume that the macroalgal gradient can only be attributed to land-based inputs of nutrients in inshore reefs. The effects of nutrient enrichment need to be considered in combination with other factors, particularly grazing by fish, sedimentation, ocean acidification and warming.
- Evidence is limited for the effects of dissolved inorganic nitrogen and dissolved inorganic phosphorus on crustose coralline algae (important for reef building), but available studies show enhanced growth under elevated conditions. The lower abundance of crustose coralline algae on inshore reefs compared to offshore reefs may be related to increased sediment loads and a reduced seawater calcium carbonate saturation state in inshore reefs.
- Comparing the effects of dissolved inorganic nutrients between and among regions is challenging due to limited spatial data. Reef communities from the Mackay Whitsunday Natural Resource Management region, and to some extent the Burdekin region have been relatively well studied, but there is a significant lack of information from other areas of the Great Barrier Reef.
- There is still debate about whether elevated dissolved inorganic nitrogen raises the susceptibility of corals to thermal stress and contributes to coral bleaching. Computer simulations both support and reject this hypothesis, and severe mass bleaching of corals in 2016 did not show a water quality effect. However, there is mounting evidence from international research groups that supports the hypothesis that nutrient enhancement can reduce thermal bleaching thresholds in corals.

- Crown-of-thorns starfish larval development can benefit from elevated nutrients which can enhance phytoplankton biomass (measured by chlorophyll *a* concentration), but up to a limit as excessive phytoplankton concentrations may reduce larval performance. However, there is evidence that crown-of-thorns starfish larvae can also survive in low nutrient water. Elevated nutrients may exacerbate the incidence or severity of outbreaks, but are likely to be one of several contributing factors along with predator removal and inherent life history traits.
- Evidence suggests that declining water quality (increased nutrients *and* sediment loads combined) contributes to seasonal outbreaks in coral disease in the Great Barrier Reef. However, a direct link between coral disease and dissolved inorganic nutrients has not been demonstrated yet and future studies should specifically address this gap.
- Bioerosion patterns show variable responses in coral reefs across the natural water quality gradient. Inshore reefs have lower rates of total bioerosion relative to midshelf and offshore reefs which typically exhibit high bioerosion rates due to the presence of microborers and increased grazing activity by parrotfish. Higher levels of nutrients and organic matter in inshore and midshelf reefs may explain increased abundance of macroborers potentially leading to increased bioerosion rates. These relationships, however, require further investigation.
- Microbial communities are very responsive to elevated nutrients and thus to gradients of water quality across the Great Barrier Reef. The effects cannot be generalised as benthic and planktonic bacterial communities, and microphytobenthos, are highly variable in species composition but this is a rich target for research to find indicators of water quality.
- Phytoplankton biomass (measured as chlorophyll *a* concentrations) responds positively to nutrient availability. The impact of elevated phytoplankton biomass on coral reefs and seagrass meadows is mostly via reduction of water clarity and consequently reduced light availability for symbiotic corals and seagrasses.
- While elevated nutrients can increase seagrass growth rates and distribution, elevated epiphytic growth has been documented on estuarine seagrasses (possibly from increased nutrients) which can lead to reduction of plant photosynthesis. It is unclear if this condition is contributing to seagrass decline.
- The direct and indirect effects of increased dissolved inorganic nutrients on freshwater streams and wetlands in the Great Barrier Reef is poorly understood and may vary with differences in landscape characteristics, rainfall, flow regimes, and among ecosystems and organisms.

6. References

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

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Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 4.2

Theme 4: Dissolved nutrients – catchment to reef

Question 4.2 What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanisms 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. Guillermo Diaz-Pulido	Griffith University	Coral reef ecology, phycology	Lead Author	All Sections
2. Catalina Reyes-Nivia	Great Barrier Reef Foundation	Coral reef ecology	Contributor	Searches, data extraction, writing
3. Maria Fernanda Adame	Griffith University	Wetland ecology, mangroves	Expert advice (wetlands, mangroves)	Wetlands section, literature identification, final revision of relevant section.
4. Angela H. Arthington	Griffith University	Freshwater ecology	Expert advice (freshwater wetlands)	Freshwater section, additional literature identification, final revision of relevant section.
5. Catherine Collier	James Cook University	Seagrass ecology	Expert advice (seagrasses)	Literature identification, final revision of relevant section.
6. Catherine Lovelock	University of Queensland	Mangrove ecology, plant physiology	Expert advice (mangroves)	Literature identification, final revision of relevant section.