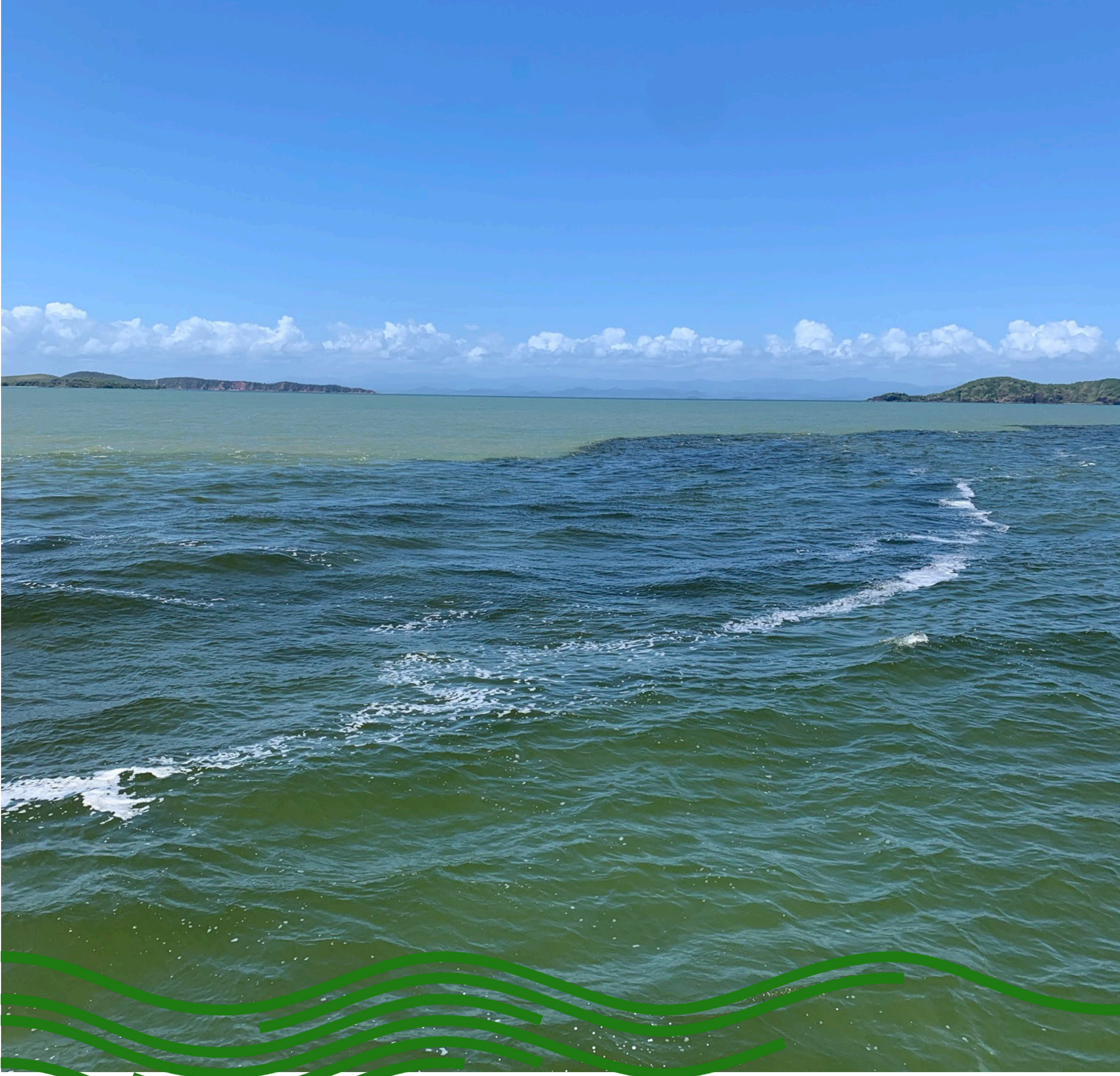

2022 Scientific Consensus Statement

Question 4.1 What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef?

Question 4.1.1 What is the variability of nutrients in coastal and marine areas of the Great Barrier Reef?

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Cover image credit: Jane Mellors, TropWATER.

Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

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

What is the Scientific Consensus Statement?

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

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

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

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

Method used to address the 2022 SCS Questions

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

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

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

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

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

Two methods were developed for the 2022 SCS:

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

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

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

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

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

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

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

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

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

Guidance for using the synthesis of evidence

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

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

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

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

Peer Review and Quality Assurance

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

Contents

Acknowledgements

Thanks to Rob Richards (Evidentiary), Jane Waterhouse (C_2O Consulting) and Mari-Carmen Pineda (C_2O Consulting) for guidance in preparing this document and early review comments. Thanks to Caroline Petus (JCU) for preparing Figure 4, Figure 6 and Figure 7, to Kate Hodge for preparing Figure 1, to Eric Lawrey for preparing Figure 10 and Figure 11, to Renee Gruber and Caroline Petus for providing Marine Monitoring Program (MMP) monitoring data to facilitate analyses, and to Murray Logan for providing statistical advice and the GAMMs used for long-term trend analyses. Thanks to Kathy Connellan for administrative assistance in preparing the review response document. Finally, sincere thanks to Renee Gruber, David Wachenfeld and two anonymous reviewers for their very detailed and constructive comments.

Executive Summary

Questions

Primary Question 4.1 What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef?

Secondary Question 4.1.1 What is the variability of nutrients in coastal and marine areas of the Great Barrier Reef?

Background

Nutrient concentrations – especially nitrogen and phosphorus concentrations – play a crucial role in water quality, impacting and supporting coral and seagrass habitats, fisheries, and the overall health of Great Barrier Reef (GBR) habitats. Changing land use has increased nutrient loads to the GBR and both modelling and coral core studies strongly suggest that this has increased nutrient concentrations in inshore and (to a lesser extent) midshelf waters. Substantial policy and land management efforts have been made to reduce nutrient loads from catchments. Understanding the distribution of nutrients in the GBR is important to determine which areas are at risk of elevated nutrient concentrations, to monitor changes in nutrient concentrations (and design robust monitoring programs), and to understand the drivers of variations in nutrient concentrations and hence the impacts of management actions. Where variations and temporal trends are driven by activities on land, they are likely to be amenable to the influence of catchment management. To understand the degree to which catchment activities drive coastal water quality, we also need to understand other drivers of variation, including year-to-year climatic variation and long-term climate change.

The most commonly discussed nutrients in the context of water quality are nitrogen and phosphorus. This review collates and summarises published evidence regarding a) the spatial and temporal distribution of nitrogen (N) and phosphorus (P) and the associated indicator, chlorophyll *a* (Chl-*a*) in the GBR, and b) the spatial and temporal variability in N, P and Chl-*a* concentrations in GBR waters. All routinely monitored and reported forms of N and P are considered, including nitrate plus nitrite (NOx), particulate nitrogen (PN), ammonium (NH_4^+ hereafter NH4), dissolved organic nitrogen (DON), phosphate (PO_4^{3-} hereafter PO4), dissolved organic phosphorus (DOP) and particulate phosphorus (PP), and where evidence relating to other forms of nitrogen, other reporting variants (such as dissolved inorganic nitrogen, DIN, which is the sum of NOx and NH4, total dissolved nitrogen, TDN, which is the sum of DIN and DOP, and total dissolved phosphorus, TDP, which is the sum of PO4 and DOP) and other nutrients, but not carbon which has been excluded from the scope of this review.

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[5]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.
- Search locations were Web of Science and Scopus. In addition, reports from the Marine Monitoring Program (MMP), the Australian Institute of Marine Science's (AIMS) Long-Term Monitoring Program, the National Environmental Science Program (NESP) Tropical Water Quality and the Cooperative Research Centre (CRC) for Coastal Zone, Estuary and Waterway Management were manually added where relevant.

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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

- Main source of evidence: GBR, as evidence from outside the GBR has very limited relevance to this question.
- From the initial keyword search, Web of Science returned 1,325 results and Scopus returned 925. After initial screening by title, 192 potentially relevant sources from Web of Science, and 159 potentially relevant sources from Scopus were identified. After removing duplicates, 238 potentially relevant sources were screened. After further screening by scanning the full text for relevance, 80 sources from the search results met the eligibility criteria and were included in the synthesis. To this set, seven relevant peer-reviewed reports from the Marine Monitoring Program, NESP Tropical Water Quality, and CRC, nine peer reviewed sources from the author's personal library and ten peer reviewed sources from professional contacts and reviewers were manually added. In total, 106 evidence items contributed to this synthesis.

Method limitations and caveats to using this Evidence Summary

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

- Only studies written in English were included.
- Only GBR derived studies were included.
- Only studies published from 1990 to the present were included.
- The distribution and variability of nutrients in benthic sediments was not considered in detail, though benthic sediment nutrient results were opportunistically included where they were found in the search results.
- The review concentrates on nitrogen, phosphorus, and Chl-*a*. Results were also reported relating to other nutrients such as silicate and iron when they arose in the search results but these were not explicitly searched for. Carbon was excluded from this Evidence Summary.
- When considering temporal trends, the Evidence Summary focused on trends over the time for which monitoring data are available (mid 2000s to 2022). A detailed assessment of evidence regarding trends over longer timescales (e.g., since European settlement) has not been conducted.
- *In situ* observations in offshore waters are sparse, so many of our conclusions relating to offshore waters are based on information from satellite ocean colour Chl-*a* observations and process models. Satellite ocean colour does not directly provide information about the distribution of nutrients but does provide an estimate of Chl-*a* which can (with an understanding of its many limitations) be used as a general indicator of nutrient status. Chl-*a* reflects nutrients stored in phytoplankton and can (if light is sufficient but nutrients are limited) reflect the supply of readily bioavailable nutrients. The nutrients associated with phytoplankton are, however, usually a small proportion of the total nitrogen and phosphorus. Natural intracellular phytoplankton Chl-*a*:N:P ratios vary depending on local conditions, light availability, phytoplankton community composition and intracellular nutrient stores.

Key Findings

Summary of evidence to 2022

In total, 106 studies, all from the GBR, were considered in this Evidence Summary. Collectively, these studies provided a temporal record of observational data covering the whole GBR including coral core data providing insight into pre-development conditions, ocean colour data extending back to 1969, data from *ad hoc in situ* studies from the 1990s, and routine monitoring at some locations from 1989 to the present day (2023). The overwhelming majority of studies focused on inshore and/or midshelf waters, with relatively few including estuary or offshore nutrient concentrations. The largest source of inshore nutrient data is the Great Barrier Reef Marine Monitoring Program (MMP).

Key findings from the body of evidence are that:

- TN, TP, DIN, PO4 and SiO4 concentrations follow a cross-shelf gradient from higher values in estuaries, mangrove creeks and inshore waters to lower values on the midshelf. In offshore

waters, relatively high concentrations of DIN, PO4 and Chl-*a* can sometimes occur in areas of oceanic upwelling.
- Concentrations of TN, TP, DIN, and PO4 are elevated in flood plumes (relative to ambient concentrations) and in areas of sediment resuspension. Chl-*a* concentrations are also elevated in flood plumes where light is sufficient.
- Silicate concentrations follow similar spatial patterns but have not been as well studied. Little observational data is available for other nutrients, including iron.
- Peak concentrations of dissolved organic and inorganic nutrients are usually found during the wet season (typically December to May) in the central and southern Great Barrier Reef (approximately from Cooktown to Gladstone) adjacent to areas of more intensive catchment development and in waters influenced by river discharge. In ambient (non flood-plume) conditions, there are no clear inshore north-south nutrient gradients.
- Offshore and midshelf variations in nutrient concentrations in surface waters are often associated with upwelling events (which bring dissolved inorganic nitrogen and phosphorus from deeper water to the surface) and *Trichodesmium* blooms (which fix atmospheric nitrogen). There is some evidence that both upwelling and *Trichodesmium* blooms are more common in La Niña years.
- Nutrient concentrations vary from year to year and are elevated in years of high rainfall and storm activity (typically La Niña years). In high rainfall years, elevated dissolved inorganic nitrogen and phosphorus and elevated particulate nitrogen and phosphorus concentrations in inshore waters are associated with flood plumes. In midshelf waters and some offshore areas, elevated dissolved inorganic nutrient concentrations and Chl-*a* concentrations in La Niña years are associated with increased intrusive upwelling.
- Nutrient concentrations can also vary over short (hourly) timescales due to physical dynamics (tidal and wave forcing and transport) and diurnal fluctuations in ecosystem metabolism (primary production and respiration).
- There have been clear temporal trends in inshore nutrient concentrations collected through the Marine Monitoring Program since 2005. Nitrite plus nitrate concentrations have increased in all monitored inshore regions, which includes the Wet Tropics, Burdekin and Mackay Whitsunday Natural Resource Management regions, and particulate nitrogen has increased in the Wet Tropics Region. In some regions, there has been a reduction in phosphate since 2017, and in the Mackay Whitsunday region, there has been a reduction in chlorophyll *a*. There is not enough long-term monitoring data to assess temporal trends in the Cape York, Fitzroy or Burnett Mary Regions, and there is no long-term monitoring program in the Burnett Mary Region to support this type of assessment in the future.
- To obtain a more complete picture about nutrient distributions in the Great Barrier Reef, future steps could include characterising organic nutrients and their link to land-based inputs, exploring the time scales over which changes in land-based inputs may affect marine nutrient concentrations, analysing long-term coastal and marine nutrient datasets to better understand the effects of land management changes, quantifying nutrient variability from marine sources, and updating Great Barrier Reef-wide nutrient budgets (quantifying all sources, sinks and stocks of nitrogen and phosphorus).

Recent findings 2016-2022

At the time of the 2017 Scientific Consensus Statement (SCS), routine monitoring of inshore water quality through the Marine Monitoring Program (MMP)had not yet been conducted for a long enough continuous period to show long-term trends. Weather events (primarily rainfall, wind and storms) create a high natural year-to-year variability in inshore water quality, which can obscure long-term trends. Against this background variability, it is difficult to detect change without a long observational record and careful statistical analysis. Some trends have become clear recently. The most recent MMP Water Quality report documented:

In the Wet Tropics region:

- A clear and substantial increase in NOx in the Barron-Daintree focus region since the start of monitoring.
- An increase in both NOx and PN (and hence TN) in the Russell-Mulgrave focus region from 2005-2015, with signs of a reduction in PO4 since 2017. No clear trend in PP.
- An increase in NOx and PN (and hence TN) in the Tully focus region, and signs of a reduction in PO4 since 2017. No clear trend in PP.

In the Burdekin region:

- A gradual increase in NOx since 2005 and signs of a reduction in PO4 since 2017. No clear trends in PN or PP.

In the Mackay Whitsunday region:

- A steady increase in NOx since 2005, but a steady decline in PO4 and signs of a decline in Chl-*a* since 2017. No clear trends in PN or PP.

Additional analysis of the MMP water quality and "Cairns Transect" data gives evidence of:

- An increase in DON in the Barron-Daintree focus region (these monitoring sites are also known as the "Cairns Transect") from around 68 $\mu g\ L^{-1}$ in 1989 to a peak of around 113 $\mu g\ L^{-1}$ in 2013, and a subsequent decline to 53 $\mu g\ L^{-1}$ by 2022.
- An increase in DOP in the Barron-Daintree focus region since 1989, from 1.1 to 5.5 $\mu g\ L^{-1}$.
- An increase in DON in the Russell-Mulgrave focus region since 2005, levelling off since 2017. No clear trends in DON in other focus regions.
- No clear trends in DOP or SiO4 in any region.
- A decline in TP in the Mackay Whitsunday region and the Johnstone Russell-Mulgrave focus region since 2012.
- An increase in TN in the Russell-Mulgrave focus region between 2005 and 2015, levelling off since 2016.
- Similar trends in TN in the Burdekin region.

There is not enough contiguous long-term monitoring data yet to assess temporal trends in the Cape York, Fitzroy or Burnett Mary Natural Resource Management (NRM) regions.

A recent analysis suggests that in midshelf Wet Tropics waters, oceanographic processes such as upwelling and intrusive events may be more important in driving year-to-year variability than previously understood. Modelling suggests that river nutrient loads may have little impact on midshelf nutrient concentrations between Cairns and Lizard Island, with most of the year-to-year variation driven instead by upwelling. This finding has not yet been sufficiently validated but indicates that more research is needed. River discharges are still considered to be the dominant driver in inshore waters.

Significance for policy, practice, and research

This Evidence Summary focused on observed distributions and trends in nutrient concentrations and did not assess the evidence for statements regarding the pressures and drivers of these trends. These factors are considered in Questions 4.4 (Prosser & Wilkinson, this SCS) and 4.5 (Burford et al., this SCS), and the effectiveness of management interventions is considered in Question 4.6 (Thorburn et al., this SCS).

The identified long-term increase (2005-2022) in ambient NOx concentrations in the inshore Wet Tropics, Burdekin and Mackay Whitsunday regions suggests that management interventions have not yet been effective in reducing marine nitrogen concentrations. PO4 concentrations, by contrast, have declined in these regions and there are signs that TP is also declining.

There is not yet enough data to assess temporal trends in the Cape York, Fitzroy or Burnett Mary NRM regions, suggesting a need for ongoing monitoring in these regions. Monitoring has recently begun in the Cape York region and was restarted in 2020 in the Fitzroy region.

This review has also identified several key knowledge gaps for further research. These include:

- Better understanding of oceanographic drivers of spatial and temporal variability in nutrient concentrations, including physical features such as eddies, upwelling and ocean currents, biological processes such as nitrogen fixation and how these are changing with climate change. This includes quantification of nutrients in *Trichodesmium* blooms, which may also be a substantial source of nitrogen.
- Better characterisation of organic nutrients in the GBR, including improved understanding of biogeochemical cycling and bioavailability of dissolved organic nitrogen and phosphorus.
- Characterisation of long-term changes in sediment nutrient stores. A large percentage of the nutrient load delivered by flood plumes is deposited to inshore benthic sediments but may subsequently be re-released through remineralisation and resuspension. Better characterisation of the timescale over which this occurs will allow more robust estimates of the timescales over which management interventions are likely to be effective.
- Development of an overall nutrient budget for the Great Barrier Reef, drawing on new data and models developed since the previous budget in 2011.
- Better characterisation of the variability and long-term trends in nutrient concentrations in offshore waters.

There is also a need for an analysis to relate long-term trends in inshore nutrient concentrations now emerging from the Great Barrier Reef Marine Monitoring Program for Inshore Water Quality (MMP WQ) to recent changes in catchment management.

Key uncertainties and/or limitations

- Marine sources of variability in nutrient concentrations in the GBR, including upwelling and nitrogen fixation, have not been well characterised. Direct observational evidence is sparse, so most evidence comes from remote sensing and process models, which have not been evaluated against offshore observational data. There is some evidence that these are changing with climate change, but this is not well understood.
- While dissolved and particulate nitrogen and phosphorus are measured and reported, their chemistry and bioavailability – especially the chemistry and bioavailability of organic nitrogen and phosphorus – in the GBR has not been well characterised, apart from a few small studies that focus on small areas.
- This review focused primarily on nitrogen and phosphorus. Few studies address the spatial and temporal distribution of other nutrients such as silicate and iron, which may also be important. Carbon is also omitted, though it is the primary currency of ecosystem productivity and plays a key role in nitrogen and phosphorus cycles.

Evidence appraisal

Overall, there is a Moderate score for confidence in the body of evidence used for this Evidence Summary. There is a High number of studies (106) with at least some relevance, though many do not directly address the question of spatial and temporal distribution and variability of nutrients in the GBR. These studies are diverse in their approaches, data sources and authorship. The majority of *in situ* observational data is from inshore and midshelf waters. *In situ* studies of offshore and estuarine nutrients are sparse but supplemented by results from satellite observations (from which estimated Chl-*a*, but not nutrient concentrations, can be derived) and process models. There is a High degree of consistency in results from different sources including observational studies.

1. Background

1.1 Context and management relevance

Nutrient concentrations are a key aspect of water quality, influencing the health, productivity, visual and cultural amenity of coastal and marine waters, including coral and seagrass habitats, and fisheries (Haynes et al., 2007).

While nutrients are required and at some level occur naturally (Moss et al., 2005), excessive nutrient loads and excessive concentrations of nitrogen (N) and phosphorus (P) have adverse effects. Globally, nutrient loads to coastal waters have tended to increase as a result of catchment development, changing land uses and growing human populations. This has frequently degraded coastal ecosystems (Schaffelke et al., 2012).

Considerable effort and expense has gone into quantifying and reducing nutrient loads from the Great Barrier Reef (GBR) catchment area to reduce adverse impacts of elevated nutrient concentrations (Armour et al., 2009; Bartley et al., 2012; Brodie et al., 2009; 2013; Davis et al., 2017; Devlin & Brodie, 2005; Joo et al., 2012; Kroon, 2012; Kroon & Brodie, 2009; Kroon et al., 2012; McCloskey et al., 2021a, 2021b; McCulloch et al., 2003a; 2003b; Waterhouse et al., 2012; 2017; Waters et al., 2014; Wooldridge et al., 2006).

Understanding the distribution of nutrients in the GBR can provide information about:

- Which coral reef and seagrass habitats, or coastal ecosystems are likely to be exposed to elevated nutrient concentrations, how frequently and for how long (Fabricius, 2011; Maughan & Brodie, 2009).
- Which coral reefs may be adapted to lower nutrient concentrations and hence potentially more susceptible to impacts from fluctuations or increases in nutrient concentrations (Fabricius, 2011).
- Where monitoring is required to detect changes in nutrient concentrations or the effects of events that may impact nutrient concentrations (Haynes et al., 2007; Kuhnert et al., 2015; Udy et al., 2005).
- What drives variations in nutrient concentrations in different parts of the GBR, where these variations are due to terrestrial influences, and from which basins they are derived (Devlin & Brodie, 2005; Waterhouse et al., 2017; Wolff et al., 2018).
- How water quality interacts with other stressors including crown-of-thorns starfish (COTS) predation pressure and climate change (Kroon et al., 2023; MacNeil et al., 2019; Mellin et al., 2019) (see Questions 2.4, Uthicke et al., and 4.3, Caballes et al., this SCS).

This information is also needed to help interpret observed habitat distribution (seagrass meadows and coral reefs) and variations in habitat condition and community structure (Carter et al., 2021; Thompson et al., 2020).

The most frequently discussed nutrients in this context are nitrogen and phosphorus. These are the two elements most likely to limit photosynthesis and primary production. Increasing the supply of the most limiting nutrients, in the presence of sufficient light, almost always increase the growth of algae and other photosynthesising organisms. Nitrogen is typically the limiting nutrient in marine systems, including the GBR (Brodie et al., 2012; Furnas et al., 2011; 2013; Garzon-Garcia et al., 2021), though phosphorus can also limit production, especially where the nitrogen supply is supplemented by marine nitrogen fixation (Ani et al., 2023).

Carbon is the basis for all known life and the primary currency for exchange of energy within ecosystems, however it is not what is usually meant in the discussion of policy relating to nutrients and nutrient pollution in coastal ecosystems. Changing carbon concentrations are hence not considered as part of Question 4.1.

Other nutrients are also important, but less often considered. Silicate sometimes controls the composition of phytoplankton communities (as diatoms require silicate to form their hard shells) and hence the production of fatty acids that are important for fisheries productivity (Volkman et al., 1989). Bioavailable iron is often the nutrient that limits fixation of atmospheric nitrogen in the open ocean, which can have important implications for overall nitrogen supply (Bell et al., 1999; Shaw et al., 2008) but is less likely to be limiting in coastal systems such as the GBR. Molybdenum and other micronutrients can also in some circumstances limit nitrogen fixation and other important biogeochemical processes (Vitousek & Howarth, 1991). These nutrients are generally considered to be of secondary importance after nitrogen and phosphorus, and therefore have received much less scientific or management attention.

This review discusses the spatial and temporal distribution and variability of nutrients in the Great Barrier Reef World Heritage Area (GBRWHA), focusing primarily on nitrogen and phosphorus. We consider nitrogen and phosphorus in all forms in GBR waters, including nitrate plus nitrite (NOx), ammonium (NH4), dissolved nitrous oxide (N_2O), phosphate (PO4), dissolved organic nitrogen and phosphorus (DON and DOP), and particulate nitrogen and phosphorus (PN and PP) in both organic and inorganic forms. Chlorophyll *a* (Chl-*a*) is considered as a secondary indicator of nutrient distributions that may be useful where direct nutrient observations are unavailable, and evidence of the distribution of *Trichodesmium* blooms is considered due to its implications for surface chlorophyll concentrations and potential nitrogen fixation. Evidence regarding silicate (SiO4) distribution and trends is also presented where available. Other nutrients (including iron, silicate, and sulfate) are considered as they arise but are not evaluated in detail. Carbon is not considered.

Spatial variations are considered with particular reference to management regions (from waters off Cape York in the north to waters off the Mary River in the south) and waterbodies (from enclosed coastal waters including estuaries to offshore GBR waters, Figure 4).

Temporal trends and variability observed over daily, seasonal and multi-year timescales since 1990 are considered, with emphasis on trends observed since the commencement of consistent inshore water quality monitoring at the commencement of the Marine Monitoring Program's (MMP) Water Quality monitoring program in 2004.

1.2 Questions

Primary question	**Q4.1** What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef?
Secondary question	**Q4.1.1** What is the variability of nutrients in coastal and marine areas of the Great Barrier Reef?

1.3 Conceptual diagrams

Four conceptual diagrams are provided to give context to this review (Figure 1 to Figure 4).

Figure 1 visually summarises some of the key processes driving nutrient distributions, variations and trends in a spatial context. These include river discharge from land, flood plume transport of nutrients, tidal processes, particularly sedimentation and resuspension, and oceanographic processes including upwelling, eddies, storm activity, variations in the Southern Oscillation Index, exchanges with the Coral Sea, and the East Australian Current (EAC).

Figure 2 provides an overview of the temporal and spatial scales over which these processes affect nutrient concentrations. Key processes are arranged along a temporal gradient (from tidal to decadal) and along a cross-shelf spatial gradient, showing how key driving forces at each scale interact to produce the observed spatial and temporal patterns and variations. A full discussion of these underlying processes is beyond the scope of this review, however it is included to provide context for the range of timescales and spatial scales over which spatial and temporal variability in nutrient concentrations is observed. Timescales range from the tidal (hourly) scale of resuspension and deposition processes to the multi-decadal scale of land use change and climate change impacts.

Figure 3 summarises the major forms of nitrogen and phosphorus, the relationships between them, and some of the major physical and chemical processes that influence their distribution.

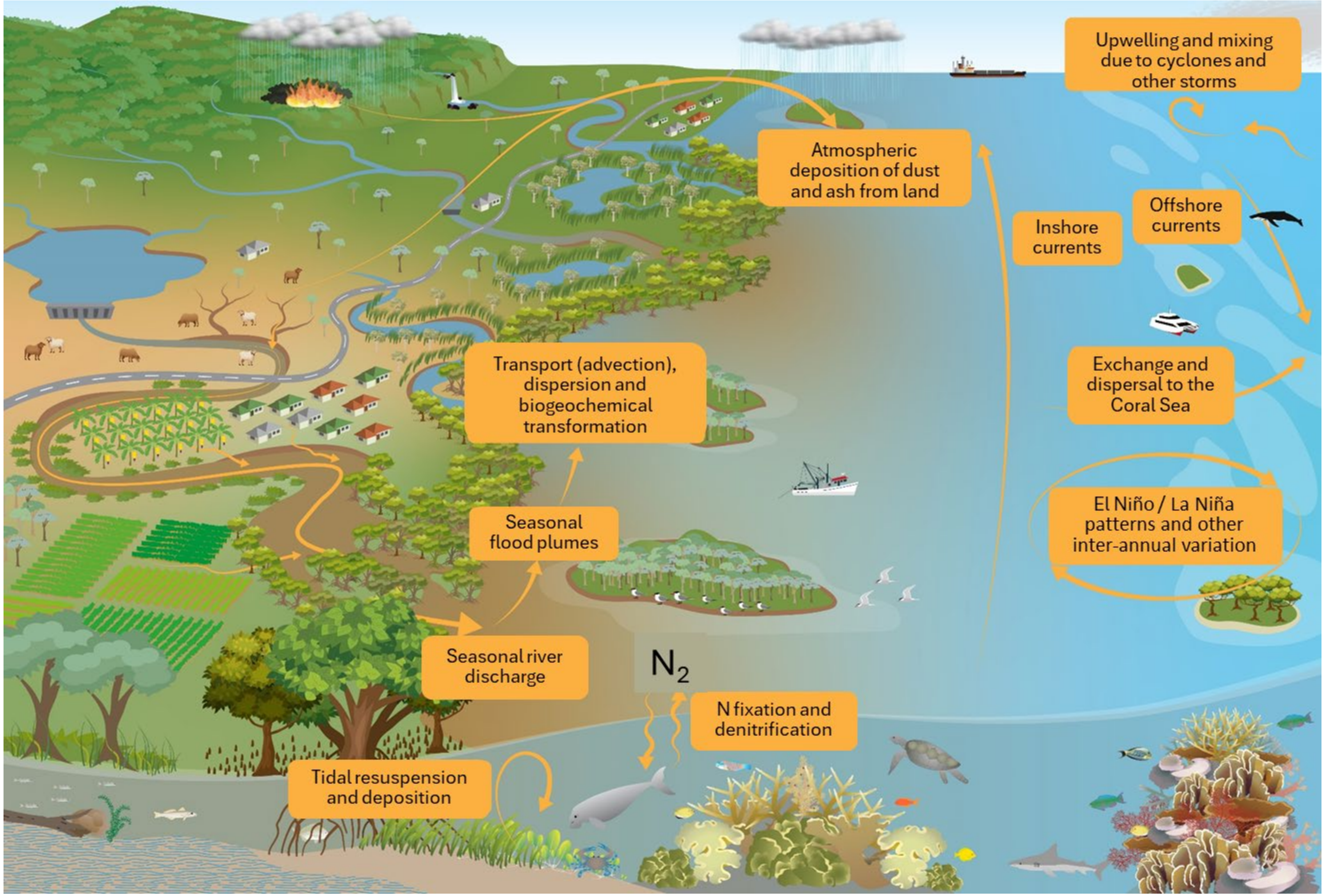

Figure 1. Key processes affecting temporal and spatial distribution of nutrients. Atmospheric deposition (via precipitation, smoke and dust) and urban runoff also play a role in the delivery of nutrients from terrestrial sources, but these are believed to be minor.

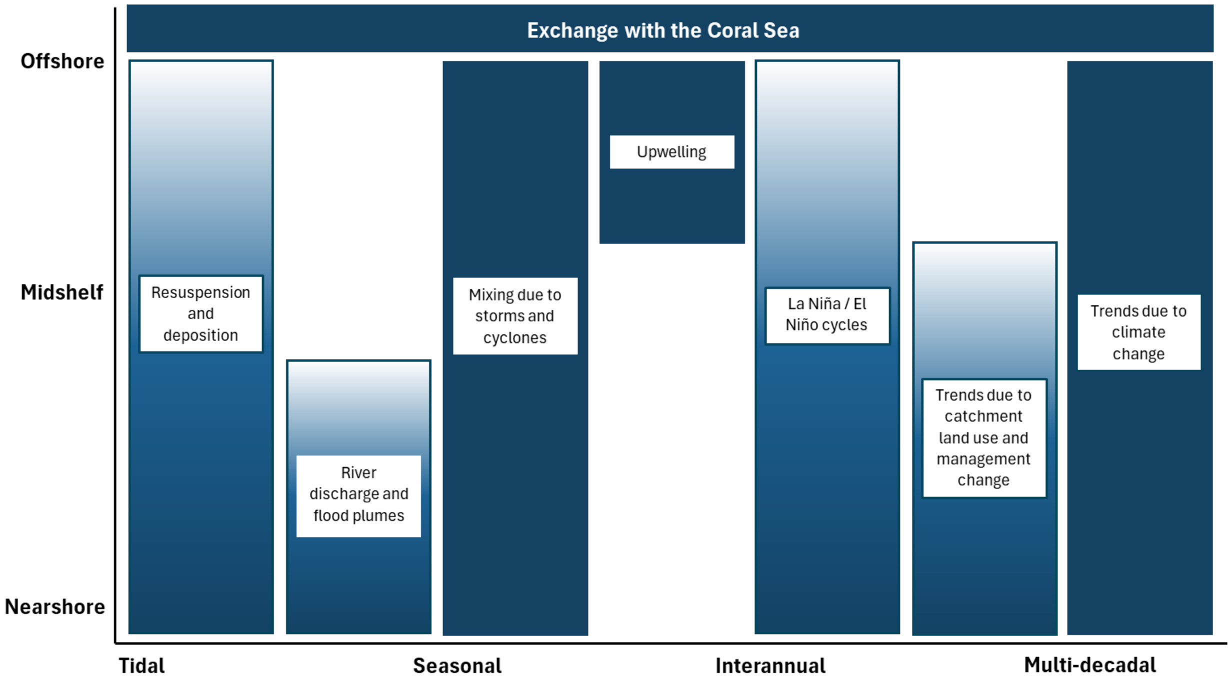

Figure 2. Relationship between timescales and spatial scales of major drivers of distribution and variations in nutrient concentrations. Colour gradient approximately indicates the relative strength of each process across the shelf. Darker shading means greater strength, lighter shading means less strength.

Finally, Figure 4 shows the spatial boundaries of the regions and waterbodies used to organise this review (as also used in several of the sources cited in this review). For management and reporting purposes (Moran et al., 2022; Waterhouse et al., 2021) the GBR is often divided spatially into six latitudinal regions that correspond with Natural Resource Management (NRM) regions, and into three to five cross-shelf waterbodies (Figure 4). From North to South, the regions are Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary. The waterbodies are: inshore (or nearshore), midshelf, and offshore. The inshore waterbody is sometimes further divided to distinguish between enclosed coastal waters including estuaries and bays, open coastal waters, and inshore waters off the coast.

Nitrogen and phosphorus (N and P) both occur in a variety of chemical forms (Figure 3). Spatial and temporal distributions are affected by physical transport processes (green arrows, Figure 3 and orange arrows, Figure 1) and biogeochemical transformations that convert nutrients from one form to another or remove them from the system (blue arrows).

Dissolved inorganic nitrogen and phosphorus (DIN and PO4) are directly bioavailable (i.e., biochemically labile), meaning that they are quickly taken up by biota and transformed to other forms, and may have immediate impacts (Furnas et al., 2005; Garzon-Garcia et al., 2021). DIN includes ammonium (abbreviated hereafter as NH4 but represented chemically as NH_4^+), nitrate (NO3 or NO_3^-) and nitrite (NO2 or NO_2^-). Nitrate and nitrite are sometimes collectively reported as NOx. DIP is usually in the form of phosphate (PO4 or PO_4^{3-}). Nitrogen and phosphorus are also present in dissolved organic forms (DON and DOP), particulate organic forms (PON and POP) and particulate inorganic forms (PIP, and NH4 adsorbed onto particles) (Garzon-Garcia et al., 2021). Nitrous oxide (N_2O) is an important greenhouse gas produced during nitrification and denitrification, but is generally present in very low concentrations.

Organic nitrogen and phosphorus are present in a range of chemical forms, though these forms are rarely measured or reported separately. Some forms of dissolved organic nitrogen and phosphorus (such as RNA, DNA and other nucleotides) are almost as bioavailable as dissolved inorganic nutrients (Baldwin, 2013), while other forms are only slowly broken down and released by bacterial processes. These less immediately available forms of organic nutrients have lower immediate impacts than a similar concentration in dissolved inorganic form, but may nevertheless be an important source of nutrients (Garzon-Garcia et al., 2018; 2021). When particulate nutrients are delivered in much greater quantities than dissolved nutrients, remineralisation of particulates can be the dominant source of nitrogen and phosphorus. Lønborg et al. (2018) has estimated that 94% of bioavailable nitrogen and 75% of bioavailable phosphorus in the Wet Tropics are in organic, rather than inorganic forms. In the dry tropics rivers of the GBR, labile (bioavailable) organic nitrogen and phosphorus have been found to remineralise within the timescales of river plume travel (days to weeks) (Garzon-Garcia et al., 2021) and to have been transformed to other forms before reaching the outer shelf (Lønborg et al., 2018).

Particulate inorganic nutrients are sometimes readily bioavailable inorganic nutrients that have been adsorbed to sediment surfaces and are readily desorbed to dissolved inorganic forms, but may also be highly refractory forms of nutrients that are tightly chemically bound and will have little ecological impact (Garzon-Garcia et al., 2021).

Particulate materials carrying nitrogen and phosphorus are often denser than water and can sink to the bottom where they may gradually break down to more readily available forms. Particulate materials associated with benthic sediments can be resuspended by tides or wind, or by the action of animals or human activities such as prawn trawling disturbing the sediments (Alongi & McKinnon, 2005; Alongi et al., 2007; Garzon-Garcia et al., 2021; Lourey et al., 2001). When sediments are resuspended, dissolved nutrients in sediment porewaters (including dissolved nutrients released by the remineralisation of particulate organic nutrients) are also released into the water (Alongi et al., 2007, 2008; 2011; Lønborg et al., 2018). In shallow inshore areas, there is often very active, continual settling and resuspension of particulate nutrients on a tidal cycle, which can produce orders of magnitude variations in measured particulate nutrient concentrations within the space of a few hours (Radke et al., 2006). During major storm events, a larger amount of particulate material (and associated dissolved porewater N and P) is likely to be resuspended, and this may occur over a large area (Alongi et al., 2007; Wolanski et al., 2008).

Particulate organic N and P also include nutrients in the form in the form of small plankton, particularly phytoplankton. This is important to recognise because phytoplankton, usually measured as Chl-*a*, can be measured optically, making it amenable to continuous logging using fluorometers (Brodie et al., 2007; Schaffelke et al., 2012), and to satellite ocean colour observation (Blondeau-Patissier et al., 2014a; 2014b; Soja-Woźniak et al., 2020), allowing distribution to be estimated and reported across the entire GBR. Where there is sufficient light available, DIN and (to a lesser extent) DIP are rapidly taken up by phytoplankton, making Chl-*a* distribution an indicator of the distribution of total bioavailable N (and to a lesser extent, P) in the relatively low-nutrient waters of the midshelf and offshore GBR (Brodie et al., 2007; Furnas et al., 2011). This indicator should be treated with caution, however, as Chl-*a*:N:P ratios vary with phytoplankton community composition (species), light availability, depth and other factors.

In considering Chl-*a* as an associated indicator of nutrient concentrations, the presence of blooms of the marine phytoplankton *Trichodesmium* have also been considered. These blooms, produce elevated surface Chl-*a* concentrations and may also be an important marine source of nitrogen as *Trichodesmium* is able to fix atmospheric nitrogen (Ani et al., 2023; Bell et al., 1999).

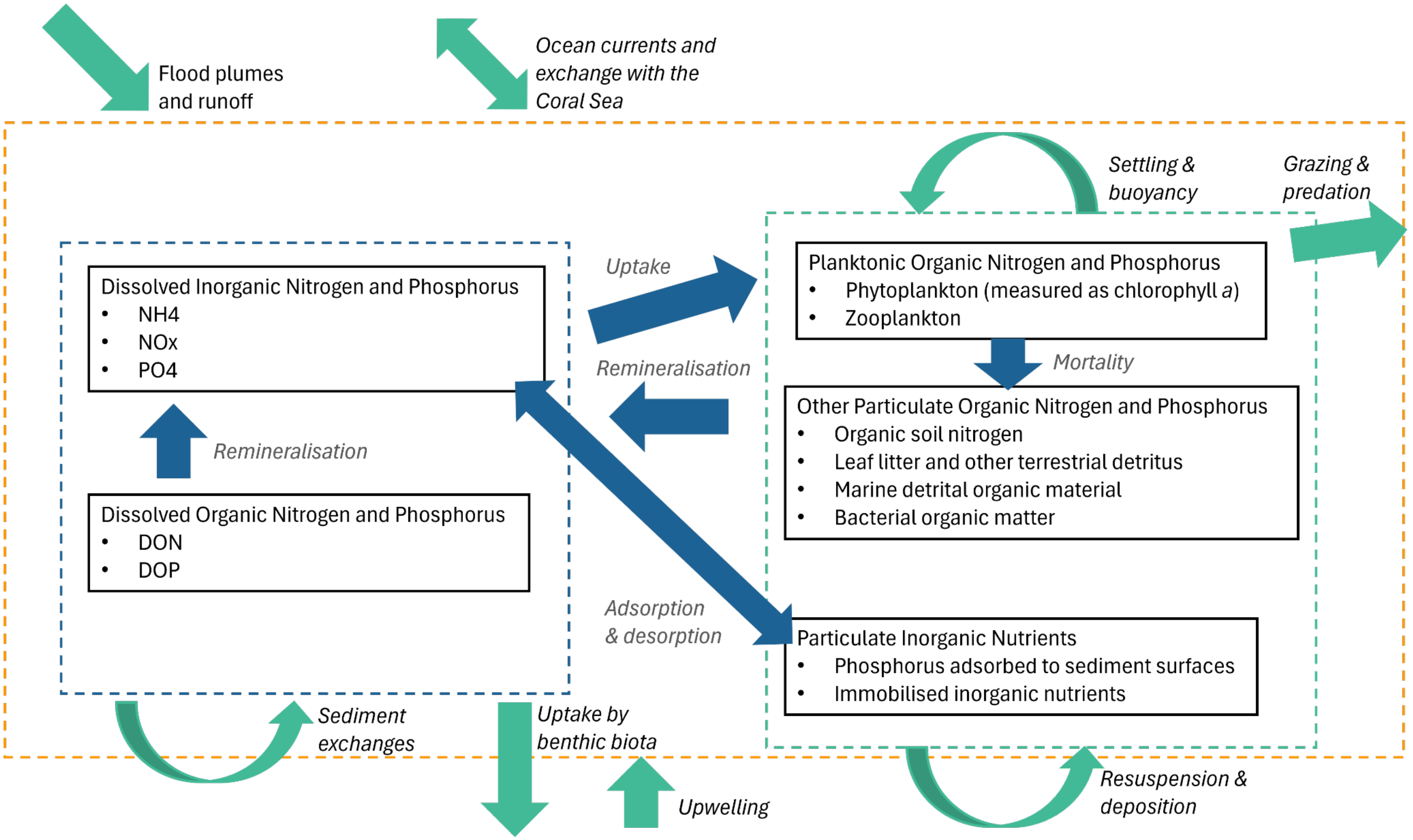

Figure 3. Forms of nitrogen and phosphorus included in this review (black text boxes), major transformations (blue arrows and text), and physical transport mechanisms that affect spatial and temporal distribution (green arrows and text). The blue dashed box on the left contains dissolved nutrients, while the green dashed box on the right contains particulate forms of nutrients. The orange dashed box encompasses process that occur within a parcel of water. This review does not itself consider mechanisms of transport and transformation, but these are understood as key mechanisms of spatial and temporal variability. Forms of nitrogen and phosphorus not included here such as nutrient stored in benthic sediments, animals and benthic plants, are excluded from the scope.

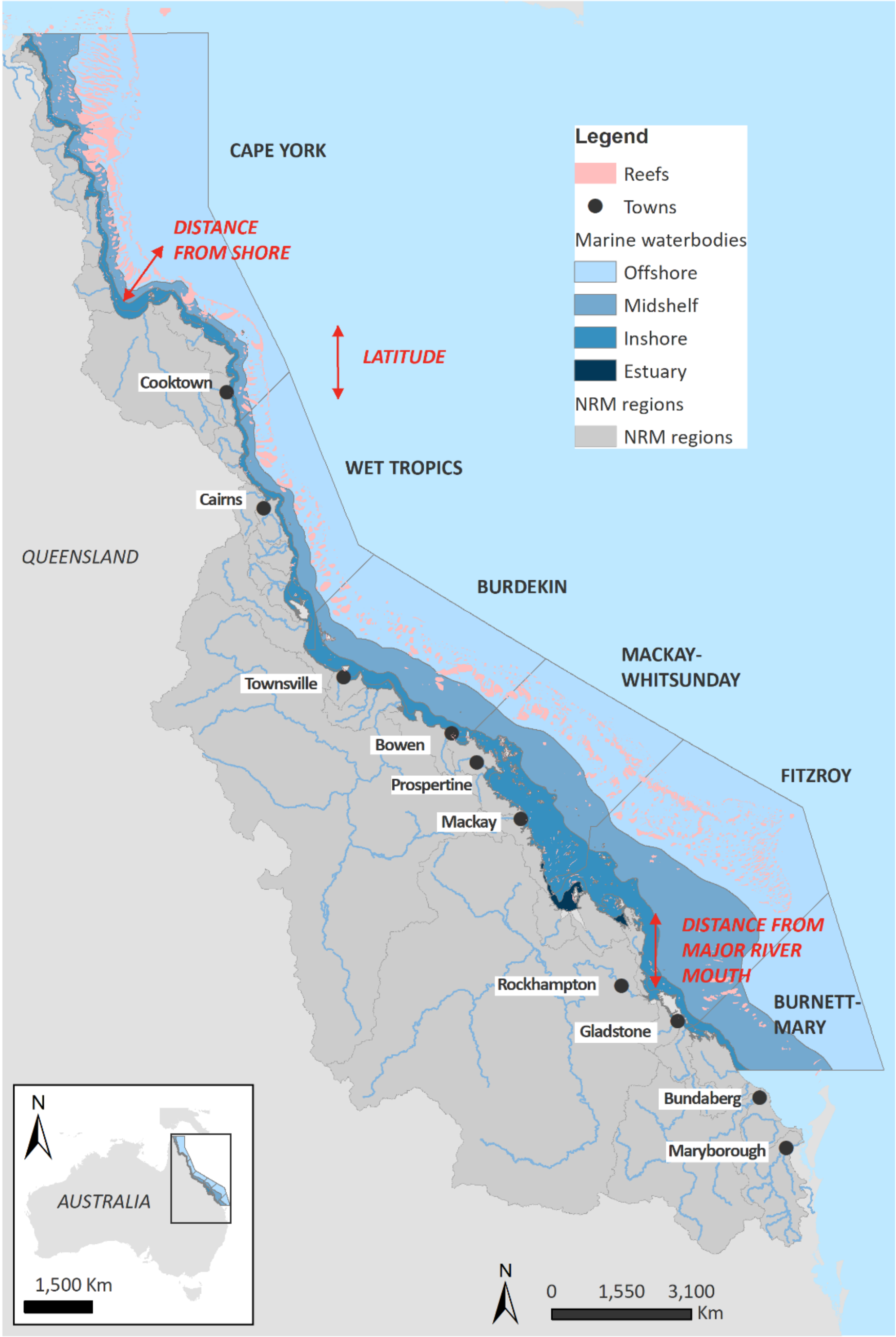

Figure 4. Key spatial considerations. Note that the Great Barrier Reef Marine Park Authority "Open Coastal", "Macro Tidal Open Coastal" and "Closed Coastal" waterbodies have been combined into a single "Inshore" waterbody and have relabelled the Authority "Macro Tidal Closed Coastal" waterbody as "Estuary" for the purposes of this review. Natural Resource Management (NRM) regions are the regions used for management and reporting purposes, for example in the Marine Monitoring Program (Moran et al., 2022; Waterhouse et al., 2021). Red arrows indicate spatial measures that may be important drivers of spatial variability.

1.4 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 linkages for this question are listed below.

Links to other related questions	Carbon is also an important nutrient. Carbon is not considered here, but is addressed in Question 2.2. **Q2.2** What are the current and predicted impacts of climate change on Great Barrier Reef ecosystems (including spatial and temporal distribution of impacts)? Nutrient distribution in the GBR is influenced by catchment loads. Questions 4.4 and 4.5 consider the sources of nutrients to the GBR, while Questions 4.6 through 4.9 consider management options to limit or reduce delivery of nutrients from catchments. **Q4.4** How much anthropogenic dissolved nutrient (nitrogen and phosphorus species) is exported from Great Barrier Reef catchments (including the spatial and temporal variation in delivery), what are the most important characteristics of anthropogenic dissolved nutrients, and what are the primary sources? **Q4.5** What are the primary biophysical drivers of anthropogenic dissolved nutrient export to the Great Barrier Reef and how have these drivers changed over time? **Q4.6** What are the most effective management practices for reducing dissolved nutrient losses (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions? What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices? **Q4.7** What is the efficacy of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality (nutrients, fine sediments and pesticides)? **Q4.8** What are the measured costs, and cost drivers associated with the use of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality? **Q4.9** What role do Natural/ Near Natural wetlands play in the provision of ecosystem services and how is the service of water quality treatment compatible or at odds with other services (e.g., habitat, carbon sequestration)? Questions 4.2 and 4.3 consider the impacts of elevated nutrient concentrations. **Q4.2** What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef? **Q4.3** 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? Theme 3 considers similar questions relating to the distribution, sources and impacts of sediments. In particular, Question 3.1 is closely related to 4.1 as it considers the spatial and temporal distribution of sediments, which carry nutrients in particulate forms. **Q3.1** What are the spatial and temporal distributions of terrigenous sediments and associated indicators within the Great Barrier Reef?

2. Method

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

2.1 Primary question elements and description

The primary question is: ***What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef?***

The secondary questions is: ***What is the variability of nutrients in coastal and marine areas of 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 question elements for Questions 4.1 and 4.1.1.

Question S/PICO element	Question term	Description
Subject/Population	Nutrients in the GBR	The focus will be on **nitrogen and phosphorus in the water column**, in all forms (dissolved, particulate, organic – including as Chl-*a* – and inorganic). Other nutrients including carbon, iron and silicate are recognised as important and will be included in the conceptual model and introduction but will not be addressed in detail. The GBR is interpreted as referring to the Great Barrier Reef World Heritage Area.
	Coastal and marine areas of the GBR	Areas within the GBR, as defined above. "Coastal areas" are as defined in the Great Barrier Reef Marine Park Authority's (GBRMPA) spatial polygons and include both "enclosed coastal" and "open coastal" areas. "Marine areas" includes any part of the GBRWHA outside these coastal areas.

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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 element	Question term	Description
Intervention, exposure & qualifiers	Associated indicators	Water quality indicators as reported in MMP Annual Reports for Inshore Water Quality (https://elibrary.gbrmpa.gov.au/jspui/handle/11017/3826, i.e., water quality indices based on nitrogen and phosphorus constituent concentrations relative to guideline values) and Reef Report Cards (https://www.reefplan.qld.gov.au/tracking-progress/reef-report-card/2020, i.e., Chl-*a*). This review will not include suspended sediments or turbidity, which are covered elsewhere.
Outcome & outcome qualifiers	Spatial distribution	Large-scale spatial patterns in water-column nutrient concentrations across the whole GBR, including latitudinal variations organised by Management Area, variations with distance from coast organised by waterbody (coastal, midshelf and offshore), and variations associated with the spatial extent of flood plumes. Polygons defining the boundaries of Management Areas are available from GBRMPA's geoportal (http://www.gbrmpa.gov.au/agssdc/rest/services) and illustrated in Figure 4. This Evidence Summary will consider all sources of evidence reported in the relevant peer reviewed literature, including *in situ* water sampling, passive loggers and gliders, remote sensing evidence and modelling. The spatial distribution of nutrients in benthic habitats and sediments is outside the scope of this question.
	Temporal distribution	Patterns observed over sub daily, daily, seasonal and multi-year timescales since 1990, with emphasis on trends observed since the commencement of consistent inshore water quality monitoring as part of the MMP in 2004.
	Variability	Variability due to tides, waves and seasonal variations, variations in weather, and variations in ocean currents and upwelling since 1990. This does not include long-term change associated with human influences, change over geological timescales, or change due to climate change, which are addressed in other questions (Questions 2.2, Fabricius et al. and 2.3, Lewis et al., this SCS).

Table 2. Definitions for terms used in Questions 4.1 and 4.1.1.

Definitions	
Nutrients	Nitrogen (N) and phosphorus (P) measurable in the water column, including dissolved inorganic nitrogen (NOx, NH4), phosphate (PO4), dissolved organic nitrogen and phosphorus (DON and DOP), particulate organic nitrogen and phosphorus (PON and POP, including N and P in living phytoplankton indicated by Chl-*a*) and phosphorus that has been immobilised or adsorbed to sediment surfaces (PIP).

Definitions	
GBR	The Great Barrier Reef Marine Protected Area. The boundaries of the area to be considered includes the area encompassed by the boundary of the GBRWHA.
Coastal and marine areas of the GBR	Areas within the GBR, as defined above. "Coastal areas" are as defined in Great Barrier Reef Marine Park Authority's spatial polygons and include both "enclosed coastal" and "open coastal" areas. "Marine areas" includes any part of the GBRWHA outside these coastal areas.
Spatial distribution, temporal distribution and variability	As defined in Table 1 above.
Waterbodies	Areas of the GBRWHA delineated by boundaries as shown in Figure 4, divided into "inshore" or "nearshore", "midshelf" and "offshore" waters.

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, accessed via James Cook University's (JCU) library, searching in ALL fields.
- Scopus, searching Title, Abstract and Keyword fields.
- Great Barrier Reef Marine Monitoring Program for Inshore Water Quality reports.
- National Environmental Science Program (NESP) Tropical Water Quality reports.
- Australian Institute of Marine Science (AIMS) Long-Term Monitoring Program Reports [if peer reviewed].
- Relevant Integrated Marine Observing System (IMOS) reports [if peer reviewed].

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 Questions 4.1 and 4.1.1.

Question element	Search terms
Subject/Population	nutrient*, nitrogen, phosphorus, chlorophyll, GBR, "Great Barrier Reef", marine, coast*, ocean, shore, inshore, offshelf, shelf, estuary, estuarine, bay, creek
Exposure or Intervention	
Comparator (if relevant)	

Question element	Search terms
Outcome	Studies found using the above search terms were examined for information in the form of numbers, tables, charts or maps that sheds light on the spatial and temporal distribution and variability of nutrients in the GBR World Heritage Area.

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 Questions 4.1 and 4.1.1.

Search strings
Web of Science: "ALL=(nutrient OR nutrients OR nitrogen OR phosphorus OR chlorophyll) AND (GBR OR "Great Barrier Reef") AND (marine OR coast OR coastal OR ocean OR shore OR inshore OR offshelf OR shelf OR estuary OR estuarine OR Bay OR creek)"
Scopus: "ABS-TI-KEY(nutrient OR nutrients OR nitrogen OR phosphorus OR chlorophyll) AND (GBR OR "Great Barrier Reef") AND (marine OR coast OR coastal OR ocean OR shore OR inshore OR offshelf OR shelf OR estuary OR estuarine OR Bay OR creek)"

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 Questions 4.1 and 4.1.1 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	Studies that provide information about the spatial or temporal distribution of nitrogen and/or phosphorus in waters of the GBR since 1990.	• Studies relating to catchment nutrients that mention marine nutrients only tangentially. • Studies that were not conducted in the GBR. • Papers relating to laboratory experiments involving nutrients that do not also provide new data about nutrient concentrations in the GBR. • Papers that discuss other nutrients but that do not provide additional information regarding nitrogen or phosphorus.
Exposure or Intervention		
Comparator (if relevant)		
Outcome		Papers discussing pre-development conditions.
Language	English	Any other language
Study type	Monitoring reports, field studies, modelling studies, remote sensing studies with relevant analyses, review articles	Laboratory studies

3. Search Results

A total of 2,250 studies were identified through online searches for peer reviewed and published literature. An additional 27 studies were identified manually through expert contact and personal collections, which represented 1.1% of the total evidence. Following secondary screening, 106 studies were eligible for inclusion in the synthesis of evidence (Table 6 and Figure 5). One study was unobtainable but assessed as unlikely to have significant additional information.

For the Web of Science search, all fields were searched to be as inclusive as possible. For the Scopus search, the search was restricted to the title, abstract, and keywords to avoid including studies where these keywords were mentioned only in the references.

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

Date d/m/y	Search strings	Sources	
A) Academic databases		Web of Science	Scopus
	ALL = (nutrient OR nitrogen OR phosphorus OR chlorophyll)* *AND (GBR OR "Great Barrier Reef")* *AND (marine OR coast* OR ocean OR shore OR inshore OR offshelf OR shelf OR estuar* OR Bay OR Creek)*	*192 of 1,325*	
	ABS-TI-KEY (nutrient OR nitrogen OR phosphorus OR chlorophyll)* *AND (GBR OR "Great Barrier Reef" OR Queensland OR Burnett OR Keppel OR Burdekin OR Whitsunday* OR "Wet tropics" OR "Cape York" OR Mackay OR "Hervey Bay")* *AND (marine OR coast* OR ocean OR shore OR inshore OR offshelf OR shelf OR estuar* OR Bay OR Creek OR sea)*		*159 of 925*
	Total items online searches	***2,250 (98.9%)***	
B) Manual search			
Date/time	Source	Number of items added	
	Author personal collection, and MMP, CRC and NESP reports mentioned above	*15*	
	Arising from cited literature in other sources	*2*	
	Sourced from professional contacts or suggested by reviewers	*10*	
	Total items manual searches	***27 (1.1%)***	
	Grand total	378 of 2,277	

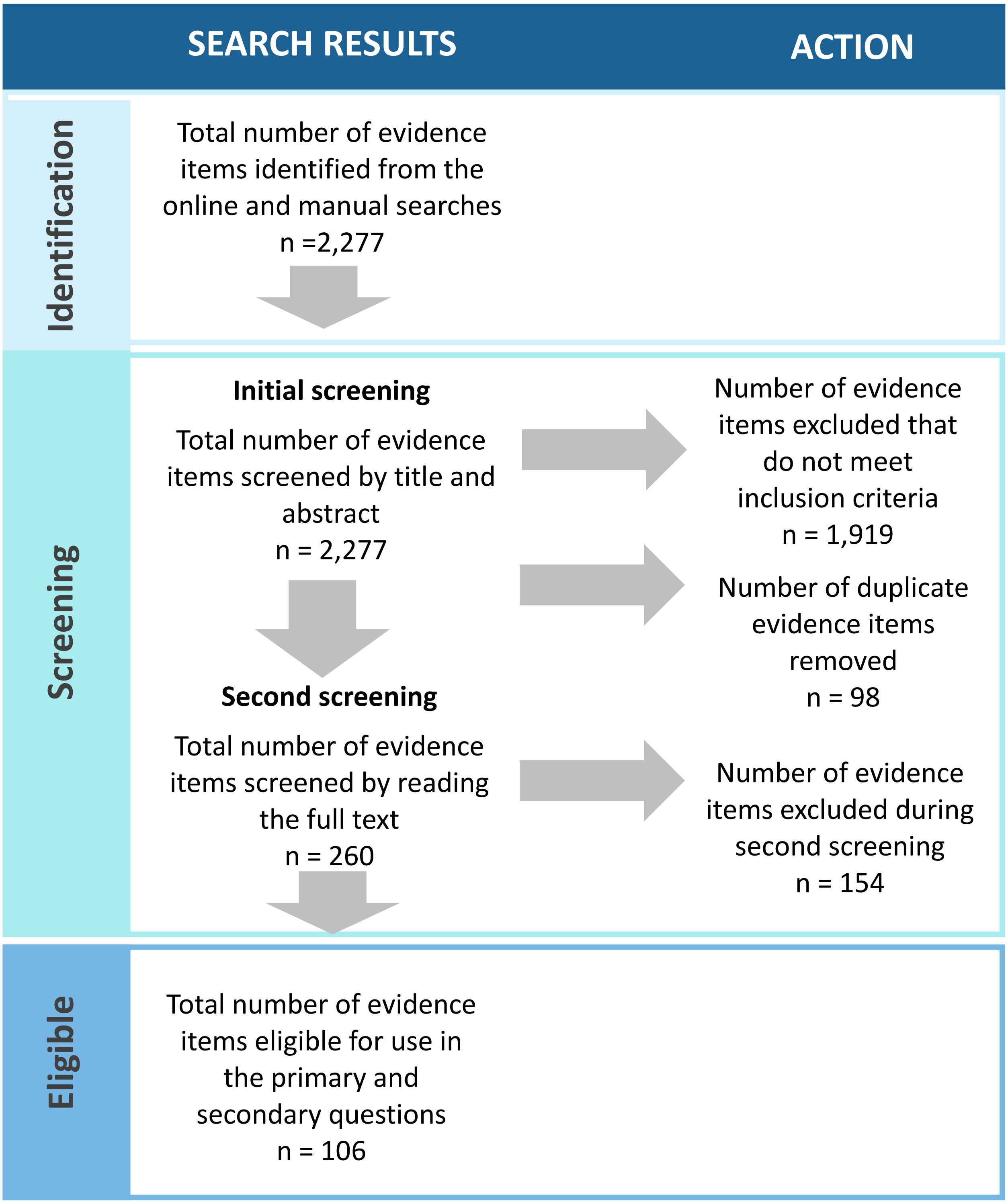


Figure 5. Flow chart of results of screening and assessing all search results for Question 4.1.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

In total, 106 studies, all from the GBR, were considered in this review. This included 90 peer reviewed journal articles, 2 peer reviewed conference papers and 14 peer reviewed reports from credible publishers such as the Great Barrier Reef Marine Park Authority (GRBMPA) and the National Environmental Science Program (NESP) Tropical Water Quality Hub. Half of the studies (58) included *in situ* nutrient sample observations, and these were complemented by data from other sources, including satellite observations, glider observations and outputs from process models (Table 7). Collectively, these studies provided a long temporal record of observational data covering the whole GBR, though most reported satellite data are from 2002 onwards (from the launch of the MODIS ocean colour satellites) and a greater richness of *in situ* data exists from 2006 onwards (i.e., when the Great Barrier Reef Marine Monitoring Program for Inshore Water Quality began, or MMP WQ). Of the studies using satellite ocean colour or aerial photography, three reported ocean-colour-derived estimates of Chlorophyll *a* (Chl-*a*), while the remainder used ocean colour data to estimate the spatial footprint of flood plumes, and combined this information with *in situ* nutrient concentrations. The single study that used glider data used fluorescence data from the glider to complement *in situ* nutrient sampling. Overall, there is a high degree of consistency amongst the findings of these studies.

The spatial relevance of the included studies is summarised in Table 8.

Table 7. Number of sources using data of each type. Note that some studies use multiple data sources so the total of all rows exceeds the total number of studies.

Study type	Number of sources
Observational – *in situ*	58
Observational – satellite	17
Observational – glider	1
Observational – aerial photography	2
Model – process	13
Model – statistical	3
Secondary – original analysis	11
Secondary – review	9
Multiple data types	16

The overwhelming majority of studies focused on inshore and/or midshelf waters (Table 8), with relatively few including estuary or offshore nutrient concentrations. Of those that did cover offshore locations, the majority were satellite or process model studies. The remaining sources were local studies that provided only sparse *in situ* nutrient observations.

The great majority of *in situ* measurements of nutrient concentrations have been taken in inshore waters. Within this waterbody, the MMP for Inshore Water Quality (Moran et al., 2022; Waterhouse et al., 2021) provides consistent, long-term monitoring of nutrients in the forms of particulate nitrogen and phosphorus (PN and PP), total dissolved nitrogen and phosphorus (TDN and TDP), ammonium (NH_4^+, hereafter NH4), nitrate plus nitrite (NO_3^- plus NO_2^-, hereafter NOx), phosphate (PO_4^{3-}, hereafter PO4), silicate (SiO_4^{4-}, hereafter SiO4) and other physico-chemical parameters including the associated indicators, chlorophyll *a* (Chl-*a*) and turbidity. Dissolved organic nitrogen and phosphorus (DON and DOP) are derived as the difference between TDN and dissolved inorganic nitrogen and the difference between TDP and PO4. The MMP water quality sampling covers from Cape York to the Mackay

Whitsunday region from 2006 to the present time (2023) with the exception of the Fitzroy region that has a gap in data collection from 2015 to 2020. Along the Cairns Transect in the Wet Tropics (now incorporated into the MMP and reported as the Barron Daintree focus region), water quality has been monitored since 1989 (Schaffelke et al., 2005).

Other studies have measured many of these constituents as well as additional parameters in inshore waters, though not as part of routine monitoring programmes. These include particulate organic carbon (Blondeau-Patissier et al., 2018), coloured dissolved organic matter (a component of dissolved organic carbon) (Blondeau-Patissier et al., 2009), nitrogen isotopes in coral skeletons (Erler et al., 2016; 2020; Lewis et al., 2012; Mallela et al., 2013), particulate organic matter, nitrogen and carbon isotopes (Marion et al., 2021) and sulfate (Watson et al., 2017).

Outside of the MMP, nutrient observations from *in situ* samples are available from a broad range of studies that focus on particular sites at particular times (Table 8). Though these data are relatively sparse, when taken as a collective body of evidence together with satellite observations and process model outputs, they provide a consistent and relatively comprehensive picture of the spatial and temporal distribution and variability in nutrient concentrations across the whole GBR.

Table 8. Number of sources relating to each Natural Resource Management (NRM) region and waterbody. Note that many studies have reported data from multiple regions or waterbodies, so the row and column sums exceed the total number of studies for each region and waterbody reported in the final row and column.

NRM Region	Estuary	Inshore	Midshelf	Offshore	Total
Cape York	6	47	33	13	**49**
Wet Tropics	7	57	42	12	**66**
Burdekin	5	48	40	14	**56**
Mackay Whitsunday	3	46	36	10	**51**
Fitzroy	7	41	36	11	**50**
Burnett Mary	1	29	27	9	**32**
TOTAL	**17**	**84**	**62**	**18**	**106**

4.1.1 Summary of evidence to 2022

Spatial distribution of nutrients

Flood plumes

Nitrogen and phosphorus concentrations that are elevated relative to ambient marine concentrations are associated with freshwater discharge from rivers, particularly in flood plumes during the November to April wet season (Alvarez-Romero et al., 2013; Australian Institute of Marine Science (AIMS), 2022; Bainbridge et al., 2012; Baird et al., 2021a; Brodie et al., 2005; 2007; 2012; Cooper et al., 2007; Crosbie & Furnas, 2001; Davies & Eyre, 2005; Devlin et al., 2012; 2013; 2015; Devlin & Brodie, 2005; Devlin & Schaffelke, 2009; Fabricius et al., 2010; Garzon-Garcia et al., 2021; Howley et al., 2017; McCulloch et al., 2003a; 2003b; Moran et al., 2022; Radke et al., 2006; Schaffelke et al., 2005; Udy et al., 2005; Waterhouse et al., 2021).

Flood plumes are usually constrained to within 25 km of the coast (Fabricius et al., 2010; Furnas et al., 2005), but occasionally intrude into midshelf waters up to 50 km from the coast after major flood events (Moran et al., 2022; Waterhouse et al., 2021; Weeks et al., 2015). In general, the spatial extent of flood plumes is greater in the central and southern GBR than in the Cape York region (Moran et al., 2022).

Most flood plumes travel northwards up the coast from their source rivers, though this can vary depending on atmospheric conditions and rate of river discharge (Baird et al., 2021a). The largest discharges are from the Burdekin and Fitzroy Rivers, which each drain catchments of more than

100,000 km^2. The plumes of both rivers extend hundreds of kilometres north of the river mouths. One analysis (Wolff et al., 2018) found that the Burdekin River was the dominant source of terrestrial nitrogen to inshore and midshelf reefs as far north as Daintree in the Wet Tropics during the 2010-2011 wet season, which had the largest Burdekin discharge since 1991.

Substantial research effort has gone into mapping the overall spatial extent of flood plumes using satellite ocean colour observations (Alvarez-Romero et al., 2013; Devlin et al., 2012; 2013; 2015; Devlin & Brodie, 2005; Devlin & Schaffelke, 2009; Howley et al., 2017; Oubelkheir et al., 2023). Devlin et al. (2012) used this approach to estimate that up to 5,970 km^2 of marine waters in the Wet Tropics region and 5,131 km^2 in the Burdekin region were exposed to flood plumes carrying high DIN loads. These methods were updated and improved by Brodie et al. (2013) and Waterhouse et al. (2017), and are now used to map the spatial extent of exposure to flood plumes each year for the MMP reports (Moran et al., 2022).

Figure 6 shows the cumulative number of weeks of exposure (from a minimum of zero to a maximum of 22 weeks) to optical water types 1 (brown-coloured water) and 2 (greenish water). Comparison with *in situ* observational records has shown that these colours generally correspond to flood plumes. Water type 1 generally indicates primary flood plume waters with high concentrations of suspended sediments and particulate nutrients. Water type 2 represents the less turbid part of flood plumes enriched in Chl-*a* and fine sediment. Water type 3 (not mapped) represents waters with suspended sediment concentrations slightly above ambient conditions and high light penetration typically found in the outer areas of river flood plumes. Water type 3 can also represent waters affected by marine processes such as upwelling or fine sediment resuspension around reefs and islands (Petus et al., 2014; 2016).

Figure 7 shows how dissolved and particulate nitrogen and phosphorus concentrations, and Chl-*a*, vary within optically-mapped flood plume waters. Samples from 15 years of *in situ* MMP water quality monitoring that were taken within two hours of a MODIS satellite overpass were identified and grouped by optical water type. Although there is a large range, mean and 75th percentile DIN, DIP, PN, PP and Chl-*a* concentrations are all higher in water type 1 (primary flood plumes) than water type 2 or 3. Figure 6 and Figure 7 have been adapted from Moran et al. (2022).

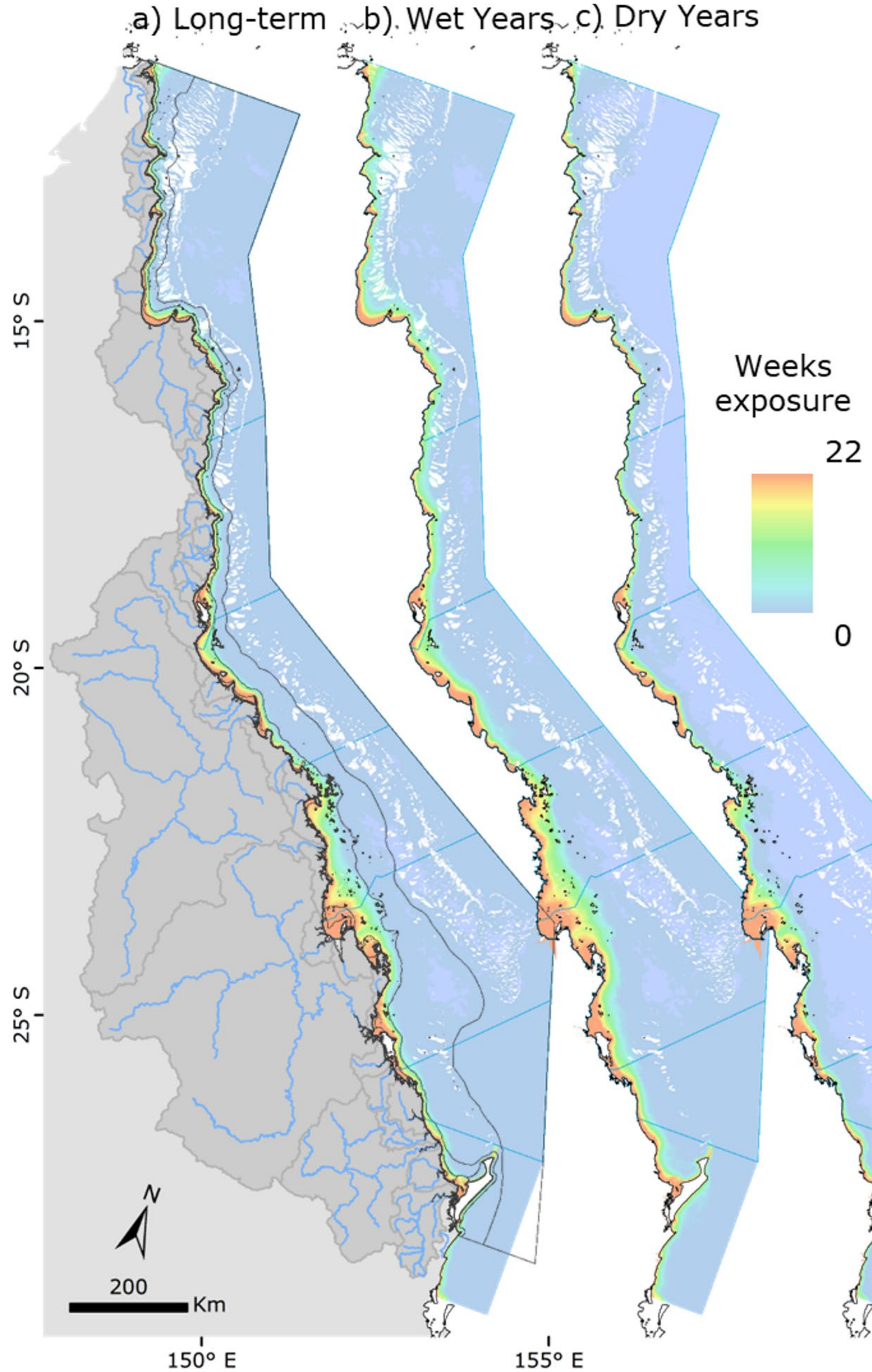


Figure 6. Annual wet season duration of exposure to water classified as optical water type 1 or 2, reflecting the spatial extent of nutrient-rich flood plumes. a) Long term average; b) typical wet-year composite (years with more rain); c) typical dry-year composite (years with less rain). This figure has been adapted from Moran et al. (2022) with permission. Thanks to Caroline Petus (TropWATER, JCU) for providing the adapted version.

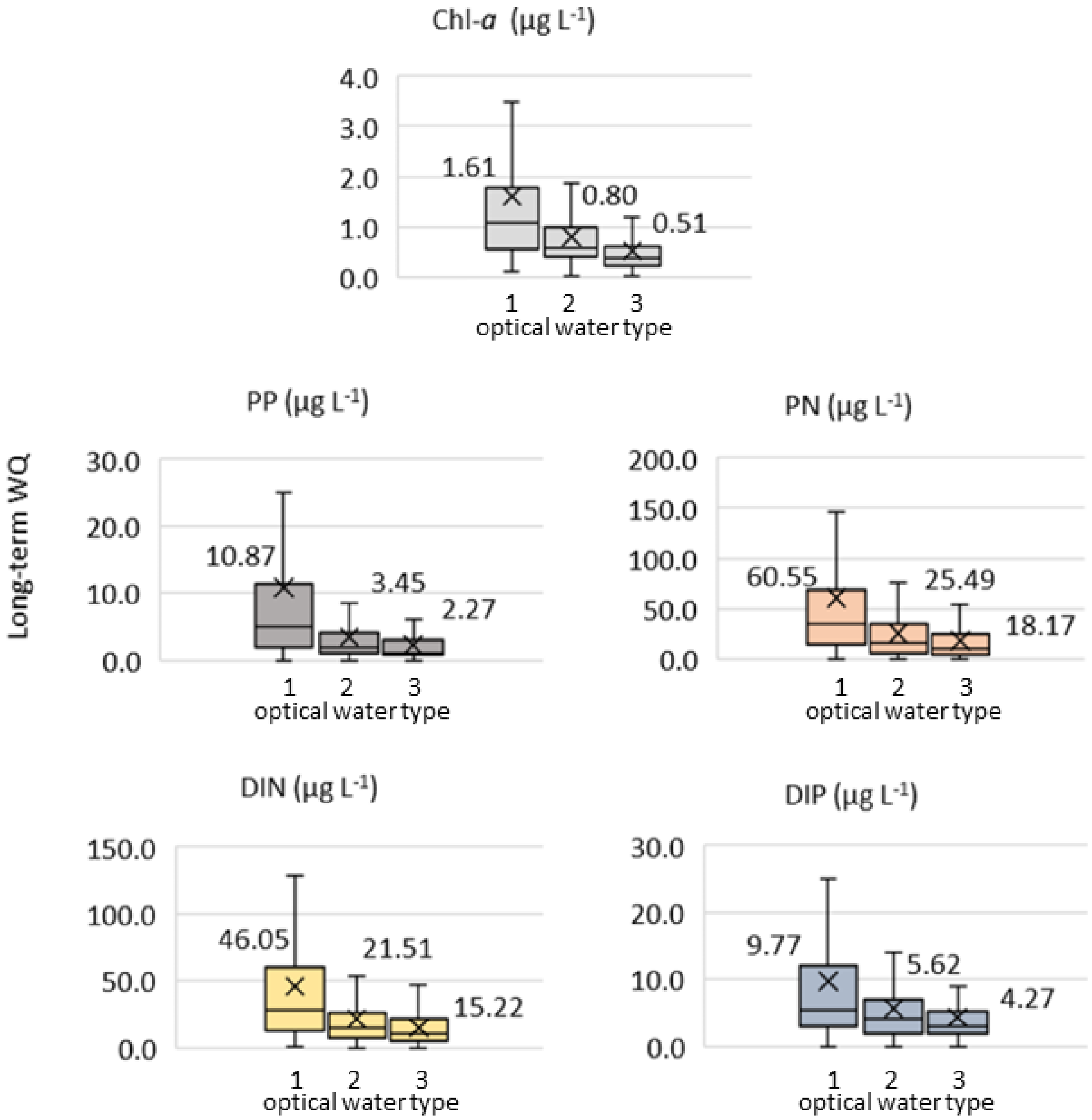


Figure 7. Boxplots showing the statistical distribution of nutrient and Chl-a concentrations in 2004-2019 MMP water quality samples taken from areas mapped as likely flood-plume waters, by optical water type. Water type 1 (brown-coloured water), type 2 (greenish water) and type 3 (greenish-blue water) colour classes are determined from satellite ocean colour observations. Crosses (x) and numbers denote the mean. Horizontal lines and the limits of shaded boxes indicate median, 25th and 75th percentile values. This figure has been adapted from Moran et al. (2022) with permission. Thanks to Caroline Petus (TropWATER, JCU) for providing the adapted version.

Figure 8 and Figure 9 present the same MMP nutrient data (DIN, PN, PO4 and DIP) as a function of observed salinity and region. Data are shown for the Cape York, Wet Tropics and Burdekin regions: nutrient versus salinity plots cannot be shown for regions further south due to a lack of regular flood-event sampling in these regions. PN and PP are elevated in freshwater, but decline rapidly due to settling near the river mouths. DIN and PO4 are elevated throughout the Wet Tropics and Burdekin region flood plumes and are relatively lower in the Cape York region.

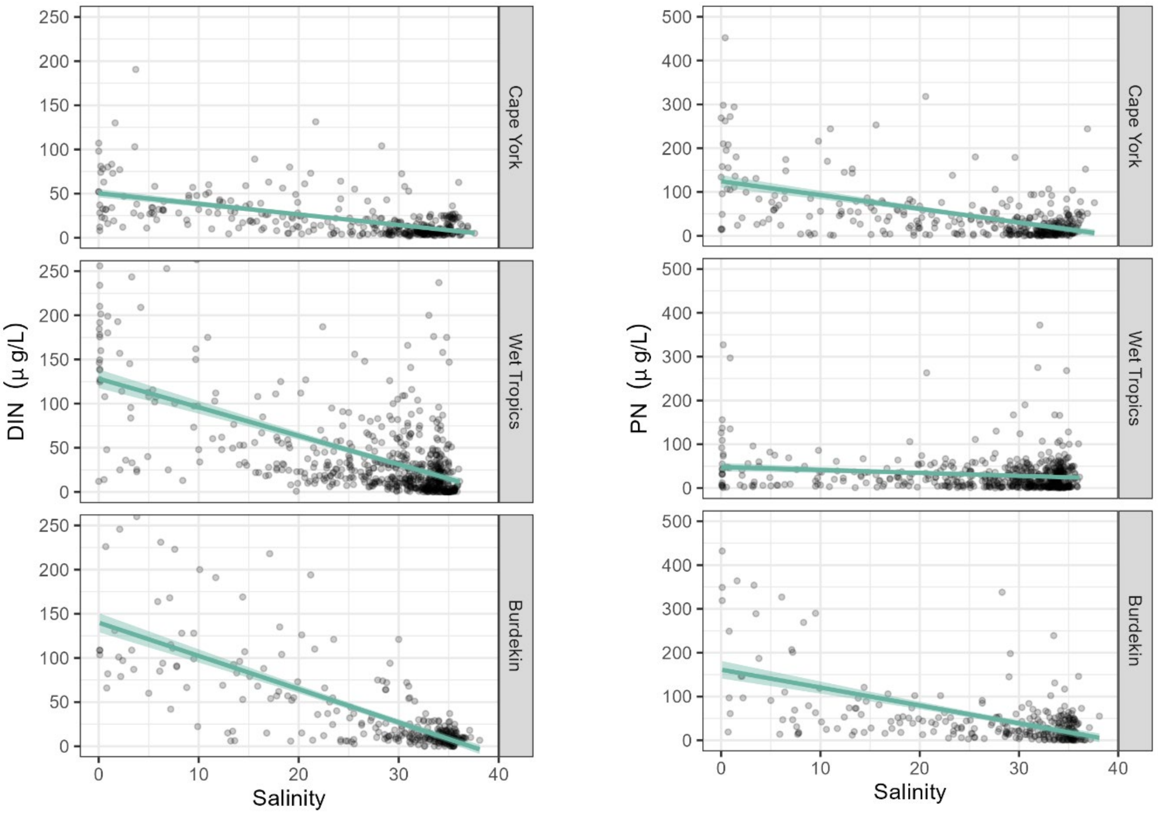


Figure 8. Dissolved inorganic nitrogen (DIN) and particulate nitrogen (PN) concentrations as a function of salinity in wet season (ambient and event) MMP water quality samples, 2004-2019. For each subplot, a linear fit is shown with 95% confidence intervals.

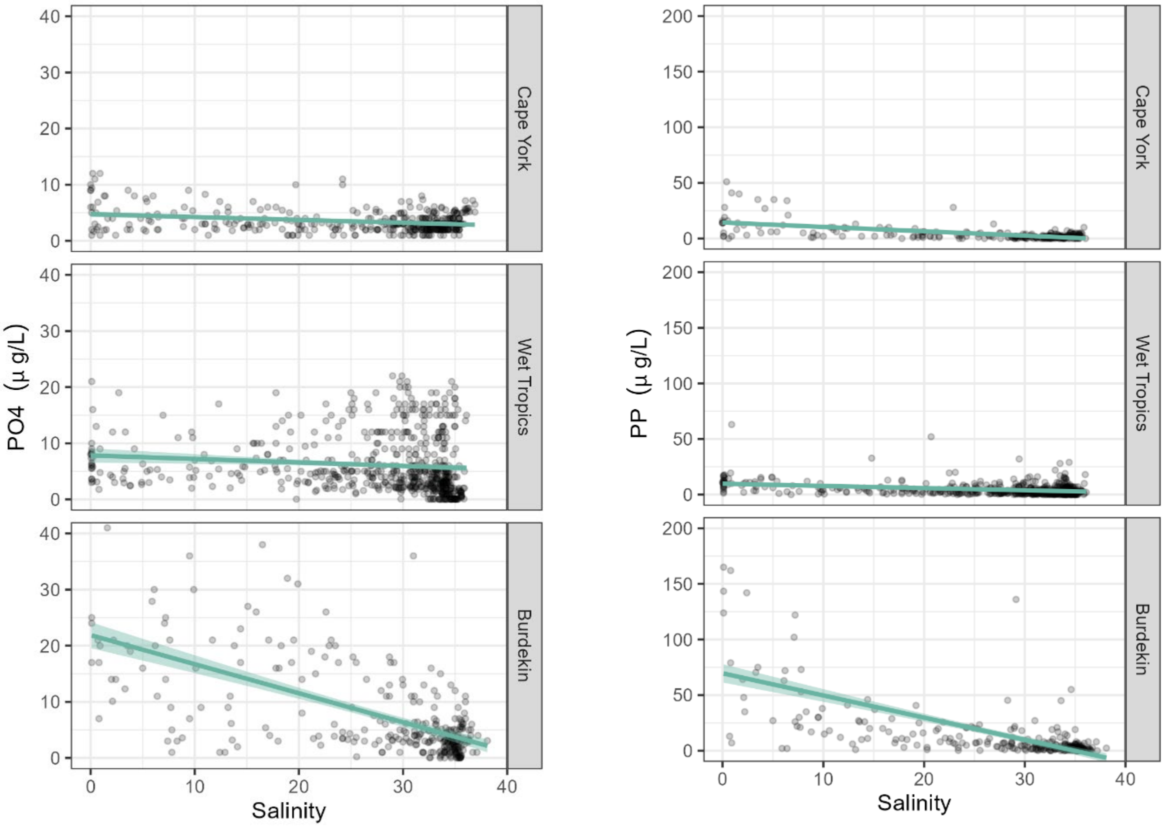


Figure 9. Phosphate (PO4) and particulate phosphorus (PP) concentrations as a function of salinity in wet season (ambient and event) MMP water quality samples, 2004-2019. For each subplot, a linear fit is shown with 95% confidence intervals.

The majority of terrestrial particulate nutrients are deposited within 10 km of the mouths of rivers, but dissolved nutrients are carried further and are taken up by biota and transformed to phytoplankton biomass (measured as Chl-*a*) as other particulate materials drop out (Devlin & Brodie, 2005). Higher Chl-*a* concentrations are often observed in the transition zone at the edge of a flood plume (Oubelkheir et al., 2023), where they have been reported up to 50 times higher than background concentrations (Brodie et al., 2010).

Additional evidence comes from studies of the flood plumes of individual rivers, which show similar results. Bainbridge et al. (2012) presented nutrient (TN and constituents and TP and constituents) concentrations as a function of salinity for each of three flood events in the Burdekin River during the 2010/2011 wet season. Howley et al. (2018) presented similar figures for 2012, 2013 and 2014 flood events affecting Princess Charlotte Bay in the Cape York region. Radke et al. (2006) showed results from February 2005 in the receiving waters of the Fitzroy River, including mixing diagrams (concentration versus salinity plots) for NOx, DON, PN, DOP, FRP (filterable reactive phosphorus), PN and SiO4, as well as spatial maps of these plus TN and TP. Radke et al. (2006) found clear gradients of declining concentrations with increasing salinity for most constituents, and declining TN and TP with distance from the river mouth, but no clear gradient for DON or DOP. Taking one last example in more detail, Devlin and Brodie (2005) reported NOx, NH4, PO4, PN, PP, DON, DOP and Chl-*a* in Burdekin, Barron, Johnstone and Herbert River flood plumes as a function of salinity, showing similar gradients in each case, with NOx ranging from ~1700 µg L^{-1} in water from each river to near zero in undiluted seawater, PO4 and NH4 higher in the Burdekin River than the Barron, Herbert or Johnstone Rivers (PO4 ~25 µg L^{-1} in the Burdekin and ~6 µg L^{-1} in the Barron and Herbert Rivers; NH4 ~140 µg L^{-1} in the Burdekin and ~40 µg L^{-1} in the Barron and Johnstone). Chl-*a*, DON and DOP, though elevated in flood plumes, did not show such a clear gradient with salinity, reflecting the transformation and processing of nutrients from dissolved inorganic to organic and particulate forms within flood plumes.

A substantial proportion of particulate organic nitrogen and phosphorus deposited in sediments in estuaries and at the mouths of rivers is later remineralised, releasing dissolved nitrogen and phosphorus to the overlying water column through porewater advection, diffusion and resuspension so that nutrient concentrations in inshore and some midshelf areas remain elevated even after the flood plumes disperse (Alongi et al., 2007; Crosswell et al., 2020; Garzon-Garcia et al., 2021; Howley et al., 2018; Lønborg et al., 2018; Marion et al., 2021). Hydrodynamic-biogeochemical modelling studies in Keppel Bay suggest that timeframes for depletion of this nutrient source to inshore waters may extend over months or years after a major flood event (Robson et al., 2008).

Ambient inshore and cross-shelf gradients

When not directly affected by flood events, gradients from higher nutrient concentrations in coastal environments to lower concentrations at the boundary between inshore and midshelf waters persist.

Nutrient concentrations in mangrove creeks are high. Murray et al. (2018) reported dry season dissolved inorganic nitrogen concentrations in mangrove creeks near the mouth of the Fitzroy River of up to 154 µg L^{1} as NO3 and up to 925 µg L^{1} as NH4. McKinnon and Klumpp (1997) reported PN ranging from 104 to 131 µg L^{-1} and Chl-*a* ranging from 0.97 to 1.07 µg L^{-1} in coastal mangroves near the mouth of the Haughton River in the Burdekin region.

In estuaries and close to river mouths, strong and consistent spatial gradients are observed. In inshore areas not directly impacted by flood plumes, nutrient concentrations are typically lower and exhibit less pronounced seasonal variation than in flood plumes, though they are still elevated relative to midshelf and offshore concentrations. Detailed plots showing clear inverse relationships between distance from the mouths of rivers and concentrations of NOx, PN and PP in inshore waters are provided in annual MMP Water Quality reports (Moran et al., 2022; Waterhouse et al., 2021) and the results from the most recent report are summarised in Table 9.

Table 9. Inshore spatial patterns observed in depth-averaged ambient (non flood-event) samples in transects from the mouths of rivers during the 2021-22 monitoring season (Moran et al., 2022). Where it is not clear that there was a significant increase or decrease with distance from river mouth, no direction is shown.

	Direction of change with increasing distance from river mouths (ambient conditions)					
	Wet season			Dry season		
Focus Region	**NOx**	**PP**	**PN**	**NOx**	**PP**	**PN**
Cape York (Pascoe)	decrease	decrease	decrease	(no data)	(no data)	(no data)
Cape York (Stewart)	-	decrease	decrease	(no data)	(no data)	(no data)
Cape York (Normanby)	increase	decrease	decrease	(no data)	(no data)	(no data)
Cape York (Annan-Endeavour)	-	decrease	decrease	-	decrease	decrease
Wet Tropics (Russell-Mulgrave)	decrease	decrease	decrease	decreased	decrease	decrease
Wet Tropics (Tully)	decrease	decrease	decrease	-	decrease	-
Burdekin	decrease	decrease	decrease	-	decrease	decrease
Mackay Whitsunday	decrease	decrease	decrease	increase	decrease	decrease
Fitzroy	decrease	decrease	decrease	decreased	decrease	decrease

Other sources have reported similar nutrient gradients in inshore waters. Webster et al. (2005), for example, reported TN declining from the mouth of the Fitzroy River to the outer edge of Keppel Bay. Alongi et al. (2015) and Cooper et al. (2007), in separate studies, both reported higher concentrations of PN and PP in inshore than midshelf waters of the Mackay Whitsunday region. Furnas et al. (2011) reported small cross-shelf gradients in NO3 and PO4 in the Cape York and Wet Tropics regions.

Cooper et al. (2007) and Cooper and Ulstrup (2009) reported that nutrient concentrations (PN, PP, DON, DOP and also Chl-*a*) declined across a gradient from inshore to outer shelf reefs in the Mackay Whitsunday region. Silicate concentrations declined from the reefs closest to the coast to those in the midshelf but were similar at the midshelf and outer reef locations, with temporal means at the midshelf and outer reef sites around 30 to 35 µg L^{1} (Cooper & Ulstrup, 2009; Cooper et al., 2007). Other authors (Ayukai, 1993; Furnas & Mitchell, 1996) have reported similarly low DIN, PO4 and SiO4 concentrations in offshore surface waters in the Wet Tropics and Burdekin regions. Furnas and Mitchell (1996) mention that this is typical for the East Australian Current. Schaffelke et al. (2005) reported data collected at inshore and offshore sites between 1980 and 2005, again showing consistently higher concentrations at inshore compared to offshore sites. Reading et al. (2021) reported that concentrations of PO4 are usually low and approach detection limits in offshore waters.

Beyond the inshore waterbody, spatial gradients are less consistent. Frade et al. (2020) found (in outputs from a process model applied across the whole GBR) that inorganic nitrogen concentrations (NH4 and NOx) and Chl-*a* peaked at midshelf reefs, though other nutrient constituents followed the typical high inshore to low offshore gradient.

There is some evidence of a cross-shelf Chl-*a* gradient. Brodie et al. (2007) reported an inshore cross-shelf gradient in Chl-*a* that was stronger in the southern GBR than the north. De'ath and Fabricius (2010) mapped Chl-*a* from 2,058 stations across the GBR sampled during three programmes between 1992 and 2006 and showed declining concentrations from the coast to the midshelf, particularly in the central and Southern GBR. Bell et al. (2014) reported on the basis of estimates from satellite ocean colour that mean Chl-*a* exceeds 0.5 µg L^{-1} in inshore regions south of Port Douglas, is typically in the 0.3 to 0.5 µg L^{-1} range in midshelf regions, and <0.2 µg L^{-1} in offshore Cape York region waters. Although there has been limited validation of the accuracy of satellite-derived Chl-*a* estimates for the GBR and inshore estimates of Chl-*a* are likely to be inaccurate due to the optical complexity of inshore waters, these values are broadly consistent with those reported by De'ath and Fabricius (2010) in a spatial analysis of an overlapping observational dataset and with inshore and offshore Chl-*a* results reported from long-term *in situ* monitoring (Moran et al., 2022) and other *in situ* studies (Cooper et al., 2007).

Concentrations of nitrous oxide (N_2O) are orders of magnitude lower than concentrations of NOx and NH4, so are rarely measured. Reading et al. (2021), however, measured N_2O as part of a study of greenhouse gas distributions and found that N_2O increases with distance from the coast from inshore to offshore and also increases with depth. This was in contrast with NH4 concentrations, which were highest midshelf. Measured N_2O concentrations were in the range 5.6 to 6.8 nM (78 to 95 ng L^1).

A few studies have reported concentrations of nutrients in benthic sediments. Although a full review of benthic sediment nutrients is beyond the scope of this report, these are worth noting briefly. In the inshore Fitzroy region, cross-shelf gradients similar to those reported in the water column have been observed in benthic sediments (Radke et al., 2010). Lourey et al. (2001), however, found no significant cross-shelf gradient in benthic sediment nutrient concentrations in the Northern GBR. Monbet et al. (2007) found that TP is relatively uniformly distributed in benthic sediments along a cross-shelf gradient in the Fitzroy region, but that the form of this phosphorus varied, with midshelf and outer shelf sediment phosphorus much less readily remineralised than estuary and inshore sediment phosphorus.

Table 10 presents a summary of quantitative nutrient values from *in situ* sampling reported by all sources, grouped by region and waterbody. Studies that reported the use of MMP Water Quality data are omitted from this table to avoid duplicate reporting. Studies for which it was not possible to separate values by region or waterbody have also been omitted. Where nutrient concentrations were reported only in graphical form, a digitising tool has been used to estimate numerical values. In some cases, the reported ranges or mean values are the result of sampling across several years; in other cases, only a single, one-off sample has been reported (refer to the original sources for more information).

Table 10 provides evidence of:

- Substantially higher concentrations of most N and P species, and of TN (524 µg L^{-1} reported by Howley et al. (2018)) and TP (62 µg L^{-1} reported in the same study), in estuaries compared to marine waters – though few estuary values have been reported.
- Clear cross-shelf gradients in the maximum reported values of all forms of N other than NO2 for which sufficient data are available to populate the table. Higher maximum values have been reported from inshore samples than midshelf, and lower values in offshore waters in most regions. The greater variability in nitrogen concentrations in inshore waters is especially associated with flood plume samples.
- Similar gradients from inshore to offshore in the reported values for phosphorus species in the Cape York region. For other regions, there have been too few reported phosphorus measurements to confirm the existence of a cross-shelf phosphorus gradient.

Table 10. In situ *nutrient concentrations reported by non-MMP sources reviewed. Sources that used MMP Water Quality data where this was known or could be ascertained from the methods or acknowledgements. BDL = Below Detection Limit.*

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
TN (µg L^{-1})	**Cape York**	524±119	288±108	112±64.4			Howley et al., 2018	Estuary values from this study were measured during a flood event. Inshore ambient values are from outside the plume during the same event.
	Wet Tropics							
	Burdekin			120			Muslim & Jones, 2003	
			<195-675				Bainbridge et al., 2012	
	Mackay Whitsunday							
	Fitzroy				50-160		Watson et al., 2017**	
	Burnett Mary							
NOx (µg L^{-1})	**Cape York**	45.1±27.9	28.0±18.6	6.02±64.4			Howley et al., 2018	
				BDL			Crosswell et al., 2020	
					0.78	0.21-0.58	Messer et al., 2017**	
	Wet Tropics			0.6±0-0.7±0.3	0.6±0	0.6±0	Crosbie & Furnas, 2001	
				0.11	1.05		Messer et al., 2017**	
	Burdekin		<20->85				Bainbridge et al., 2012	

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
	Mackay Whitsunday		<1-164				Brodie et al., 2010	
				0.6	0.6±0-4±4.6	0.6±0-7.1±6.7	Crosbie & Furnas, 2001	
				0.76		0.52-1.05	Messer et al., 2017**	Higher end of range for mid and outer is post cyclone.
	Fitzroy				10		McMahon & Santos, 2017	
				0.18			Messer et al., 2017**	
	Burnett Mary							
NO3 **(µg L^{-1})**	**Cape York**			0.34±0.1			Fabricius & De'ath, 2004	
				0.1-0.4		0.3	Furnas et al., 2011	
				0.14±0.06			Fabricius et al., 2005**	
	Wet Tropics			2.0±1.0			Fabricius & De'ath, 2004	
				0.1-0.3		1.4	Furnas et al., 2011	
		49-84					Murray et al., 2020	Range is between seasonal means.
				0.83±0.46			Fabricius et al., 2005**	

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
	Burdekin			16.5±3.5	3.9±0.4-9.8±2.9	8.3±2.4	Capone et al., 1992	
		3-70					Murray et al., 2018	Range is seasonal means.
				9.4			Muslim & Jones, 2003	
	Mackay Whitsunday			BDL*	BDL-3.5*	3.2-3.6*	Alongi et al., 2015	
		<0.1-76*					Murray et al., 2020	Range is between seasonal means.
	Fitzroy	1-245*					Murray et al., 2018	Range is seasonal means.
		7-85*		BDL*			Radke et al., 2010	
					BDL-5.6*		Watson et al., 2017**	
	Burnett Mary							
NO2 **(µg L^{-1})**	**Cape York**			0.17±0.03			Fabricius & De'ath, 2004	
				0.1		0.1	Furnas et al., 2011	
				0.009±0.002			Fabricius et al., 2005**	
	Wet Tropics			0.27±0.04			Fabricius & De'ath, 2004	
				0.1		0.3	Furnas et al., 2011	
				0.018±0.0036			Fabricius et al., 2005**	

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
	Burdekin							
	Mackay Whitsunday		<0.5-15				Brodie et al., 2010	
	Fitzroy				BDL-2		Watson et al., 2017**	Range is between seasonal means.
	Burnett Mary							
NH4 or NH3 (Values reported as NH_3 indicated with an asterisk) ($\mu g\ L^{-1}$)	**Cape York**			2.2±0.3			Fabricius & De'ath, 2004	
				<0.1-0.4		<0.1-0.3	Furnas et al., 2011	"Offshore" value may combine midshelf and offshore sites.
				0.7			Crosswell et al., 2020	
				0.4±0.15			Fabricius et al., 2005**	
				-	0.69*	BDL-0.43*	Messer et al., 2017**	
	Wet Tropics			3.4±1			Fabricius & De'ath, 2004	
				0.3-0.6		0.8-2.0	Furnas et al., 2011	
		1-18					Murray et al., 2020	Range is seasonal means.
				1±0-2.2±1	1±0-1.7±01	1±0-1.7	Crosbie & Furnas, 2001	
				0.68±0.19			Fabricius et al., 2005**	
				BDL*	BDL*		Messer et al., 2017**	

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
	Burdekin			22.5±9.5	8.5±3.2-9.4±4.2	7.7±7.7	Capone et al., 1992	
		0.4-250					Murray et al., 2018	Range is seasonal means.
				12			Muslim & Jones, 2003	
	Mackay Whitsunday			2.2-2.5	2.4-5.9	2.1-3.1	Alongi et al., 2015	
		1-190					Murray et al., 2020	Range is seasonal means. Higher end of range for mid and outer is post cyclone.
				1	1±0.1-27.2±3.4	1±0.1-18.9±4	Crosbie & Furnas, 2001	
			<1-38*				Brodie et al., 2010	
				1.96*		1.54-1.96*	Messer et al., 2017**	
	Fitzroy	3-920					Murray et al., 2018	Range is seasonal means.
					10		McMahon & Santos, 2017	
				1.26*			Messer et al., 2017**	
					BDL-1.42*		Watson et al., 2017**	Range is between seasonal means.
	Burnett Mary							
DIN **(µg L^{-1})**	**Cape York**		15.96-81.9	21.98		21	Oubelkheir et al., 2023	During flooding, inshore ambient is outside of flood plume.

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
	Wet Tropics		271.5±12				Wolanski et al., 2008	Range is seasonal means.
	Burdekin					4.8-25.8	Ayukai, 1993	Range is seasonal means.
	Mackay Whitsunday			1.5±0.6-6.3±2.1			Cooper & Ulstrup, 2009	
	Fitzroy							
	Burnett Mary							
PN **(µg L^{-1})**	**Cape York**			19.7±1.8			Fabricius & De'ath, 2004	
		186±133	65.8±70	21±16.8			Howley et al., 2018	Estuary value from Howley et al. (2018) is during flood event. Inshore (ambient/unspecified) value is from outside plume during event.
				17.5-21.6		13-14	Furnas et al., 2011	
				1.6±0.3			Fabricius et al., 2005**	
	Wet Tropics			35.7±5.3			Fabricius & De'ath, 2004	
				19.2-20.9		14.6-17.4	Furnas et al., 2011	
				3.1±0.57			Fabricius et al., 2005**	
	Burdekin			8.33-35.7			Fabricius & Dommisse, 2000	
			15-255				Bainbridge et al., 2012	
				22	11-14	14-15	Alongi et al., 2015	

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
	Mackay Whitsunday		5-7962				Brodie et al., 2010	
				13±1-20.0±3			Cooper et al., 2009	
		104-131					McKinnon & Klumpp, 1997	
	Fitzroy							
	Burnett Mary							
DON **(µg L^{-1})**	**Cape York**	259±104	188±79.8	75.6±63.0			Howley et al., 2018	Estuary value from Howley et al. (2018) is during flood event. Inshore (ambient/unspecified) value is from outside plume during event.
				70-77		62-78	Furnas et al., 2011	
	Wet Tropics			83-140	67-74		Furnas et al., 2011	
	Burdekin			99			Muslim & Jones, 2003	
	Mackay Whitsunday		61-266				Brodie et al., 2010; Cooper et al., 2009	
				90.3±14.3-108±15.8			Cooper et al., 2009	
	Fitzroy							
	Burnett-Mary							
TDN **(µg L^{-1})**	**Cape York**			118±8.3			Fabricius & De'ath, 2004	
				8.1±0.8			Fabricius et al., 2005**	
	Wet Tropics				91±10-95±22		Carreira et al., 2020	

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
				117±14.1 9.3±1.8			Fabricius & De'ath, 2004 Fabricius et al., 2005**	
	Burdekin				120±10		Carreira et al., 2020	
	Mackay Whitsunday				110±15		Carreira et al., 2020	
	Fitzroy							
	Burnett Mary							
TP **(µg L^{-1})**	**Cape York**	62±37	19±9	6±3			Howley et al., 2018	Estuary value from Howley et al. (2018) is during flood event. Inshore (ambient/unspecified) value is from outside plume during event.
	Wet Tropics							
	Burdekin		<25-210				Bainbridge et al., 2012	
	Mackay Whitsunday							
	Fitzroy				BDL-4.0		Watson et al., 2017**	Range is between seasonal means.
	Burnett Mary							
PO3-4 **(µg L^{-1})**	**Cape York**			0.6 BDL		3	Furnas et al., 2011 Crosswell et al., 2020	

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
					0.53	0.43-0.62	Messer et al., 2017**	
	Wet Tropics			1-2		3.7-4.7	Furnas et al., 2011	
			11±3				Wolanski et al., 2008	
				0.6±0-2±0.3	0.6±0-0.9±0	0.6±0-3	Crosbie & Furnas, 2001	
				0.65	0.68		Messer et al., 2017**	
	Burdekin					2-4.67	Ayukai, 1993	Range is seasonal means.
	Mackay Whitsunday			3.1-3.4	3-4.0	2.8-4.0	Alongi et al., 2015	
				0.6	0.6±0-3±2	0.6±0-2±1	Crosbie & Furnas, 2001	Higher end of range for mid and outer is post cyclone.
				0.87		0.74-1.49	Messer et al., 2017**	
	Fitzroy				9		McMahon & Santos, 2017	
				0.59			Messer et al., 2017**	
	Burnett Mary							
PP	**Cape York**			3.0±0.4			Fabricius & De'ath, 2004	
(μg L^{-1})		47±34	9±9	<3±<3			Howley et al., 2018	Estuary value from Howley et al. (2018) is during flood event. Inshore (ambient/unspecified) value is from outside plume during event.
				3		2	Furnas et al., 2011	
				0.1±0.01			Fabricius et al., 2005**	

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
	Wet Tropics			5.0±0.9			Fabricius & De'ath, 2004	
				2		2	Furnas et al., 2011	
				0.18±0.04			Fabricius et al., 2005**	
	Burdekin			1.44-2.24			Fabricius & Dommisse, 2000	
			10-165				Bainbridge et al., 2012	
	Mackay Whitsunday			4.3-6.5	2	2	Alongi et al., 2015	
			1-481				Brodie et al., 2010	
				2±0.3-3.4±0.3			Cooper et al., 2009	
	Fitzroy							
	Burnett Mary							
DOP **(µg L^{-1})**	**Cape York**	5.9±6.5	6.8±4.7	0.6±0.6			Howley et al., 2018 Furnas et al., 2011	Estuary value from Howley et al. (2018) is during flood event. Inshore (ambient/unspecified) value is from outside plume during event.
				4.3-7.4		2-4.0	Furnas et al., 2011	
	Wet Tropics			7.1-8.1		4.3	Furnas et al., 2011	
	Burdekin			4.90			Muslim & Jones, 2003	

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
			<30				Bainbridge et al., 2012	
	Mackay Whitsunday		4-21	4.7±0.9-7.4±0.9			Brodie et al., 2010 Cooper et al., 2009	
	Fitzroy							
	Burnett Mary							
DIP **(µg L^{-1})**	**Cape York**							
	Wet Tropics							
				6			Muslim & Jones, 2003	
	Mackay Whitsunday			3±0.6-3.4±0.6			Cooper et al., 2009	
	Fitzroy							
	Burnett Mary							
TDP **(µg L^{-1})**	**Cape York**			13±2 0.45±0.19			Fabricius & De'ath, 2004 Fabricius et al., 2005**	
	Wet Tropics			17±2 0.78±0.05			Fabricius & De'ath, 2004 Fabricius et al., 2005**	
	Burdekin							
	Mackay Whitsunday							
	Fitzroy							

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
	Burnett Mary							
Chl-*a*	**Cape York**			0.4±0.04			Fabricius & De'ath, 2004	
(µg L^{-1})			1.7±1.8	0.3±0.1			Howley et al., 2018	
				0.09-0.24	0.06-0.28		McKinnon et al., 2005	
					0.57	0.08-0.31	Messer et al., 2017	
				0.21-0.36		0.20-0.28	Furnas et al., 2011	
			0.29-11.15	0.20		2.97	Oubelkheir et al., 2023	
		1-5.1		0.4-0.9			Crosswell et al., 2020	
				0.41±0.15			Fabricius et al., 2005**	
	Wet Tropics				0.50±0.21-0.1±0.23		Carreira et al., 2020	
				0.56±0.09			Fabricius & De'ath, 2004	
				0.07-0.34	0.03-0.17	0.64	McKinnon et al., 2005	
				0.43	0.30		Messer et al., 2017	
				0.23-0.44		0.19-0.26	Furnas et al., 2011	
				0.3±0.3-0.8±0.3	0.3±0.3-0.4±0.1	0.1±0.1-0.3	Crosbie & Furnas, 2001	
				0.68±0.16			Fabricius et al., 2005**	
	Burdekin				0.44±0.21		Carreira et al., 2020	

	Region	Estuary	Inshore (flood plume)	Inshore (ambient or unspecified)	Midshelf	Offshore	Reference (** indicates that values were extracted from figures using a digitising tool)	Notes
				0.17-0.34			Fabricius & Dommisse, 2000	
		0.97-1.07					McKinnon & Klumpp, 1997	
				1.35			Bainbridge et al., 2012; Muslim & Jones, 2003	
			<1-2.7				Bainbridge et al., 2012	
						0.05-0.84	Ayukai, 1993**	Range is seasonal means.
	Mackay Whitsunday				0.25±0.17		Carreira et al., 2020	
				0.34±0.05-0.56±0.11			Cooper et al., 2009	
				0.51		0.31-0.43	Messer et al., 2017	
				1.9	0.7±0.2-5.2±6.0	0.9±0.4-3.6±3.1	Crosbie & Furnas, 2001	Higher end of range for mid and outer is post cyclone.
	Fitzroy				200-1200		Glud et al., 2008; Radke et al., 2010	Over coral spawning.
				0.24			Messer et al., 2017	
		0.8-2.6		0.0-0.94			Radke et al., 2010	
	Burnett Mary							

Marine sources of spatial variability

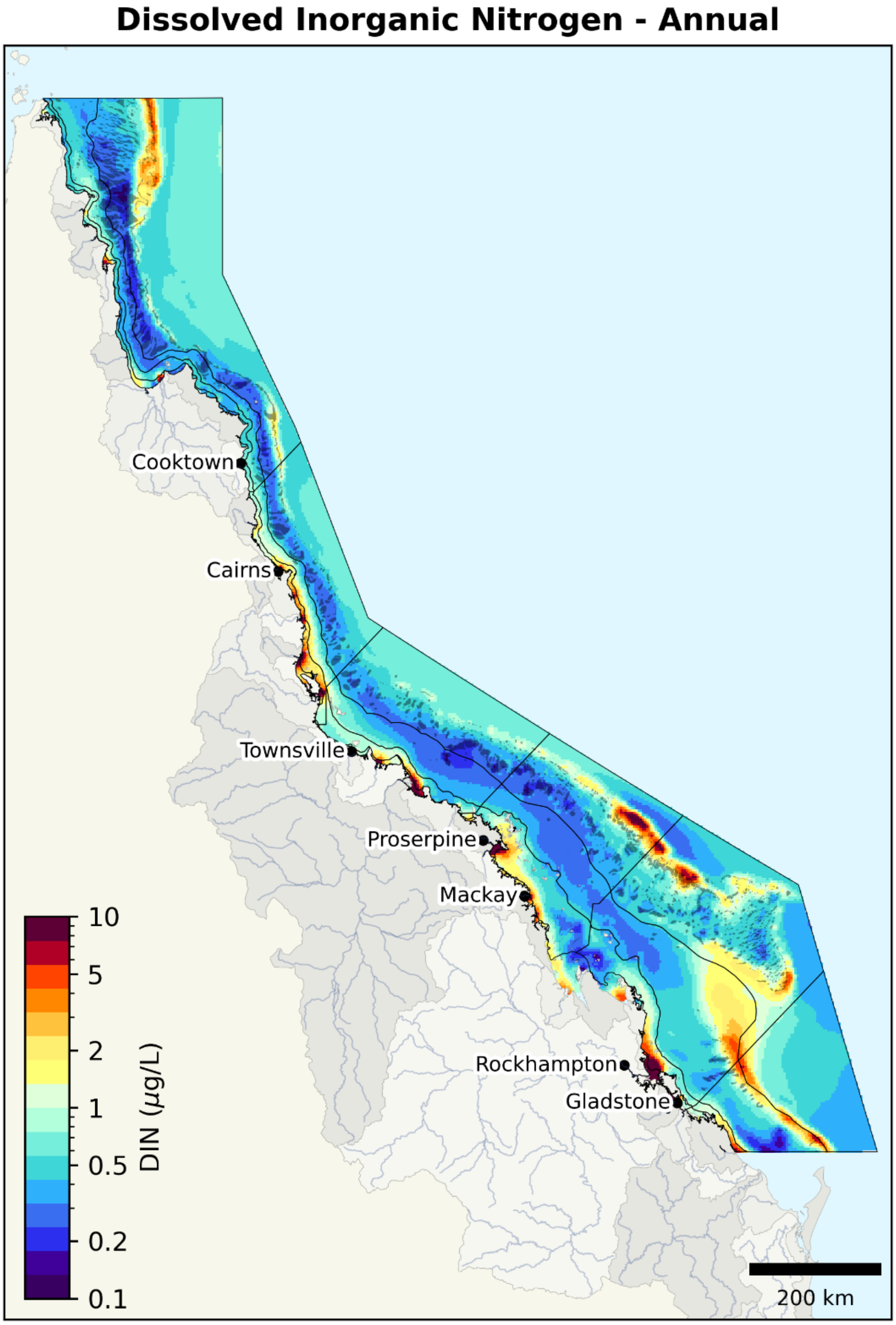
Trichodesmium blooms (and their associated stores of nitrogen and phosphorus) aggregate at the surface where they form striking spatial patterns such as windrows and eddy swirls. Blooms may be visible at spatial scales ranging from a few square kilometres to tens of thousands of square kilometres (Blondeau-Patissier et al., 2018; McKinna et al., 2011). Surface aggregations of *Trichodesmium* occur mainly during periods of low wind strength and intermediate to high sea surface temperature (Blondeau-Patissier et al., 2018; Muslim & Jones, 2003). Concentrations are typically highest in the Wet Tropics and Fitzroy regions (Blondeau-Patissier et al., 2009; 2018). *Trichodesmium* blooms are associated with higher PN concentrations (Fabricius, 2000) and nitrogen fixation by *Trichodesmium* is likely to be a significant source of nitrogen to offshore surface waters, possibly of equal or greater magnitude than the contribution of terrestrial nitrogen loads to the inshore GBR (Ani et al., 2023; Bell et al., 1999). Quantifications of this nitrogen source have so far been speculative, relying on satellite observations or process models with broad assumptions and very limited direct observational data (Ani et al., 2023).

Seasonal coastal upwelling and intrusions due to offshore eddy currents associated with the East Australian Current (EAC) are also sources of both spatial and temporal variability in surface nutrient concentrations (Berkelmans et al., 2010; Brodie et al., 2007; Furnas & Mitchell, 1996; Ghosh et al., 2022; Liston et al., 1992; Middleton et al., 1994; Weeks et al., 2010; 2015). In the midshelf Fitzroy region, the Capricorn Eddy is a persistent feature off the Capricorn Bunker group of reefs (Weeks et al., 2010). The footprint of the EAC itself is also visible in Chl-*a* spatial patterns (Oke et al., 2015).

Although there is no regular offshore monitoring programme and *in situ* observational data in areas of upwelling are limited (Table 8), the eReefs marine models suggest that there is a persistent region of elevated NOx (Figure 10) and (to a slightly lesser extent) PO4 (referred to as DIP in the models, Figure 11) associated with the Capricorn Eddy and offshore Swain reefs in the offshore Fitzroy and Burdekin regions. Smaller areas of elevated dissolved inorganic nitrogen and phosphorus concentrations can be seen in the model output in the offshore Wet Tropics and Cape York regions (Figure 10 and Figure 11).

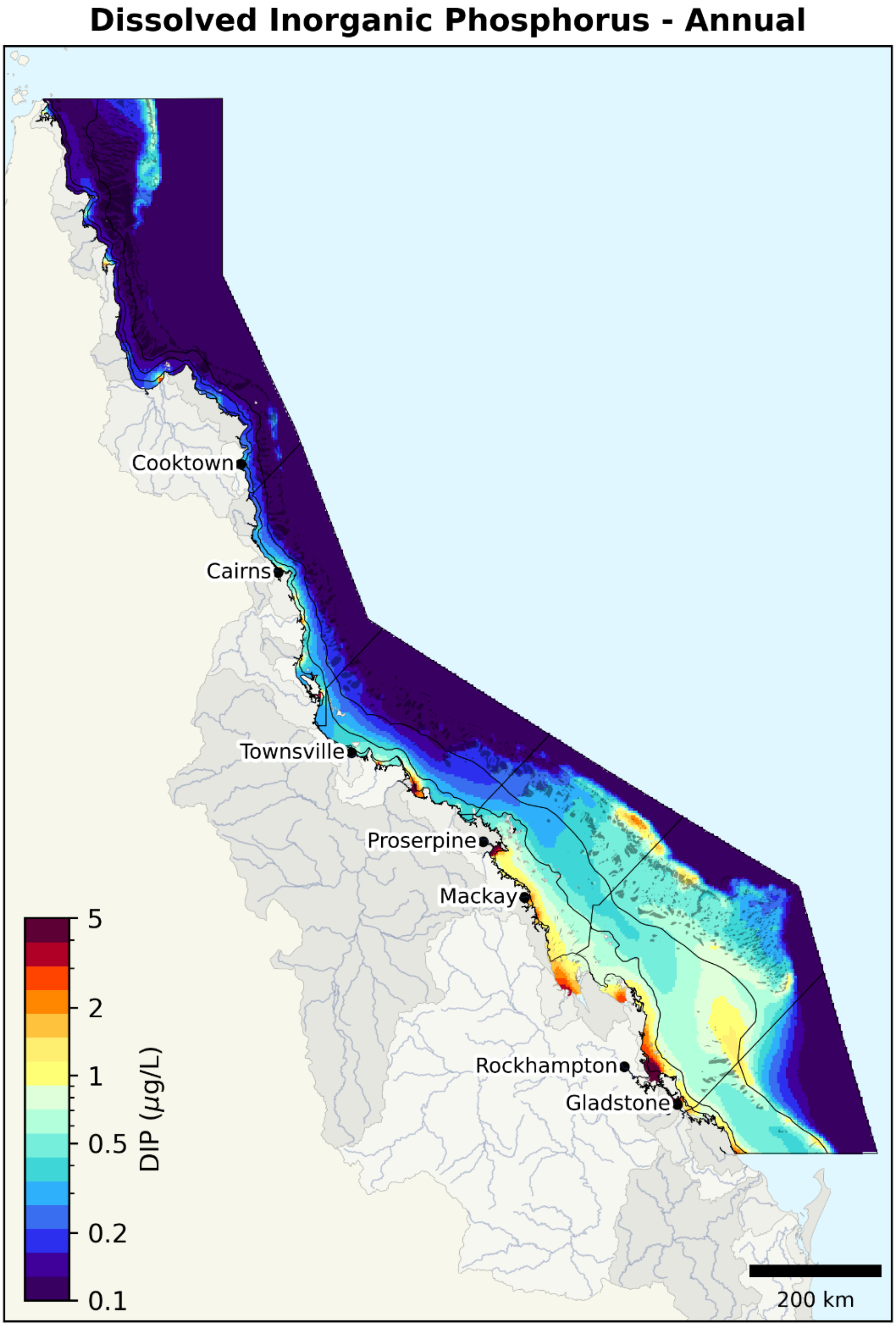
Although the accuracy of simulated concentrations of nutrients in offshore waters from these models has not been evaluated, evidence from other sources is generally consistent with the existence of areas of upwelling in at least some of the areas indicated by the models. De'ath and Fabricius (2010), for example, showed evidence of an area of elevated Chl-*a* in a region approximately corresponding to the offshore peak in dissolved inorganic nitrogen in the Fitzroy region in Figure 10.

Alongi et al. (2015) reported elevated concentrations of PO4 and NO3 at the shelf break in the Mackay Whitsunday region consistent with a tongue of upwelled water below 80 m but did not find evidence of upwelling at the surface at the time of sampling.



Data: GBR4_H2p0_B3p1_Cq3b_Dhnd, Variable: DIN, Aggregation: mean
Depth: 3 m, Time range: Jan 2011 - Dec 2018, Produced by: Eric Lawrey (AIMS) 10 Aug 2023

Figure 10. Long-term (2011-2019) spatial mean distribution of Dissolved Inorganic Nitrogen (NOx + NH4) in the GBR predicted by the eReefs marine models (biogeochemical model v 3.1) (AIMS, 2022; Skerratt et al., 2019). Black lines indicate the boundaries of the regions and waterbodies as shown in Figure 4.



Dissolved Inorganic Phosphorus - Annual

Data: GBR4_H2p0_B3p1_Cq3b_Dhnd, Variable: DIP, Aggregation: mean
Depth: 3 m, Time range: Jan 2011 - Dec 2018, Produced by: Eric Lawrey (AIMS) 10 Aug 2023

Figure 11. Long-term (2011-2019) spatial mean distribution of Dissolved Inorganic Phosphorus (equivalent in the model to PO4) in the GBR predicted by the eReefs marine models (biogeochemical model v 3.1) (AIMS, 2022; Skerratt et al., 2019). Black lines indicate the boundaries of the regions and waterbodies as shown in Figure 4.

Sampling to assess variability at the small spatial scale of individual reefs in the Wet Tropics and Burdekin regions, Carreira et al. (2020) found that Chl-*a*, NOx and PO4 concentrations were all highly heterogeneous at this scale, with a coefficient of variability up to 76% for Chl-*a* but no clear spatial patterns.

Latitudinal spatial patterns

In inshore Cape York waters, flood plume DIN and PO4 concentrations are generally lower in the Cape York region than in the Wet Tropics or Burdekin regions of the central GBR (Figure 8 and Figure 9). PP is also present in much higher concentrations in Burdekin and Mackay Whitsunday flood plumes than in flood plume waters in Cape York or the Wet Tropics (Figure 9; Moran et al., 2022).

Ambient inshore nutrient concentrations show no consistent north-south gradient in the most recent MMP Water Quality observations (Table 11).

Some studies have suggested that offshore nutrient concentrations may be lower in the Cape York region than in the Wet Tropics, and lower in the Wet Tropics than in the Mackay Whitsunday or Fitzroy regions. Fabricius and De'Ath (2004) reported PN 170% higher in water around Wet Tropics reefs than around reefs in Princess Charlotte Bay (Cape York region) and Crosbie and Furnas (2001) reported that Chl-*a* is generally higher in the Mackay Whitsunday region than the Wet Tropics, particularly offshore (median 1.0 µg L^{-1} in the offshore Mackay Whitsunday and 0.2 µg L^{-1} in the Wet Tropics). This is generally consistent with the predictions of process models (e.g., Figure 10 and Figure 11), though these models do suggest a possible area of elevated offshore DIN in the northern part of the offshore Cape York region. Table 10, however, suggests that we do not have enough *in situ* data to conclusively report the existence of any consistent latitudinal trend in either midshelf or offshore nutrient concentrations.

Silica (as SiO4) is monitored and reported in inshore waters through the MMP Water Quality but is not included as a water quality indicator and therefore not analysed or discussed in any detail in the annual reports. Elevated concentrations (not considered problematic for silicate) are found at each river mouth monitoring site, with the highest local median value in 2020-21 at the Cape York region “Pascoe River Mouth South” site reported as approximately 3,690 µg L^{-1}, from 5 samples (Moran et al., 2022). High SiO4 concentrations are also reported for river mouth sites in the Wet Tropics (median 575 µg L^{-1} at the Russell Mulgrave Mouth Mooring and 615 µg L^{-1} at the Tully River Mouth Mooring, with lower values (still elevated relative to marine SiO4 concentrations) at river mouths further south: 263 µg L^{-1} at the Burdekin River Mouth Mooring, 227 µg L^{-1} at the O’Connell River Mouth Mooring, and 139 µg L^{-1} at the Fitzroy River Mouth in 2020-21 (Moran et al., 2022). Concentrations drop rapidly with distance from river mouths (Howley et al., 2018; Moran et al., 2022), with the lowest reported inshore monitoring site median for 2020-21 approximately 33.5 µg L^{-1} at the “Keppels South” site in the Fitzroy region (Moran et al., 2022). Similar low SiO4 concentrations are reported in the Keppels by Messer et al. (2017), however a study at Heron Island Reef in the midshelf Fitzroy region (Watson et al., 2017) found a substantial (unexplained) peak (around 3,000 µg L^{-1}) in SiO4 in July, contrasting with low concentrations at other times of the year.

Other studies reporting SiO4 concentrations have generally reported values consistent with MMP Water Quality data at inshore locations (Wolanski et al., 2008), though Fabricius et al. (2005) reported lower SiO4 concentrations (between 10 and 30 µg L^{-1}) at coastal sites from the Burdekin, Wet Tropics and Cape York regions during 9 visits between 2000 and 2002 and somewhat lower (around 122 µg L^{-1}) concentrations have also been reported in Princess Charlotte Bay in the Cape York region (Fabricius & De'ath, 2004).

Temporal trends, patterns and variability in the distribution of nutrients

Long-term temporal trends

Annual MMP Water Quality reports give detailed monitoring results, graphical trends and 95% confidence intervals for Chl-*a*, NOx, PO4, PN and PP in each focus region, and compare these with established guideline values. Summary statistics, including mean, median, 5th, 20th, 80th and 95th quantiles are provided for all variables including DIN, DON, DOP, Chl-*a*, NOx, PN, PO4, PP and SiO4 , as well as physical variables and suspended sediment concentrations (Moran et al., 2022).

For inshore nutrient trends, the MMP Water Quality provides detailed statistical (seasonally-corrected GAMM) analyses from which long-term (2004-2021) trends can be determined. The statistical method used for long-term trend analysis is designed to be robust to the 2015 changes in program design (which increased the frequency of sampling as well as the number of sites sampled within each region). As an additional check, analyses of trends in water quality indicators included in the annual MMP reports are also repeated using only sampling locations and frequency consistent with the original study design. Moran et al. (2022) analysed inshore nutrient monitoring data from 2005-2022 and reported the following trends:

In the Wet Tropics reporting region:

- A clear increase in NOx in the Barron-Daintree focus region since the start of monitoring.
- An increase in both NOx and PN (and hence TN) in the Russell-Mulgrave focus region from 2005-2015, with signs of a reduction in PO4 since 2017. No clear trend in PP.
- An increase in NOx and PN (and hence TN) in the Tully focus region, with signs of a reduction in PO4 since 2017. No clear trend in PP.

In the Burdekin region:

- A gradual increase in NOx since 2005 and signs of a reduction in PO4 since 2017. No clear trends in PN or PP.

In the Mackay Whitsunday region:

- A steady increase in NOx since 2005, but a steady decline in PO4 and signs of a decline in Chl-*a* since 2017. No clear trends in PN or PP.

In most regions, NOx accounts for around 2% of TN and PO4 accounts for <30% of TP, so a change in dissolved inorganic nutrient concentrations, though biologically significant (see Question 4.2, Diaz-Pulido et al., this SCS), does not necessarily imply a change in TN or TP. While the MMP Water Quality reports do not report trends in other measured constituents, the MMP data have been published, allowing the same methods to be applied. From this analysis and from pre-2005 data that has been reported for the Barron-Daintree focus region at monitoring sites also known as the “Cairns Transect” (Schaffelke et al., 2012), the following can be reported:

- An increase in DON in the Barron-Daintree focus region (these monitoring sites are also known as the “Cairns Transect”) from around 68 $\mu g\ L^{-1}$ in 1989 to a peak of around 113 $\mu g\ L^{-1}$ in 2013, and a subsequent decline to 53 $\mu g\ L^{-1}$ by 2022.
- An increase in DOP in the Barron-Daintree focus region since 1989, from 1.1 to 5.5 $\mu g\ L^{-1}$.
- An increase in DON in the Russell-Mulgrave focus region since 2005, levelling off since 2017. No clear trends in DON in other focus regions.
- No clear trends in DOP or SiO4 in any region.
- A decline in TP in the Mackay Whitsunday region and the Johnstone Russell-Mulgrave focus region since 2012.
- An increase in TN in the Russell-Mulgrave focus region between 2005 and 2015, levelling off since 2016. Similar trends in TN in the Burdekin region.

Monitored nutrient constituents and regions not mentioned above show no clear long-term trends over the 2004-2021 period of monitoring. MMP Water Quality monitoring in the Cape York and Fitzroy regions has not yet been run for a sufficient continuous period to allow long-term trends to be confidently assessed (Moran et al., 2022), while the Burnett Mary region is not included in the MMP Water Quality and has no equivalent long-term monitoring program.

Table 11 provides mean ambient inshore concentrations of each nutrient species monitored as part of the MMP in each region in 2022, 2015 (the year in which a revised sampling design was implemented) and 2004 (the start of the monitoring program), in addition to Chl-*a* results. The trends mentioned above have been highlighted – note that the comments above are derived from the full trend time-series, not just the three years shown in the table and may not be obvious from the three years shown in some instances.

*Table 11. Estimated mean ambient inshore concentrations (in $\mu g\ L^{-1}$) of nutrients and Chl-a from MMP long-term monitoring, with 95% confidence intervals. Event concentrations (i.e., concentrations from samples taken when flood-plumes from rainfall events are present) are excluded from this analysis to facilitate the detection of long-term trends, following the statistical method described by Moran et al. (2022) for trend analysis. Note that this will obscure latitudinal variations that are evident mostly when flood plumes are present. Focus regions in parentheses are part of the Wet Tropics NRM region. Results are shown for 2022, 2015 (the first year of the new sample design) and 2005 (the first full year of MMP monitoring). * denotes focus regions where there has been a long-term increase in concentrations over the duration of the MMP. ** denotes focus regions where there has been a clear long-term decrease. Where the estimates are unreliable for 2005 due to a steeply sloping GAMM trend at the start of the monitoring record, these estimates have been omitted.*

	Focus Region	2022	95% CI	2015	95% CI	2005	95% CI
TN	(Barron Daintree)	87.03	(76.31-99.26)	99.73	(93.07-106.86)	85.46	(71.04-102.80)
	(Russell Mulgrave)*	102.50	(92.24-113.90)	108.50	(102.26-115.12)	78.18	(59.95-101.95)
	(Tully Herbert)*	107.09	(93.94-122.07)	113.92	(103.49-125.41)	56.18	(15.80-199.83)
	Burdekin	93.79	(81.79-107.55)	104.60	(94.24-116.10)	72.91	(56.82-93.57)
	Mackay Whitsunday	99.52	(85.65-115.63)	105.96	(94.19-119.21)	100.19	(74.67-134.42)
	Fitzroy*	126.92	(111.87-143.99)	101.17	(84.55-121.06)	87.67	(71.89-106.92)
NOx	(Barron Daintree)*	2.06	(1.19-3.56)	0.96	(0.76-1.22)	0.47	(0.22-1.00)
	(Russell Mulgrave)*	5.43	(2.78-10.58)	2.41	(1.47-3.97)	0.79	(0.17-3.75)
	(Tully Herbert)*	1.87	(0.81-4.35)	2.87	(1.51-5.45)	1.25	(0.00-3724.14)
	Burdekin*	3.90	(2.03-7.50)	1.39	(0.94-2.06)	0.36	(0.09-1.47)
	Mackay Whitsunday*	3.24	(1.67-6.29)	3.22	(2.15-4.82)	0.89	(0.18-4.36)
	Fitzroy	2.02	(0.96-4.24)	2.79	(0.97-7.98)		
NH4	(Barron Daintree)	4.41	(2.52-7.71)	4.43	(3.31-5.93)	1.05	(0.51-2.16)
	(Russell Mulgrave)	3.50	(2.22-5.52)	4.62	(3.57-5.98)	2.57	(0.95-6.92)
	(Tully Herbert)	2.73	(1.88-3.97)	5.08	(3.87-6.67)		
	Burdekin	2.72	(1.55-4.78)	3.64	(2.72-4.88)	2.42	(0.82-7.13)
	Mackay Whitsunday*	4.04	(2.53-6.45)	4.48	(3.42-5.88)	1.85	(0.61-5.60)
	Fitzroy	6.46	(5.15-8.11)	6.81	(4.49-10.31)		
PN	(Barron Daintree)	13.05	(10.97-15.53)	13.76	(11.88-15.94)	15.29	(12.47-18.74)
	(Russell Mulgrave)*	12.73	(10.66-15.19)	16.44	(14.46-18.69)	11.75	(7.93-17.41)
	(Tully Herbert)*	15.10	(12.31-18.52)	20.17	(16.97-23.97)	22.25	(4.58-108.05)
	Burdekin	12.64	(9.54-16.76)	15.25	(11.87-19.61)	14.85	(9.80-22.51)
	Mackay Whitsunday	13.39	(10.72-16.72)	17.32	(14.44-20.78)	13.35	(8.78-20.30)
	Fitzroy	16.56	(12.30-22.28)	14.28	(10.01-20.37)	14.64	(10.03-21.38)
DON	(Barron Daintree)	62.55	(53.10-73.68)	77.00	(70.68-83.88)	66.51	(53.02-83.41)
	(Russell Mulgrave)*	79.03	(68.59-91.07)	79.90	(73.59-86.75)	57.19	(39.63-82.54)
	(Tully Herbert)	84.32	(73.82-96.31)	82.67	(76.52-89.32)	25.87	(6.08-109.98)
	Burdekin	75.52	(65.48-87.10)	83.24	(76.09-91.07)	53.37	(40.18-70.88)
	Mackay Whitsunday	81.99	(69.17-97.19)	83.02	(73.61-93.64)	79.01	(56.07-111.34)
	Fitzroy	105.89	(96.31-116.43)	70.67	(59.00-84.64)	71.55	(58.76-87.13)
TP	(Barron Daintree)	9.96	(8.57-11.59)	11.37	(10.22-12.65)		
	(Russell Mulgrave)**	9.49	(8.23-10.94)	10.83	(9.68-12.12)		
	(Tully Herbert)	10.93	(9.41-12.70)	11.40	(10.02-12.96)	5.89	(1.91-18.18)
	Burdekin	10.02	(8.14-12.35)	10.21	(8.69-12.00)		
	Mackay Whitsunday**	11.11	(9.25-13.34)	14.63	(12.50-17.12)		
	Fitzroy	12.22	(8.79-16.99)	10.38	(6.93-15.54)		

	Focus Region	2022	95% CI	2015	95% CI	2005	95% CI
PO4	(Barron Daintree)**	1.37	(1.07-1.75)	2.72	(2.40-3.09)	2.23	(1.58-3.16)
	(Russell Mulgrave)**	1.44	(1.14-1.82)	3.09	(2.64-3.60)	2.80	(1.64-4.79)
	(Tully Herbert)**	1.31	(0.91-1.87)	2.02	(1.61-2.54)		
	Burdekin**	1.39	(1.01-1.92)	2.32	(1.90-2.84)	3.03	(1.60-5.75)
	Mackay Whitsunday**	2.31	(1.59-3.35)	4.58	(3.45-6.08)	7.22	(3.42-15.24)
	Fitzroy	2.02	(1.08-3.77)	2.42	(1.10-5.35)		
PP	(Barron Daintree)	2.85	(2.06-3.94)	3.75	(2.82-4.97)	2.36	(1.62-3.43)
	(Russell Mulgrave)	2.38	(1.78-3.19)	2.85	(2.17-3.75)	2.21	(1.46-3.35)
	(Tully Herbert)	3.18	(2.41-4.19)	3.63	(2.83-4.67)	1.24	(0.22-6.99)
	Burdekin	2.49	(1.68-3.69)	2.88	(2.00-4.15)	3.05	(1.83-5.08)
	Mackay Whitsunday	2.83	(2.15-3.74)	4.20	(3.33-5.31)	2.97	(1.82-4.84)
	Fitzroy	3.59	(2.10-6.15)	3.29	(1.80-6.01)	2.70	(1.44-5.07)
DOP	(Barron Daintree)	5.51	(4.49-6.76)	4.79	(4.33-5.30)		
	(Russell Mulgrave)	5.35	(4.49-6.39)	5.04	(4.56-5.55)		
	(Tully Herbert)	6.26	(5.12-7.67)	5.56	(4.89-6.32)	4.40	(0.71-27.36)
	Burdekin	5.65	(4.43-7.19)	5.14	(4.53-5.84)		
	Mackay Whitsunday	5.95	(4.93-7.19)	5.86	(5.25-6.53)		
	Fitzroy	6.05	(5.19-7.04)	4.24	(3.11-5.79)		
SiO4	(Barron Daintree)	124.05	(87.62-175.61)	98.48	(76.18-127.31)	123.67	(80.23-190.64)
	(Russell Mulgrave)	174.16	(113.60-267.01)	123.73	(85.22-179.65)	230.37	(111.97-473.97)
	(Tully Herbert)	202.60	(116.63-351.94)	176.30	(108.37-286.82)	81.15	(1.71-3858.92)
	Burdekin	133.92	(80.33-223.25)	98.63	(63.24-153.81)	82.51	(37.54-181.34)
	Mackay Whitsunday	112.40	(69.62-181.47)	115.20	(76.08-174.42)	41.62	(18.86-91.83)
	Fitzroy	129.16	(78.66-212.07)	77.72	(38.43-157.19)		
Chl-*a*	(Barron Daintree)	0.33	(0.25-0.45)	0.54	(0.43-0.69)	0.46	(0.32-0.65)
	(Russell Mulgrave)**	0.30	(0.22-0.40)	0.47	(0.37-0.60)	0.41	(0.22-0.76)
	(Tully Herbert)**	0.36	(0.25-0.51)	0.53	(0.39-0.72)		
	Burdekin	0.33	(0.22-0.51)	0.47	(0.33-0.68)	0.71	(0.37-1.38)
	Mackay Whitsunday**	0.41	(0.31-0.55)	0.74	(0.59-0.92)	0.65	(0.39-1.09)
	Fitzroy	0.41	(0.26-0.63)	0.37	(0.21-0.67)		

Ocean colour observations suggest that the magnitude and extent of Chl-*a* peaks attributable to *Trichodesmium* blooms in the GBR have increased over the last two decades (Blondeau-Patissier et al., 2014a; 2018). There is some limited *in situ* observational support for this trend from *Trichodesmium* cell counts at the Yongala National Reference Station (Davies et al., 2018). A possible mechanism for this is climate change strengthening the East Australian Current and associated eddy and upwelling activity in midshelf and offshore waters, enhancing the marine supply of nutrients to the surface (Berkelmans et al., 2010; Weeks et al., 2010).

Although multi-decadal temporal trends are explicitly beyond the scope of this review, we will mention this briefly. Over longer (multi-decadal) timescales, modelling studies, theoretical analyses and some *in situ* observations show that it is very likely that nutrient concentrations in inshore waters have increased substantially (Baird et al., 2021a; Bell, 1991; Bell et al., 2014). Some authors have argued that this influence has extended further across the GBR (Bell et al., 2014), but this is not well supported with *in situ* evidence and has been disputed (Furnas et al., 2014). Past nutrient concentrations have not proven easy to reconstruct from coral geochemical records (Lewis et al., 2012). Mallela et al. (2013), however, presented coral core evidence from the inshore Wet Tropics region (Dunk Island) suggesting that phosphorus concentrations increased eightfold between 1949 and 2008. Erler et al. (2020) used coral core nitrogen isotope ratios to argue that coastal nitrogen fixation rates increased between 1680 and 2012, reflecting increased phosphorus loads.

Seasonal patterns

In estuaries, TN and TP are higher in the wet season than in the dry season (Murray et al., 2020). Some studies of GBR estuaries have found the same pattern in dissolved inorganic nutrients (Eyre & Balls, 1999), while others have found the converse (Murray et al., 2020) or no consistent seasonal pattern in inorganic nutrient concentrations, for example. Eyre (1993) found that DIN was higher in the Moresby River Estuary in the wet season, but that PO4 showed no seasonal signal. High river discharge in the wet season brings high concentrations of particulate materials and can flush inorganic nutrients from soils into rivers, but can also reduce dissolved nutrient concentrations by dilution.

Schaffelke et al. (2005) also reported a strong seasonal pattern in SiO4 concentrations, with higher concentrations at Fitzroy and Burdekin region sites in the wet season than the dry season, especially inshore.

In inshore waters, wet season river discharges and the associated flood plumes – discussed above – are the main source of seasonal variability in nitrogen and phosphorus concentrations. TN and TP are elevated during the wet season during flood events, and are hence more variable in the wet than dry season (McKinnon et al., 2013; Schaffelke et al., 2012; Uthicke & Altenrath, 2010). Outside flood plumes, seasonal variations in nitrogen and phosphorus concentrations are minimal, with wet season concentrations similar to those observed in the dry season (e.g., Lønborg et al., 2018; McKinnon et al., 2005; Moran et al., 2022). Results from three inshore sites in the Wet Tropics and Burdekin regions by Lønborg et al. (2018) are summarised briefly in Table 12. These are consistent with the range of values reported in the longer-term results from the MMP (Moran et al., 2022).

Table 12. Ambient seasonal nutrient concentrations reported by Lønborg et al. (2018) at three inshore sites in the Wet Tropics and Burdekin regions.

	Dry season concentration (µg L^{-1})	Wet season concentration (µg L^{-1})
Dissolved inorganic nitrogen	1.8 to 3.2	0.56 to 2.8
Dissolved inorganic phosphorus	1.9 to 3.1	1.2 to 3.1
Particulate nitrogen	11.8 to 23.7	17.4 to 34.0
Particulate phosphorus	1.9 to 3.7	1.9 to 5.9
Chlorophyll *a*	0.08 to 0.54	0.43 to 0.84

Chl-*a* shows a slightly different seasonal signal, peaking toward the end of the wet season (Ayukai, 1995; Brodie et al., 2005; Kuhnert et al., 2015; McKinnon et al., 2005; Schaffelke et al., 2012) or the beginning of the dry season (Skerratt et al., 2019; Thompson et al., 2014) at both inshore and midshelf sites, reflecting a combination of lingering elevated nitrogen and phosphorus concentrations from wet-season river discharge, greater light availability as particulate materials settle, and a seasonal increase in incident light. PO4 is also often higher in the dry season (Schaffelke et al., 2012).

Trichodesmium blooms are another source of seasonal variability in Chl-*a* concentrations and nitrogen stores across the GBR (Fabricius & Dommisse, 2000). While these have proven difficult to quantify, satellite evidence suggests that *Trichodesmium* blooms, though occurring all year around, peak in May in the northern GBR and in November in the southern GBR (Blondeau-Patissier et al., 2018).

In offshore waters, elevated nutrient concentrations associated with upwelling events are more frequent between October and April across the GBR (Berkelmans et al., 2010) and in both summer and winter in the Fitzroy region (Ghosh et al., 2022) than in autumn or spring.

Interannual variability

Cyclones and other storms are the primary driver of year-to-year variability (as opposed to long-term trends) in water quality in the GBR (Moran et al., 2022; Skerratt et al., 2019). Storms and associated rainfall increase: a) the delivery of nutrient-rich river water from catchments to the GBR, b) (in the case of cyclones) wind-driven resuspension of sediments and release of associated pore-water nutrients, and c) vertical mixing, which in deeper areas brings nutrients from bottom waters to the surface.

Annual MMP Water Quality reports (Moran et al., 2022; Waterhouse et al., 2021) compare each year's estimated flood plume extent with the typical extent in dry (low rainfall) years and the typical extent in wet (high rainfall) years, as shown in Figure 6. As a long-term average, approximately 44,000 km^2 (13%) of the GBRWHA is exposed to water likely to contain elevated concentrations of nutrients associated with flood plumes each year (Waterhouse et al., 2021), though this spatial "footprint" of flood plumes varies substantially between wet and dry years. It should be noted that these optical "footprints" include not only flood plumes, but also areas that are turbid due to resuspension and other processes. An estimate of the magnitude of this error is not available.

A recent analysis of modelled nutrient concentrations by Kroon et al. (2023) suggests that in midshelf Wet Tropics waters, oceanographic processes such as upwelling and intrusive events may be more important in this year-to-year variability than previously understood, though river discharges are still believed to be the dominant driver in inshore waters. Upwelling in the GBR has been found to be associated with warm summers and has been observed in some cases to precede coral bleaching events by a few weeks (Berkelmans et al., 2010).

River discharge varies substantially from year to year, particularly south of the Wet Tropics (Moran et al., 2022). In wet years such as the 2010-2011 water year (where "water year" is defined as the period from May of one year to the April of the following year), nutrient concentrations including Chl-*a* in inshore and midshelf waterbodies can be much higher than in dry years that have relatively little river discharge (Devlin et al., 2013; Moran et al., 2022; Thompson et al., 2014). In particularly wet years, the Burdekin flood plume has extended north to the Daintree and from the coast to midshelf and (in diluted form) occasionally to offshore waterbodies (Alvarez-Romero et al., 2013; Moran et al., 2022; Wolff et al., 2018).

Much of the variation in year-to-year storm activity and river discharge is driven by variations in the Southern Oscillation Index (SOI). Skerratt et al. (2019) reported that DIN is highest in the midshelf Burdekin region during La Niña (i.e., strongly positive SOI) years in both model and monitoring results. Higher Chl-*a* concentrations have also been reported in model results for La Niña years (Wooldridge & Brodie, 2015).

Benthuysen et al. (2016) reported data suggesting that intrusive upwelling events in the offshore central Great Barrier Reef may also be influenced by the SOI, with large intrusions more frequent in El Niño years (negative SOI).

Another possible source of temporal variability is atmospheric input of nutrients derived from dust storms and ash from bushfires. Shaw et al. (2008) presented evidence from ocean colour observations for an increase in Chl-*a* driven by a 2002 dust storm; however this was disputed by Mackie (2010). Furnas et al. (2011) asserted that, "as GBR weather primarily comes from offshore, most regional rainfall is unlikely to be significantly contaminated by terrestrial dust." We found no empirical measurements of atmospheric deposition of nutrients in GBR waters in the studies reviewed.

Short timescale variability

Elevated particulate nutrient concentrations are associated with resuspension of nutrient-rich muddy sediments deposited in inshore areas during previous flood events. Resuspension of nutrient-rich sediments occurs due to semi-diurnal tidal currents in coastal waters (Crosswell et al., 2020; Radke et al., 2010; Robson et al., 2008; Webster et al., 2006), and on a larger spatial scale due to wind mixing during storm events (Alongi et al., 2007). Concentrations of particulate materials including the associated nutrients at river mouth sites can vary by orders of magnitude over a tidal cycle (Robson et al., 2008).

Ayukai (1993) studied diurnal variations in nutrient concentrations at Davies Reef (midshelf Burdekin region), finding that DIN and PO4 concentrations were higher at night than during the day, while the converse was true for Chl-*a*, reflecting light-driven diurnal ecosystem metabolism processes.

McMahon and Santos (2017) studied variations in dissolved organic and dissolved inorganic nitrogen and phosphate in lagoon sites close to Heron Island. They found that, within a few hundred metres of the reef, NOx and PO4 dropped rapidly with distance from shore and varied strongly as a function of tidal height, reflecting groundwater nutrient inputs derived from guano on the island.

Most other sources do not report the time of day of samples, and diurnal variations are likely to be much smaller beyond the immediate vicinity of reefs and estuaries.

Mass coral spawning (which occurs on a few nights each wet season) represents a potentially significant transfer of organic nutrients from reefs into the water column, but the impact of this on nutrient concentrations appears to be short-lived (Glud et al., 2008).

Substantial variations in nutrient concentrations over short timescales can also be caused by the formation of *Trichodesmium* surface blooms (Shaw et al., 2008) or by offshore upwelling events over the scale of a few days (Brodie et al., 2007; Middleton et al., 1994).

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

At the time of the 2017 SCS, routine monitoring of inshore water quality through the MMP Water Quality had not yet been conducted for a long enough continuous period to show long-term trends, as the high inter-annual variability due to weather events makes it difficult to detect change without a long observational record and careful statistical analysis. Some trends have since become clear. The most recent MMP Water Quality report (Moran et al., 2022) and additional analysis of MMP Water Quality data (AIMS, 2022) and Cairns Transect data (Schaffelke et al., 2012), provide evidence in inshore waters of:

In the Wet Tropics region:

- A clear and substantial increase in NOx in the Barron-Daintree focus region since the start of monitoring.
- An increase in NOx and PN in the Russell-Mulgrave focus region (both levelling off since 2015), with signs of a reduction in PO4 in recent years.
- An increase in NOx and PN in the Tully focus region, with signs of a reduction in PO4 in recent years.
- An increase in DON in the Barron-Daintree focus region (these monitoring sites are also known as the "Cairns Transect") from around 68 µg L^{-1} in 1989 to a peak of around 113 µg L^{-1} in 2013, and a subsequent decline to 53 µg L^{-1} by 2022.
- An increase in DOP in the Barron-Daintree focus region since 1989, from 1.1 to 5.5 µg L^{-1}.
- An increase in DON in the Russell-Mulgrave focus region since 2005, levelling off since 2017.
- A decline in TP in the Russell-Mulgrave focus region since 2012.
- An increase in TN in the Russell-Mulgrave focus region between 2005 and 2015, levelling off since 2016.
- A decline in Chl-*a* in the Russell-Mulgrave and Tully-Herbert focus regions.

In the Burdekin region:

- A gradual increase in NOx since 2005 and signs of recent improvement in PO4.
- An increase in TN between 2005 and 2015, levelling off since 2016.

In the Mackay Whitsunday region:

- A steady increase in NOx since 2005, accompanied by a steady decline in PO4 and signs of a decline in Chl-*a* in the most recent years.
- A decline in TP since 2012.

There is not yet enough contiguous long-term monitoring data to assess temporal trends in the Cape York, Fitzroy or Burnett Mary regions.

A recent analysis (Kroon et al., 2023) suggests that in midshelf Wet Tropics waters, oceanographic processes such as upwelling and intrusive events may be more important in driving year-to-year variability than previously understood, though river discharges are still believed to be the dominant driver in inshore waters.

4.1.3 Key conclusions

- TN, TP, DIN, DIP and SiO4 concentrations follow a cross-shelf gradient from higher values in estuaries and mangrove creeks and inshore waters to lower values offshore.
- Concentrations are elevated in flood plumes and in areas of sediment resuspension.
- Inshore dissolved inorganic nutrient concentrations are typically higher in the central and southern GBR (approximately from Cooktown to Gladstone), particularly within the flood plumes of large rivers such as the Burdekin and Fitzroy Rivers, and are lower in the northern GBR (Cape York region).
- Silicate concentrations follow similar spatial patterns but are less well studied. Little observational data are available for other nutrients, including iron.
- Dissolved inorganic nutrient concentrations and concentrations of particulate organic nutrients associated in soils and sediments are elevated in flood plumes.
- Particulate nutrients deposited to coastal sediments are a subsequent source of dissolved nutrients due to remineralisation and resuspension.
- In inshore waters, nutrient concentrations show a clear seasonal signal, mostly due to the influence of flood plumes in the wet season. Outside flood plumes, ambient nutrient concentrations do not show strong seasonal variations. Inshore nutrient concentrations also vary on short timescales due to tidal fluctuations and diurnal fluctuations in photosynthetic activity.
- In inshore waters and occasionally in midshelf waters, nutrient concentrations vary from year to year and are elevated in years of high river discharge and storm activity, (typically La Niña years).
- Offshore and midshelf variations in nutrient concentrations in surface waters are often associated with intrusive upwelling events and *Trichodesmium* blooms. There is some evidence that these are more common in La Niña years.
- There have been clear temporal trends in inshore nutrient concentrations collected through the Marine Monitoring Program since 2005. Nitrite plus nitrate concentrations have increased in all monitored inshore regions, which includes the Wet Tropics, Burdekin and Mackay Whitsunday Natural Resource Management regions, and particulate nitrogen has increased in the Wet Tropics Region. In some regions, there has been a reduction in phosphate since 2017, and in the Mackay Whitsunday region, there has been a reduction in Chl-*a*.

4.1.4 Significance of findings for policy, management and practice

The identified long-term increase (2005-2022) in ambient NOx in the inshore Wet Tropics, Burdekin and Mackay Whitsunday regions suggests that management interventions have not yet been effective in reducing marine impacts of catchment nitrogen loads. PO4 concentrations, by contrast, have declined in these regions and there are signs that TP is also declining.

The lack of well-quantified N and P budgets for the GBR means that we cannot be confident that catchment nutrient efforts will measurably change water quality in the GBR beyond the inshore footprint of flood plumes.

There is not yet enough data to assess temporal trends in the Cape York, Fitzroy or Burnett Mary NRM regions, suggesting a need for ongoing monitoring in these regions. Monitoring has recently begun in the Cape York region and was re-commenced in 2019 in the Fitzroy region.

This review has identified several key knowledge gaps for further research, documented in Section 4.5 (Knowledge gaps).

4.1.5 Uncertainties and/or limitations of the evidence

- Marine sources of variability in nutrient concentrations in the GBR, including upwelling and nitrogen fixation, have not been well characterised. Direct observational evidence of midshelf and offshore nutrient concentrations and variability is sparse, so most evidence comes from remote sensing and models, which have not been evaluated against offshore observational data. There is some evidence that these are changing with climate change, but this is not well understood.

- While dissolved and particulate nitrogen and phosphorus are measured and reported, their chemistry and bioavailability – especially the chemistry and bioavailability of organic nitrogen and phosphorus – in the GBR has not been well characterised, apart from a few small studies that focus on small areas.
- This review focuses primarily on nitrogen and phosphorus. Few studies address the spatial and temporal distribution of other nutrients such as silicate and iron, which may also be important. Carbon is also omitted, though it is the primary currency of ecosystem productivity and plays a key role in nitrogen and phosphorus cycles.

4.2 Contextual variables influencing outcomes

Table 13. Summary of contextual variables for Questions 4.1 and 4.1.1.

Contextual variables	Influence on question outcome or relationships
Climate change	Climate change is expected to drive changes in catchment hydrology, ground cover and land management, which will have flow-on implications for catchment nutrient loads to the GBR and hence, inshore nutrient concentrations. These catchment-based changes are beyond the scope of this review, but are covered in Question 4.4 (Prosser & Wilkinson, this SCS). The magnitude and extent of Chl-*a* peaks attributable to *Trichodesmium* blooms in the GBR have increased over the last two decades (Blondeau-Patissier et al., 2014a; 2018). A possible mechanism for this is climate change strengthening the East Australian Current and associated eddy and upwelling activity at the shelf edge, enhancing the marine supply of nutrients to the surface (Berkelmans et al., 2010; Weeks et al., 2010). Climate change also affects biogeochemical process rates and biological community structures in various ways, which may have unpredictable flow-on effects for nutrient concentrations. Evidence relating to climate change impacts on water quality is reviewed in detail in Question 2.2 (Fabricius et al., this SCS).
Climate variability (e.g., El Niño-Southern Oscillation, ENSO)	Nutrient concentrations in inshore and midshelf waters are higher in years of high river discharge and high storm activity, and hence typically higher in La Niña years (i.e., strongly positive SOI years) (Skerratt et al., 2019). Models suggest that higher Chl-*a* concentrations are also expected in La Niña years (Wooldridge & Brodie, 2015).
Episodic events	Nutrient concentrations are elevated in flood plumes. The spatial extent of flood plumes from each river varies depending on the size of the episodic flow event and meteorological conditions (Baird et al., 2021b; Wolff et al., 2018). It is possible that dust storms and bushfires provide an atmospheric source of nutrients and that this results in a temporary increase in Chl-*a* concentrations (Shaw et al., 2008). This evidence is disputed (Mackie, 2010).
Catchment management and land use change	Development of agricultural land has increased nutrient loads from rivers and this in turn has increased nutrient concentrations in the GBR, particularly the inshore GBR (Baird et al., 2021a; McCloskey et al., 2021a, 2021b). The evidence for this comes mostly from catchment process studies and modelling studies of the marine impacts of these changes. While the magnitude of the expected marine response to catchment changes have been disputed, the direction of change is generally agreed (Ridd et al., 2013). Attempts to reconstruct pre-

Contextual variables	Influence on question outcome or relationships
	monitoring marine nutrient concentration trajectories from coral cores have proven difficult (Erler et al., 2016), but the physical and conceptual basis is clear. Long-term trends in inshore water quality monitoring data (post 2005) have only recently emerged (Moran et al., 2022), and an analysis to relate the observed trends to changes recent in catchment management or land use would be timely.

4.3 Evidence appraisal

Relevance

The relevance of the overall body of evidence to the question was evaluated as Moderate due to the inclusion of many studies that were not designed to address this specific question but that contained some incidentally relevant data (nutrient concentrations at particular study sites). The temporal relevance of the overall body of evidence was also assessed as Moderate. Note that a higher overall relevance rating would have been achieved had the number of studies included been limited, but at a cost of excluding some relevant information from studies not specifically focused on this question. Combining spatial, temporal and methodological relevance to the question, the relevance of the overall body of evidence was rated Moderate.

In total, 79 of the sources considered were assessed as either “very relevant” or “moderately relevant” to the question. Thirty-six studies were assessed as “very relevant” to the spatial aspect of the question, 33 studies were assessed as “moderately relevant”, and 37 had low relevance. The temporal aspect of the question was less extensively studied, with 23 “very relevant” studies, 39 “moderately relevant” studies, 9 with “low relevance”, and the remainder not addressing temporal variations.

Consistency, Quantity and Diversity

In total, 106 studies were used as evidence for this question. Based on the authors’ professional judgement this is considered to be a high total number of studies forming the pool of available evidence. Many of these included nutrient observations as an incidental part of a study focused on something else (e.g., Fabricius et al., 2010), rather than being designed to address the question of spatial and temporal distributions and variations in nutrients in the GBR. These were included as additional points of evidence, and complemented more nutrient-focused studies such as the Marine Monitoring Program Inshore Water Quality reports (Moran et al., 2022; Waterhouse et al., 2021). Half (58 studies) contained nutrient data derived from *in situ* sampling. Seventeen studies contained data from satellite ocean colour observations, 12 from process-based models, and 3 from other technologies (aerial photography, autonomous underwater vehicle (glider) data or statistical models). Twenty studies provided no new nutrient data but were included for their additional analysis or review of data presented in other studies (Table 7).

In this Evidence Summary, 58 of the 106 studies included reported original *in situ* nutrient observations and many of the remaining studies compared satellite or model data with these *in situ* data (Table 7). There is moderate agreement between *in situ* and satellite Chl-*a* observations in offshore waters, but poor agreement in optically-complex inshore waters (Robillot et al., 2018). In this review, remote sensing Chl-*a* estimates were used only to assess the qualitative direction of change. Satellite ocean colour data has also been used to assess the spatial footprint of flood plumes, for which it is more reliable.

The most widely used process models for the GBR are those that comprise the eReefs hydrodynamic-biogeochemical model suite. These have been extensively evaluated against inshore MMP Water Quality results where they generally provide reasonable agreement, with some caveats (Skerratt et al., 2019). Modelled nutrient concentrations have not been evaluated in detail for midshelf or offshore waters due to the lack of a regular monitoring program for these waterbodies.

Barring methodological errors, contamination, or sample storage problems, *in situ* samples provide high confidence regarding accuracy with respect to nutrient concentrations at the reported time and location, but provide limited spatial or temporal coverage relative to the scale of the whole GBR and are rarely sufficient to capture the scale of spatial heterogeneity or temporal variations (Jones et al., 2016; Kuhnert et al., 2015).

Beyond the MMP Water Quality, regular observational data can be derived from ocean colour satellite observations, which (from June 2002 onwards) provide estimates of Chl-*a* in the optical surface layer (Furnas & Carpenter, 2016; Jones et al., 2016) as well as the spatial extent of flood plumes (Alvarez-Romero et al., 2013; Brodie et al., 2007; 2012; Devlin et al., 2013; 2015; Devlin & Schaffelke, 2009; Petus et al., 2014), and from process models such as the eReefs marine models, which can provide daily three-dimensional (3D) estimates of TN, TP, Chl-*a*, DON, DOP, NH4, PO4, labile and refractory organic N and P and several other nutrient constituents over the whole GBR from December 2010 to the present. Model predictions have been calibrated and evaluated against MMP Water Quality data and IMOS *in situ* monitoring data (Skerratt et al., 2019), but simulated offshore nutrient concentrations have not been systematically evaluated against *in situ* observations and so should be considered speculative. Chl-*a* from a data assimilating version of the eReefs models, which ingests ocean colour observation data for greater accuracy (Jones et al., 2016), is used for production of the GBR Report Cards (Australian & Queensland Government, 2022; Robillot et al., 2018) and Outlook Reports (GBRMPA, 2019). Both satellite and model data sources are subject to known inaccuracies but when used with caution in combination with sparse *in situ* observational data, are often the most comprehensive available information regarding nitrogen and phosphorus distributions (Skerratt et al., 2019).

Satellite observations provide estimated Chl-*a* concentrations in the optical surface layer and can be used to map the spatial and temporal extent of flood plumes that carry nutrient-rich water from rivers (Alvarez-Romero et al., 2013; Devlin et al., 2012), while some process models provide estimates of nitrogen and phosphorus in a variety of chemical forms in three dimensions (Skerratt et al., 2019). Satellite Chl-*a* estimates are less accurate than process model outputs in optically complex inshore waters (Robillot et al., 2018) but are probably more accurate than process models offshore. Both these more spatially and temporally extensive data sources require validation against *in situ* observations.

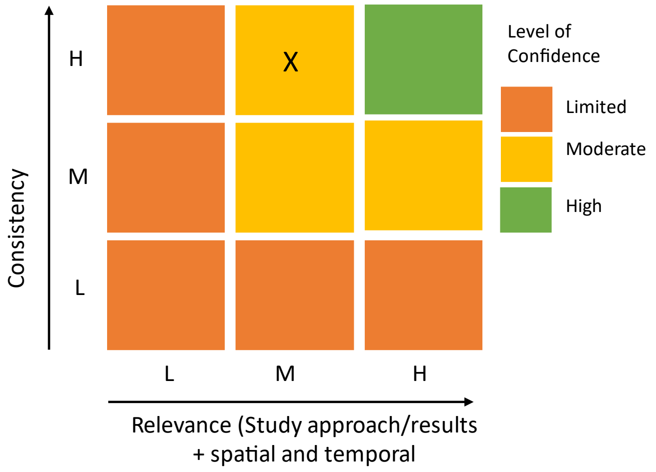
The temporal extents of these three data sources are comparable. While individual studies provide sporadic nutrient observations as far back as the 1980s (Alongi, 1990; Bell, 1991), routine satellite ocean colour observations of the GBR have been available since mid-2002 (Blondeau-Patissier et al., 2014a), routine monitoring of inshore water quality has been conducted since 2004 (Moran et al., 2022) and operational water quality process models for the GBR are available from 2010 onwards (Baird et al., 2021a).

The overwhelming majority of studies focused on inshore and/or midshelf waters (Table 8), with relatively few including estuary or offshore nutrient concentrations. Of those that did cover offshore locations, the majority were satellite or process model studies. The remainder were local studies that provided only sparse *in situ* nutrient observations.

Confidence

Overall, we have a Moderate level of confidence in the body of evidence. There is a High number of studies with at least some relevance. These studies are diverse in their approaches, data sources and authorship. While different studies address different aspects of the question, taken together they provide a consistent picture of the spatial and temporal variability of nutrients in the GBR.

Table 14. Summary of results for the evidence appraisal of the whole body of evidence in Questions 4.1 and 4.1.1. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency.

Indicator	Rating	Overall measure of Confidence
Relevance (overall)	Moderate	
-To the Question	Moderate	
-Spatial	Moderate	
-Temporal	Moderate	
Consistency	High	
Quantity	High (106 items)	
Diversity	High (55% original *in situ* data, 8% reviews, 37% either new analyses of existing data, modelling studies, or remote sensing)	

4.4 Indigenous engagement/participation within the body of evidence

A low degree of Indigenous engagement or direct participation has been reported. Only Howley et al. (2017) and recent Marine Monitoring Program reports (Moran et al., 2022; Waterhouse et al., 2021) prominently acknowledged Traditional Owner involvement.

4.5 Knowledge gaps

Table 15. Summary of knowledge gaps for Question 4.1 (and secondary Question 4.1.1).

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
Quantification of nutrients in *Trichodesmium* blooms.	How much nitrogen is missed in nitrogen budgets as a result of not monitoring *Trichodesmium* and avoiding surface blooms during routine sampling? How can *Trichodesmium* nutrient stores across the GBR be accurately quantified?	If this is a significant component of the nitrogen budget, improved management of phosphorus and iron generation from catchments could help to reduce nitrogen fixation and hence reduce nitrogen concentrations.
Atmospheric contributions to nutrient supply, e.g., from dust storms and bushfires.	Does iron limit nitrogen fixation in the outer GBR?	Improved management of dust storms, erosion and bushfires could reduce marine nitrogen fixation and hence provide an additional means

	What is the spatial and temporal distribution of nutrients from atmospheric sources in the GBR?	to reduce nitrogen loads to the GBR.
Long-term temporal changes in sediment nutrient stores	Are concentrations of nitrogen and phosphorus in inshore sediments changing over time and if so, at what rate? Do benthic sediment nutrient stores delay the impact of changes in land use or land management, and if so, over what time frame?	A better understanding of the time scale over which inshore and midshelf nutrient concentrations can be expected to respond to changes in land use and land management.
Better understanding of spatial and temporal patterns in marine sources of nutrients (e.g., upwelling)	Where and when does upwelling control surface nitrogen and phosphorus supplies? How is this changing with climate change? How much nitrogen is removed through denitrification?	Better understanding of likely changes in water quality with climate change and catchment change.
While process models have been used to evaluate the expected impacts of land management improvements on coastal and marine nutrient concentrations, recently observed long-term (decadal) trends in nutrient concentrations have not yet rigorously examined in the context of recent changes in land management or other drivers of change.	To what extent are long-term and recent trends in inshore nutrient monitoring data attributable to changes in land management?	Improved targeting of land management activities.
Nutrient budgets for the GBR have not been updated since Furnas et al. (2011). These budgets highlighted large uncertainties in inputs and outputs and poor quantification of processes controlling N and P cycles.	To what extent are the conclusions of Furnas (2011) regarding the sources and sinks of nitrogen and phosphorus in the GBR modified by new evidence?	Improved prioritisation of management interventions.
Better understanding of the capacity of the system to buffer or ameliorate changes in catchment nutrient loads.	How much nitrogen is lost to denitrification? How much nitrogen and phosphorus are immobilised or buried in the benthic sediments? How much nitrogen and phosphorus leave the system via dispersal to the Coral Sea? How do all of these changes scale with catchment nutrient loads?	Better understanding of likely changes in water quality achievable through catchment change.
Limited *in situ* observational data in midshelf and offshore waterbodies.	How variable are nutrient concentrations in midshelf and offshore waterbodies?	Improved calibration and evaluation of process models that are used to inform management.

5. Evidence Statement

The synthesis of the evidence for **Question 4.1** was based on 106 studies undertaken in the Great Barrier Reef and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (55% original *in situ* data, 8% reviews, 37% either new analyses of existing data, modelling studies, or remote sensing), and has a *Moderate* confidence rating (based on *High* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

Understanding the distribution of nutrient concentrations, and how they change over time, is important because nutrients, especially nitrogen and phosphorus, play a crucial role in the water quality and overall health of Great Barrier Reef ecosystems, supporting coral reefs, seagrass meadows and fisheries. Multiple lines of evidence demonstrate that nutrient concentrations originating from land-based activities follow a cross-shelf gradient with the highest concentrations found in estuaries and inshore waters and lower concentrations in offshore waters. Peak concentrations of dissolved organic and inorganic nutrients are usually found during the wet season (typically December to May) in the central and southern Great Barrier Reef (approximately from Cooktown to Gladstone) adjacent to areas of more intensive catchment development and in waters influenced by river discharge. Weather patterns, river discharge and associated land-based inputs, as well as marine processes such as upwelling and nitrogen fixation are among the key drivers of nutrient variability. Nutrient concentrations vary from year to year and are highest in years of high rainfall and river discharge, and storm activity (typically La Niña years). Inshore nutrient concentrations can also vary over short timescales due to tidal movements and diurnal fluctuations in photosynthetic and metabolic activity. Changing land use has increased nutrient loads exported to the Great Barrier Reef, and both modelling and coral core studies strongly suggest that this has increased nutrient concentrations in inshore and (to a lesser extent) midshelf waters.

Supporting points

- Multiple lines of evidence provide a temporal record of nutrient distribution across the whole Great Barrier Reef. This includes coral core data that provides insight into pre-development conditions, ocean colour data extending back to 1969, data from *ad hoc in situ* studies from the 1990s, and routine monitoring from 1989 at some locations (e.g., the 'Cairns transect' from the Barron River mouth to midshelf areas) to present. The majority of studies focus on inshore and/or midshelf waters, with relatively few studies including estuary or offshore nutrient concentrations. The largest source of inshore nutrient data is the Great Barrier Reef Marine Monitoring Program which started in 2005.
- Multiple datasets show that total phosphorus, total nitrogen, dissolved inorganic nitrogen, phosphate and silica concentrations follow a cross-shelf gradient from higher values in estuaries, mangrove creeks and inshore waters to lower values in midshelf waters. In offshore waters, relatively high concentrations of dissolved inorganic nitrogen and chlorophyll *a* can sometimes occur in areas of oceanic upwelling.
- Concentrations of total phosphorus, total nitrogen, dissolved inorganic nitrogen and phosphate are elevated in flood plumes (relative to ambient concentrations) and in areas of sediment resuspension. Chlorophyll *a* concentrations are also elevated in flood plumes where light is sufficient. Silicate concentrations follow similar spatial patterns but have not been as well studied. Little observational data is available for micronutrients, including iron.
- Flood plumes in the Great Barrier Reef, carrying land-based nutrients and other pollutants, are usually constrained to distances within 25 kilometres of the coast, but - can extend up to 50 kilometres from the coast after major flood events; into midshelf waters. In general, the spatial extent of flood plumes is greater in the central and southern Great Barrier Reef than in the Cape York region. Most flood plumes travel northwards up the coast from their source rivers, though this can vary with the wind direction and rate of river discharge.

- Most terrestrial particulate nutrients are deposited within 10 kilometres of river mouths, but dissolved nutrients are carried further and are taken up by biota and transformed into phytoplankton biomass (measured as chlorophyll *a*). Higher chlorophyll *a* concentrations are often observed in the mixing zones at the edge of flood plumes.
- A substantial proportion of particulate organic nitrogen and phosphorus that is deposited in sediments in estuaries and at river mouths is later remineralised, releasing dissolved nitrogen and phosphorus into the water column so that nutrient concentrations in inshore and some midshelf areas remain elevated even after the flood plumes have dispersed.
- Offshore and midshelf variations in nutrient concentrations in surface waters are often associated with upwelling events (which sometimes bring dissolved inorganic nitrogen and phosphorus from deeper water to the surface) and *Trichodesmium* blooms (which fix atmospheric nitrogen). There is some evidence that both upwelling and *Trichodesmium* blooms are more common in La Niña years.
- There have been clear temporal trends in inshore nutrient concentrations collected through the Marine Monitoring Program since 2005. Nitrite and nitrate concentrations have increased in all monitored inshore regions, which includes the Wet Tropics, Burdekin and Mackay Whitsunday marine Natural Resource Management regions, and particulate nitrogen has increased in the Wet Tropics region. In some regions, there has been a reduction in phosphate since 2017, and in the Mackay Whitsunday region, there has been a reduction in chlorophyll *a*. There is not enough long-term monitoring data to assess temporal trends in the Cape York, Fitzroy or Burnett Mary regions, and there is no long-term monitoring program in the Burnett Mary region to support this type of assessment in the future.
- To obtain a more complete picture about nutrient distributions in the Great Barrier Reef, future steps could include characterising organic nutrients and their link to land-based inputs, exploring the time scales over which changes in land-based inputs may affect marine nutrient concentrations, analysing long-term coastal and marine nutrient datasets to better understand the effects of land management changes, quantifying nutrient variability from marine sources, and updating Great Barrier Reef-wide nutrient budgets (quantifying all sources, sinks and stocks of nitrogen and phosphorus).

6. References

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

Body of Evidence

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Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 4.1

Theme 4: Dissolved nutrients – catchment to reef

Primary Question 4.1 What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef?

Secondary Question 4.1.1 What is the variability of nutrients in coastal and marine areas of the Great Barrier Reef?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Barbara Robson	AIMS	Biogeochemistry, nutrient cycles and modelling	Lead Author	All Sections
2. Aimee Brown	Independent consultant		Contributor	Searches and data extraction
3. Sven Uthicke	AIMS	Effects of water quality, climate change, COTS	Contributor	All sections/Comment and revision