2022 Scientific Consensus Statement

Question 4.5 What are the primary biophysical drivers of anthropogenic dissolved nutrient export to the Great Barrier Reef and how have these drivers changed over time?

Question 4.5.1 What proportion of nutrient is lost by surface and subsurface pathways?

Question 4.5.2 How do nutrients transform during the transport and delivery to the Great Barrier Reef lagoon (e.g., bioavailability of particulate nutrients)?

Michele Burford[1], Jianyin (Leslie) Huang[1,2], Zoe Bainbridge[3], Joanne Burton[4], Mohammad Bahadori[4], Gillian McCloskey[4], Michael Newham[4]

[1]Griffith University, [2]University of South Australia, [3]Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), James Cook University, [4]Department of Environment, Science and Innovation

Citation

Burford M, Huang J, Bainbridge Z, Burton J, Bahadori M, McCloskey G, Newham M (2024) Question 4.5 What are the primary biophysical drivers of anthropogenic dissolved nutrient export to the Great Barrier Reef and how have these drivers changed over time? In Waterhouse J, Pineda M-C, Sambrook K (Eds) 2022 Scientific Consensus Statement on land-based impacts on Great Barrier Reef water quality and ecosystem condition. Commonwealth of Australia and Queensland Government.

The 2022 Scientific Consensus Statement was led and coordinated by C_2O Consulting coasts | climate | oceans.

The 2022 Scientific Consensus Statement is funded by the Australian Government's Reef Trust and Queensland Government's Queensland Reef Water Quality Program.

Cover image credit: CSIRO.

Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

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

What is the Scientific Consensus Statement?

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

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

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

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

Method used to address the 2022 SCS Questions

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

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

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

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

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

Two methods were developed for the 2022 SCS:

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

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

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

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

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

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

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

Guidance for using the synthesis of evidence

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

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

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

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

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

Peer Review and Quality Assurance

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

Contents

Acknowledgements ii
Executive Summary 1
1. Background 6
1.1 Questions 7
1.2 Conceptual diagram 7
1.3 Links to other questions 9
2. Method 10
2.1 Primary question elements and description 10
2.2 Search and eligibility 11
a) Search locations 12
b) Search terms 12
c) Search strings 12
d) Inclusion and exclusion criteria 12
3. Search Results 14
4. Key Findings 16
4.1 Narrative synthesis 16
4.1.0 Summary of study characteristics 16
4.1.1 Summary of evidence up to 2022 19
4.1.1.1 Rainfall and rain intensity 19
4.1.1.2 Surface runoff 20
4.1.1.3 Water residence time 21
4.1.1.4 Fertiliser application rates and methods 22
4.1.1.5 Crop irrigation 23
4.1.1.6 Direct nutrient release from erosion 24
4.1.1.7 Subsurface (groundwater) inputs to rivers 24
4.1.1.8 Topography effects 25
4.1.1.9 Reservoirs 26
4.1.1.10 Interaction with floodplains 27
4.1.1.11 Atmospheric deposition 27
4.1.1.12 In-stream processing 28
4.1.1.13 Transformation from particulate to dissolved forms 28
Synthesis of secondary questions 29
4.1.2 Recent findings 2016-2022 (since the 2017 SCS) 31
4.1.3 Key conclusions 32
4.1.4 Significance of findings for policy, management and practice 33
4.1.5 Key uncertainties and/or limitations 34
4.2 Contextual variables influencing outcomes 34
4.3 Evidence appraisal 36
4.4 Indigenous engagement/participation within the body of evidence 38
4.5 Knowledge gaps 38
5. Evidence Statement 41
6. References 43
Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 4.5 48

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 also to Marie Vitelli (AgForce) for submitting literature for consideration in this synthesis.

Executive Summary

Questions

Primary Question 4.5 What are the primary biophysical drivers of anthropogenic dissolved nutrient export to the Great Barrier Reef and how have these drivers changed over time?

Secondary Question 4.5.1. What proportion of nutrient is lost by surface and subsurface pathways?

Secondary Question 4.5.2 How do nutrients transform during the transport and delivery to the Great Barrier Reef lagoon (e.g., bioavailability of particulate nutrients)?

Background

Nutrients are a fundamental requirement for life and occur naturally in our land and aquatic ecosystems. However, globally nutrient loads have increased due to human activities, resulting in an excess in aquatic systems, i.e., anthropogenic nutrients. These excess nutrients, particularly nitrogen (N) and phosphorus (P), have detrimental effects on ecosystem health and water quality. Nutrients originating on the land, both from natural sources (e.g., soil) and from synthetic inputs (e.g., fertiliser), can be transformed as they move through soil and freshwater systems. However, rivers also have the capability to reduce the environmental effects of land-derived nutrients on coastal environments by net removal of nutrients (e.g., transformation to nitrogen gas via denitrification). The relative importance of these transformations is related to many factors, with a major effect being the hydrological regime. Nutrient loads entering the Great Barrier Reef (GBR) from its catchments have increased substantially since European settlement, due to anthropogenic factors, such as soil disturbance and erosion, and fertiliser application (see Questions 2.3, Lewis et al., and 4.4, Prosser and Wilkinson, this Scientific Consensus Statement (SCS)). Substantial policy and land management efforts have been made to reduce nutrient loads from catchments (see Question 7.1, Coggan et al., this SCS). However, scientific knowledge of the efficacy of management actions and their benefits has lagged behind. Understanding how nutrients, especially anthropogenic dissolved nutrients, are transformed as they move from land to freshwater will improve catchment management plans to reduce nutrient loads, and impacts on GBR ecosystems (see Question 4.2, Diaz-Pulido et al., this SCS).

This review focused on the following species of dissolved nitrogen and phosphorus: dissolved inorganic nitrogen [DIN, ammonium (NH_4-N) and nitrate/nitrite (NOx)]; dissolved inorganic phosphorus (DIP) or filtered reactive phosphate (FRP); dissolved organic nitrogen (DON, and its sub-components); and dissolved organic phosphorus (DOP). As the transformations of particulate nutrients can result in dissolved inorganic nutrient release, particulate nutrients [particulate nitrogen (PN) and phosphorus (PP)] were also examined in this context. A range of primary biophysical drivers that can influence forms and loads of dissolved nutrients including fertiliser application rates, crop irrigation, rainfall intensity, erosion, surface and subsurface runoff, and groundwater were examined. In addition, information on various transformation pathways for nutrients in both soil and water, such as nitrogen removal processes (e.g., denitrification, incorporation of inorganic nutrients into plant and algal biomass), were examined in the 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

[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

synthesised into final products to inform policy. For this question, an Evidence Summary method was used.

- Search locations included Web of Science, Scopus and Google Scholar, in addition to National Environmental Science Program (NESP) Tropical Water Quality reports, Department of Science, Information Technology and Innovation Reports and Queensland and Australian Government's Paddock to Reef Integrated Monitoring, Modelling and Reporting Program.
- Main source of evidence: Studies conducted within the GBR, as evidence from outside the GBR has very limited relevance to this question.
- From the initial search, Web of Science returned 136 results, Scopus returned 73 and the top 130 studies from Google Scholar (from a total of 520 results) were considered. After initial screening by title and abstract, and removing duplicates, 34 studies from Web of Science, 18 from Scopus and 32 from Google Scholar were selected for the second screening. After reading the full text, 30 studies met the inclusion criteria and were incorporated into the Evidence Summary In addition, 22 studies were added manually from the authors' personal collections, SCS literature submissions and cited in searched items. In total, 52 studies were used in this synthesis.

Method limitations and caveats to using this Evidence Summary

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

- Only studies written in English were included.
- Only GBR derived studies were included.
- Only two academic databases were searched.
- Only studies published post 1990 were included.
- The use of specific keywords in the evidence searches may also limit some relevant studies.
- The focus of this review is on anthropogenic dissolved inorganic nutrients and particulate nutrients, and their transformation in freshwater. The nutrient species and transformation in estuaries are not considered.
- The primary biophysical drivers considered in this study were: fertiliser application, crop irrigation, rainfall and rain intensity, topography effects, direct release from erosion, surface and subsurface runoff, groundwater, atmospheric deposition, residence time, reservoirs, interaction with floodplains, in-stream processing and transformation from particulate to dissolved form.
- The land use sources of these nutrients examined were agriculture (sugarcane, horticulture, irrigated and dryland cropping, and grazing), urban (diffuse sources) and other non-agricultural land uses (roads, sewage treatment plants and industry).

Key Findings

Summary of evidence to 2022

A total of 52 eligible studies were selected that were relevant to Question 4.5 including 37 primary studies (observational, experimental and modelled), 13 secondary studies (reviews or conceptual research) and two mixed studies (a mixture of observational, experimental and modelled or a mixture of observational and reviews). A total of 12 biophysical drivers were identified in the literature including fertiliser, rainfall, erosion, topology, surface and subsurface runoff and groundwater. Rainfall and rainfall intensity affects surface runoff into river systems and was identified as one of the most important drivers of nutrient inputs and the scale of transformations in rivers. Approximately 67% of studies included the impact of rainfall and rainfall intensity on anthropogenic dissolved nutrient export to the GBR, with a focus on the wet season.

Nutrients were delivered to rivers by two mechanisms: surface and subsurface runoff. Among the land uses generating nutrients, sugarcane (42 studies, 81%) and grazing/dairy (40 studies, 77%) were most frequently discussed, with fewer studies on other land uses. Comparing the number of studies among different regions and climatic conditions, the Wet Tropics region dominated (38 studies) followed by the Burdekin (34 studies). The nutrient forms discussed were similar between studies.

Key conclusions from the body of evidence are that:

- Increased rates of fertiliser application, increased cultivation area, low efficiency irrigation systems and heavy rainfall can lead to increased nutrient export, especially nitrogen, in surface runoff, deep drainage and groundwater. Considerable variation in nutrient export can occur between sites and years.
- Rainfall and subsequent runoff events can lead to substantial increase in nitrogen loads (in dissolved and particulate form) in GBR rivers. Highly variable flow regimes range from extended periods of low rainfall, through to extreme rainfall events causing extensive flooding. This spatial and temporal variation leads to high levels of uncertainty in generalising about nutrient loads, forms and their transformations.
- Subsurface inputs of nutrients to freshwater systems (such as via groundwater movement) are increasingly being recognised as important sources of nutrient delivery to the GBR, but in the few studies reviewed, the contribution of subsurface inputs relative to inputs from surface runoff was highly variable. Deep drainage was a larger export pathway than surface runoff from many of the sugarcane and banana sites in the Wet Tropics basins, Burdekin Delta and Bundaberg. Studies have shown potentially high nitrogen loadings to groundwater and have inferred a significant contribution of subsurface nitrogen to dissolved inorganic nitrogen loads in streams. However, there is limited quantification of the spatial and temporal contribution of groundwater in the context of the total nitrogen budget of basins.
- The proportion of nutrients exported by surface and subsurface pathways has not been quantified but can be affected by many factors such as soil type, land uses and management, vegetative ground cover, rainfall, fertiliser application and irrigation practices.
- In several studies undertaken in the Wet Tropics and Mackay Whitsunday Natural Resource Management regions, matching nitrogen supply to crop nitrogen requirements, better application methods (subsurface application or different fertiliser forms) and the timing of rainfall and/or irrigation contributed to reduced nitrogen export in runoff while maintaining similar crop yields.
- Increased residence times in rivers during periods of low flow can allow for further in-stream processes which transform, store or remove nutrients, e.g., denitrification in sediments, uptake by aquatic plants and sediment storage in the rivers. However, the relative importance of different processes for nutrient export requires further study.
- Floodplains typically act as a sink for sediment and nutrients (both particulate and dissolved) and therefore effective management of floodplains is important for reducing nutrient (and sediment) loads at the end-of-catchments.
- Microbial mineralisation and chemical processes in freshwaters have been shown to make nitrogen more bioavailable, particularly conversion of particulate nitrogen to dissolved inorganic nitrogen. Bioavailability depends on sediment characteristics such as soil type, land use and sediment source (surface or subsurface). The few studies investigating these processes have been conducted in the Burdekin and Wet Tropics regions, and very little research into nutrient transformation has been conducted in other regions, including the source of land-based dissolved inorganic nitrogen from the Fitzroy region.
- Studies showed that reservoirs in the GBR catchment area are responsible for significant trapping and transformation of nutrients, particularly phosphorus, due to their increased water residence time. Remineralisation processes within reservoirs typically increase the proportion of bioavailable nutrients which has the potential to promote algal growth both within reservoirs and impact rivers downstream. These findings support those of other studies globally.
- More studies focus on nitrogen compared to phosphorus. This is, in part, because nitrogen is generally considered the major limiting nutrient in marine waters, both globally and in the GBR. Additionally, phosphorus is typically strongly bound to soils. However, it is possible that phosphorus can limit primary productivity in rivers and the GBR at times and at certain locations.

As a result, phosphorus transformation processes should not be ignored and the impact of anthropogenic phosphorus discharges to rivers/streams should be determined.

Recent findings 2016–2022

Of the 52 studies, 21 (approximately 40%) were published for the period 2016–2022, with 15 of these examining the impact of rainfall on nutrient concentrations and species, followed by erosion (13 studies), fertiliser contribution (12 studies), surface runoff (ten studies), particulate nutrient and topography effects (both eight studies). Four studies examined in-stream processes, irrigation effects, floodplains and subsurface flow. Two studies examined atmospheric deposition. Only one study explicitly discussed water residence time.

In terms of the findings, recent studies continue to identify fertiliser inputs, erosion, surface runoff and rainfall as key factors affecting nutrients in freshwater. There was an increased number of studies on particulate nutrients, specifically on the transformation from particulate to dissolved form (termed bioavailable nutrients) in freshwater, reflecting an increased understanding of the importance of this process. With the exception of studies on the importance of particulate nutrient transformations, there has been limited progress on our understanding of GBR freshwater systems in the last 5–6 years.

Significance for policy, practice, and research

This review examined primary biophysical drivers that influence anthropogenic dissolved nutrient export to the GBR, and aimed to examine how these drivers change over time. In addition, this review aimed to determine the proportion of nutrients that is exported through surface and subsurface pathways and understand the transformation of nutrients during their transport within freshwater reaches of the GBR catchment area. It is clear that in the period since the last Scientific Consensus Statement, there has been little change in our understanding of the dominant sources and transformations of nutrients in the GBR catchment area. Much of the research has broadened our knowledge across time and over a greater area, consolidating previous findings. However, in terms of nutrient transformations, there are relatively few novel studies, with the exception being the finding that soil-derived particulate nutrients are a more important source of bioavailable nutrients in freshwaters (and marine waters) than previously thought. Additionally, there is little or no information on how the drivers change over time with a few exceptions. For instance, studies showed that the fertiliser application rates on sugarcane and banana reduced over time. In addition, a warming global climate can be associated with more variable rainfall in the Queensland tropics.

The main drivers of anthropogenic nutrient loss have been identified as fertiliser, erosion, rainfall and rainfall intensity, surface runoff and in-stream processes, and groundwater. Managing nitrogen fertiliser to reduce nitrogen export, and managing erosion to reduce fine sediment and particulate nutrients exports are well understood. For example, studies have shown that reducing the fertiliser application rate reduced N export in runoff and deep drainage in sugarcane. Typically, studies have not examined the relative importance of these drivers or their linkages in detail, however, in terms of management of the GBR catchment area, it is important that linkages and their interacting effects are considered. Additionally, climate variability, including droughts and extreme rainfall events can lead to an increased variability on the export of N from the land to waterways. This also impacts on the capacity of rivers and streams to transform nitrogen.

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

- Many studies related to nutrient export by surface and subsurface pathways focus on agricultural areas, in particular nitrogen export from sugarcane of the Wet Tropics. Therefore, investigation of other crops, such as banana and other horticulture, is required.
- Export of DON from urea-based fertiliser used in grain cropping and livestock grazing.
- Improved quantification of deep drainage export and linkages to loads entering the GBR.
- Greater understanding of the interactions between N in groundwaters and in streams and rivers, and the role of groundwater in the total N budget of catchments.

- Information on nutrient transformations and their role in assimilating nutrients in rivers is still very limited. For instance, the origin and fate of refractory DON are unclear, including whether it is mineralised or consumed by bacteria, and the role of organic carbon inputs in stimulating this.
- Nitrogen mineralisation in rivers and the effect on ammonium (NH_4-N) exports is poorly understood.
- Managing for particulate nutrient bioavailability, as well as fine sediment and dissolved nutrient hotspots, is becoming a higher priority and requires more information about where hotspots of nutrients are located in the catchments.
- Spatial knowledge of bioavailable N (BAN), especially for high priority catchments with the highest sediment loads, such as the Fitzroy, Herbert and Mary River basins.
- The impact of anthropogenic phosphorus discharges to rivers and streams.
- The function of floodplains and their effect on nutrient transformation and assimilation.

Key uncertainties and/or limitations

- A majority of the studies included are from sugarcane land use.
- There are studies related to nutrient export by surface and subsurface pathways, however, most studies focus on agricultural areas and nitrogen (not phosphorus). The proportion of nutrient lost by surface and subsurface pathways can be affected by many factors, such as soil type, vegetative ground cover, climatic condition, fertiliser application and irrigation practices. Nutrient export can vary considerably between sites and years.
- There are few studies which examine the transformation processes of nutrients in soil and water in detail, and it is often difficult to generalise within and across the GBR catchment area. Additionally, the importance of various transformation processes will vary over different hydrological states within each catchment system. Therefore, there is a high level of uncertainty in the links between hydrological states and transformations which makes it difficult to assess/predict the effectiveness of management actions.
- There is limited coverage of understanding in some regions from the GBR (e.g., the DIN from the Fitzroy Natural Resource Management (NRM) region is poorly understood).

Evidence appraisal

Overall, the confidence in the body of evidence for the primary question is Moderate, with a High rating for overall relevance of the body of evidence to the primary question. Each of the secondary questions (Q4.5.1 and Q4.5.2) was addressed using 17 studies. The consistency is considered Moderate for the primary question. Findings across the primary studies were generally consistent from this review as the studies reported similar conclusions on the impacts of primary biophysical drivers on the forms and loads of dissolved nutrients. The 52 studies used in this review are considered to be a Moderate representative sample. The diversity of the studies is also considered to be High. There were two different study types used in the review: 1) primary studies (experimental, observational, or modelled) and 2) secondary studies (reviews or Systematic Reviews). A total of 37 studies (71%) were classed as primary studies, 13 (25%) were classed as secondary studies and two studies (4%) were classed as mixed studies. For the primary studies, 81% were observational studies, 3% were laboratory experiments and 16% were focused on modelling approaches.

1. Background

Nutrients play an important role in freshwater and marine ecosystems. However, excessive amounts of nutrients can pose a threat to the ecological health of the Great Barrier Reef (GBR) (see Question 4.2, Diaz-Pulido et al., this SCS). Human activities such as agricultural grazing of animals, forest clearing, catchment and agricultural intensification have increased the nutrient and sediment loads delivered from catchments to the GBR since European settlement (see Questions 3.3 and 4.4, Prosser and Wilkinson, this SCS). The 2017 Scientific Consensus Statement (SCS) identified that particulate and dissolved organic nutrients comprised the majority of the end of catchment nutrient loads delivered to the GBR, but very little was known of their sources, export or transformation as they are transported from terrestrial to marine environments. Although the 2017 SCS suggested that dissolved nutrients might move via surface and subsurface pathways, this was only reported in a few studies, and the proportion of nutrients exported by these pathways was not reported. Therefore, this review examines the literature on primary biophysical drivers that affect anthropogenic dissolved nutrient export to the GBR and examines how these drivers have changed over time. Moreover, the review aims to determine the proportion of nutrients that is lost by surface and subsurface pathways, and examines knowledge on the transformation of nutrients as they are transported through freshwater reaches of the GBR catchment area (estuarine waters are not considered in this study). This review aims to identify: 1) key findings on nutrient processes in freshwater that can provide foundational knowledge to facilitate better management practices for different land uses; and 2) the knowledge gaps that will require further investigation.

The export and transformation of nutrients from the GBR catchment area can be related to many factors, such as catchment characteristics, transport distance to the coast, water source and water residence time. The 2017 SCS identified that nutrient loads from GBR basins have typically increased due to anthropogenic factors such as soil disturbance, erosion and fertiliser application. Because of that, 12 primary biophysical drivers were examined in the available literature, which covered the sources, environmental factors and catchment processes (Figure 1). Additionally, recent studies have reported that the transformations of particulate nutrients could result in dissolved inorganic nutrient release (Garzon-Garcia et al., 2018b; 2021), so the transformations of particulate nutrients were included in this review. The biophysical drivers with potential to impact anthropogenic dissolved nutrient export to the GBR include fertiliser application rates, irrigation, rainfall intensity, topography effect (hillslope), direct release from erosion, delivery from surface and subsurface runoff, atmospheric deposition, residence time, reservoirs, interaction with floodplains, river transport, and transformation from particulate to dissolved form.

Dissolved nutrients covered in this study were species of nitrogen (N) and phosphorus (P) carried in solution by freshwater. The review considered dissolved inorganic nitrogen (DIN: ammonium and nitrate/nitrite), dissolved inorganic phosphorus (DIP), dissolved organic nitrogen (DON, and its subcomponents), and dissolved organic phosphorus (DOP). The dominant land uses generating these nutrients examined in this review were agriculture (sugarcane, horticulture, irrigated and dryland crops and grazing), urban (diffuse sources), and other non-agricultural land uses (roads, sewage treatment plants (STPs) and industry).

This question examines how nutrients are transformed as they move from land to freshwater before entering estuaries, while Question 4.4 (Prosser and Wilkinson, this SCS) examines the literature on nutrient loads and forms from anthropogenically altered land uses. The distribution of nutrients in the marine environment is covered in Question 4.1 (Robson et al., this SCS) with fate and impacts covered in Question 4.2 (Diaz-Pulido et al., this SCS). The focus of this question is on dissolved inorganic nutrients, as particulate nutrients and sediment are examined in Question 3.3 (Prosser and Wilkinson, this SCS) and Question 3.4 (Wilkinson et al., this SCS). As the transformation of particulate nutrients may result in dissolved inorganic nutrient release, particulate nutrients [particulate nitrogen (PN) and particulate phosphorus (PP)] are also included in this context. Questions 4.6 (Thorburn et al., this SCS) and 4.7 (specifically the role of wetlands, Waltham et al., this SCS) consider management options to limit or reduce delivery of nutrients from the catchment area to the GBR and therefore these topics are not discussed here.

1.1 Questions

Primary question	**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?
Secondary questions	**Q4.5.1** What proportion of nutrient is lost by surface and subsurface pathways?
	Q4.5.2 How do nutrients transform during the transport and delivery to the Great Barrier Reef lagoon (e.g., bioavailability of particulate nutrients)?

Nutrients originating from the land may be transformed as they move through the soil and freshwater systems. The importance of these transformations is related to many factors, such as flow pathways and water residence time. Nutrient loads from the adjacent catchments have typically increased due to anthropogenic factors such as soil disturbance, erosion and fertiliser application. This question examines how nutrients are transformed as they move from land to freshwater before entering estuaries.

1.2 Conceptual diagram

The conceptual diagram representing the scope of the question is provided below (Figure 1). The diagram contains four main parts: source, transport, drivers and end point. Nutrients are generated from sources such as agriculture, urban and other non-agricultural land uses, and are transported to waterways by way of surface and subsurface flow until they reach the end point, the GBR. The drivers cover agricultural practices, environmental factors and catchment processes, and the influence they have on nutrient transformation during transport from the source. The drivers from this conceptual diagram are addressed in the Primary Question 4.5. The mechanisms (surface and subsurface flow) of nutrient delivery are addressed in Secondary Question 4.5.1 and the nutrient transformations in rivers/creeks are examined in Secondary Question 4.5.2.

The forms of nutrients examined are summarised based on the sources. Several transformation pathways for nutrients such as denitrification, incorporation of inorganic nutrients into plant and algal biomass, desorption of nutrients from soil particles are also summarised for rivers and creeks.

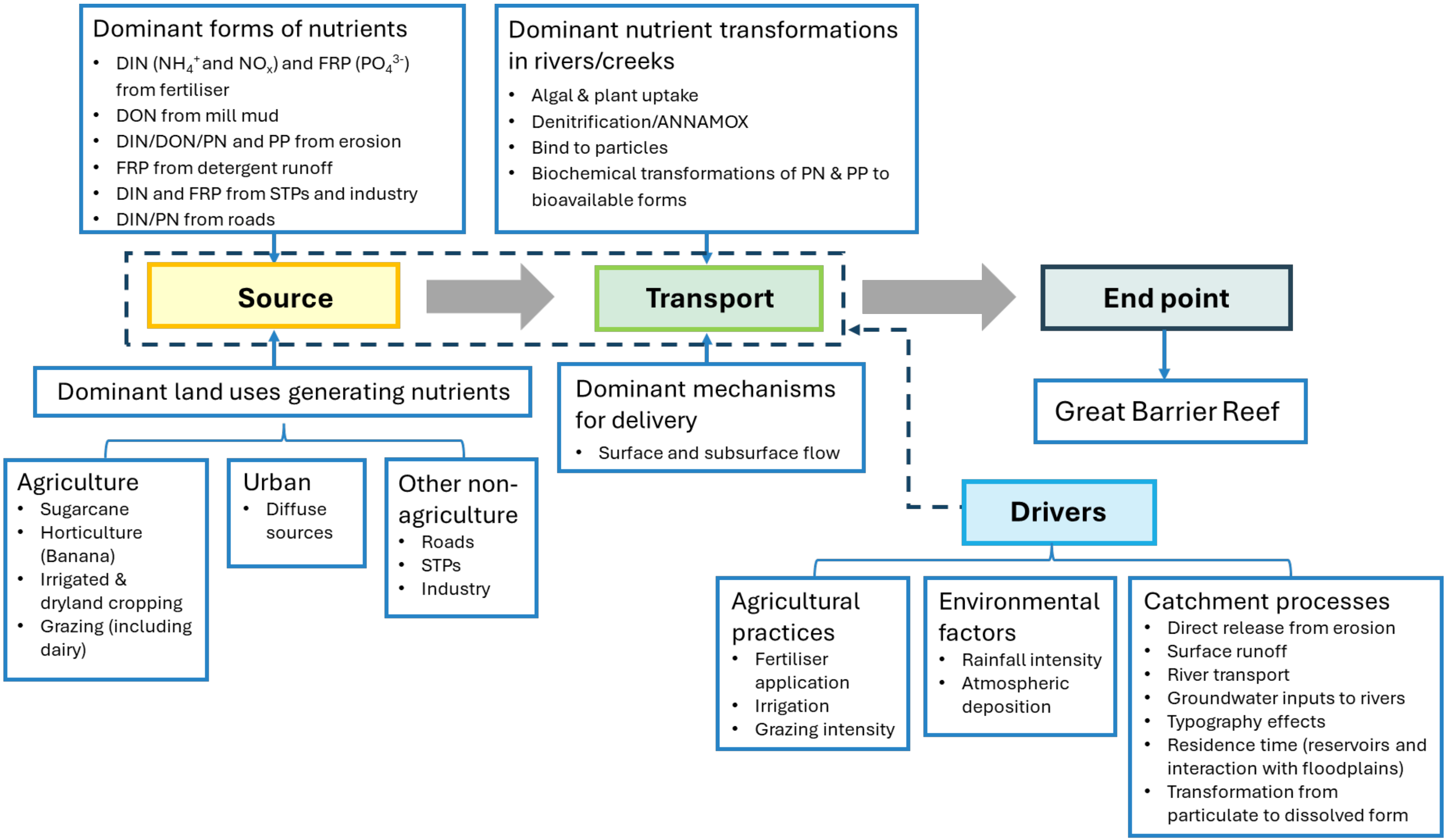


Figure 1. Conceptual diagram for the sources, transport and transformation of anthropogenic dissolved nutrients from the GBR catchment area. Sources are covered in detail in Question 4.4 (Prosser and Wilkinson, this SCS). ANNAMOX = Anaerobic ammonium oxidation, PN = particulate nitrogen, PP = particulate phosphorus, STP = sewage treatment plant.

1.3 Links to other questions

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

Links to other related questions	Questions 3.3 and 3.4 examine anthropogenic sediment and particulate nutrient export to the GBR. **Q3.3** How much anthropogenic sediment and particulate nutrients are exported from Great Barrier Reef catchments (including the spatial and temporal variation in delivery), what are the most important characteristics of anthropogenic sediments and particulate nutrients, and what are the primary sources? **Q3.4** What are the primary biophysical drivers of anthropogenic sediment and particulate nutrient export to the Great Barrier Reef and how have these drivers changed over time? **Q4.1** What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef? Questions 4.2 and 4.3 consider the impacts of elevated nutrient concentrations in the GBR. **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? Question 4.4 examines the sources of nutrient loads and forms from anthropogenically altered land uses in the GBR. **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? Questions 4.6 and 4.7 (specifically wetlands) consider management options to limit or reduce delivery of nutrients from catchments. **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)?

2. Method

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

2.1 Primary question elements and description

The primary question is: ***What are the primary biophysical drivers of anthropogenic dissolved nutrient export to the Great Barrier Reef and how have these drivers changed over time?***

The secondary questions are:

- 4.5.1 ***What proportion of nutrient is lost by surface and subsurface pathways?***
- 4.5.2 ***How do nutrients transform during the transport and delivery to the Great Barrier Reef lagoon (e.g., bioavailability of particulate nutrients)?***

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 4.5, 4.5.1 and 4.5.2.

Question S/PICO elements	Question term	Description
Subject/Population	GBR	The GBR is interpreted as referring to the Great Barrier Reef World Heritage Area.
	Dissolved nutrients from human activities	Dissolved nutrients: dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), dissolved organic nitrogen (DON, and its subcomponents), and dissolved organic phosphorus (DOP). Particulate nutrients: particulate nitrogen (PN) and particulate phosphorus (PP). The dominant land uses generating nutrients that were included in this review are: agriculture (sugarcane, horticulture, irrigated and dryland crops, and grazing), urban (diffuse sources) and other non-agricultural land uses (roads, STPs and industry).

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

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

Question S/PICO elements	Question term	Description
Intervention, exposure & qualifiers	Primary biophysical drivers	Primary biophysical drivers: fertiliser application, crop irrigation, rainfall and rain intensity, topography effect (hillslope), direct release from erosion, delivery from surface and subsurface runoff, atmospheric deposition, residence time, reservoirs, interaction with floodplains, river transport and transformation from particulate to dissolved forms.
Outcome & outcome qualifiers	Nutrient loss	Measures of nutrient export as a result of human activities- dissolved nutrients transported from upstream areas to the end of the catchments, rivers and creeks. Only the freshwater areas will be considered.

Table 2. Definitions for terms used in Questions 4.5, 4.5.1 and 4.5.2.

Definitions	
GBR	The GBR is interpreted as referring to the Great Barrier Reef World Heritage Area (GBRWHA).
Anthropogenic	Pollution (in this case excess nitrogen and phosphorus) originating from human activity. Several land uses were selected, including agriculture (sugarcane, horticulture, irrigated and dryland crops, and grazing), urban and other non-agricultural land uses (roads, STPs and industry).
Dissolved nutrient	Dissolved nutrients: dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP); dissolved organic nitrogen (DON, and its subcomponents) and dissolved organic phosphorus (DOP).
Particulate nutrient	Particulate nitrogen (PN) and particulate phosphorus (PP).
Primary biophysical drivers	Fertiliser application, crop irrigation, rainfall and rain intensity, topography effect (hillslope), direct release from erosion, delivery from surface and subsurface runoff, atmospheric deposition, residence time, reservoirs, interaction with floodplains, river transport and transformation from particulate to dissolved form.
Freshwater	Dissolved nutrients transported from upstream areas to brackish water extent of rivers and creeks. Only the freshwater areas will be considered.

2.2 Search and eligibility

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

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

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

a) Search locations

Searches were performed in:

- Scopus, searching Title, Abstract and Keyword fields
- Web of Science, searching in ALL fields
- Google Scholar
- National Environmental Science Program (NESP) Tropical Water Quality Hub reports
- Department of Science, Information Technology and Innovation Reports and Queensland and Australian Government’s Paddock to Reef Integrated Monitoring, Modelling and Reporting Program.

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 for Question 4.5.

Question element	Search terms
Subject/Population	nutrient, anthropogenic, Great Barrier Reef
Exposure or Intervention	fertiliser, irrigation, rainfall, hillslope, erosion, atmospheric deposition, surface runoff, groundwater, residence time, reservoirs, floodplains, river transport, particulate nutrient
Outcome	freshwater

c) Search strings

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

Table 4. Search strings used for electronic searches for Question 4.5.

Search strings
Scopus: “article title, abstract, keywords”= “nutrient” AND “anthropogenic” AND “great barrier reef” AND (“fertiliser” OR “irrigation” OR “rainfall” OR “hillslope” OR “erosion” OR “atmospheric deposition” OR “surface runoff” OR “groundwater” OR “residence time” OR “reservoirs” OR “floodplains” OR “transport” OR “particulate nutrient”) AND “freshwater”
Web of Science: ”all”= “nutrient” AND “anthropogenic” AND “great barrier reef” AND (“fertiliser” OR “irrigation” OR “rainfall” OR “hillslope” OR “erosion” OR “atmospheric deposition” OR “surface runoff” OR “groundwater” OR “residence time” OR “reservoirs” OR “floodplains” OR “transport” OR “particulate nutrient “) AND “freshwater”
Google Scholar: “nutrient” AND “anthropogenic” AND “great barrier reef” AND (“fertiliser” OR “rainfall” OR “hillslope” OR “erosion” OR “surface runoff” OR “groundwater” OR “residence” OR “floodplains” OR “transport” OR “particulate nutrient”) AND “freshwater”

d) Inclusion and exclusion criteria

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

Table 5. Inclusion and exclusion criteria for Question 4.5 applied to the search returns.

Question element	Inclusion	Exclusion
Subject/Population	Studies undertaken in the GBR. Papers reporting on anthropogenic dissolved nutrients in freshwater.	• Papers that have not taken place in the GBR. • Papers that do not contain anthropogenic dissolved nutrient (dissolved inorganic nitrogen and phosphate) in freshwater. • Papers that do not cover agriculture (sugarcane, horticulture, banana, irrigated and dryland crops, and grazing), urban (diffuse sources) and other non-agricultural land uses (roads, STPs and industry). • Studies undertaken outside of Australia.
Exposure or Intervention	Papers that provide information about primary biophysical drivers that are listed in the conceptual diagram.	Papers that do not discuss the primary biophysical drivers that are listed in the conceptual diagram.
Outcome	Papers that mention the anthropogenic dissolved nutrient in freshwaters.	Papers that discuss the anthropogenic dissolved nutrient in estuaries and marine waters.
Language	English	Any other language
Study type	Studies published on or after 1990. Monitoring reports, field studies, modelling studies and laboratory studies.	

3. Search Results

A total of 729 studies (73 results from Scopus, 136 results from Web of Science and 520 from Google Scholar) were identified through online searches for peer reviewed and published literature. An additional 31 studies were identified manually through expert contact and personal collections, which represented approximately 4% of the total evidence considered. After initial screening by title and abstract, and removing duplicates, 16 from Scopus, 32 studies from Web of Science, and 32 from Google Scholar were selected for the second screening. After reading the full text, 30 of the online studies and 22 of the manually added studies met the eligibility criteria and were included in the synthesis. In total, 52 studies were eligible for inclusion in the synthesis of evidence (Table 6) (Figure 2).

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

Date	Search strings	Sources	
A) Academic databases		Scopus	Web of Science
	Search string 1: "nutrient" AND "great barrier reef" AND "freshwater"	*34 of 36*	*32 of 82*
	Search string 2: "nutrient" AND "anthropogenic" AND "great barrier reef" AND "freshwater"	*9 of 9*	*11 of 11*
	Search string 3: "nutrient" AND "great barrier reef" AND ("fertiliser" OR "irrigation" OR "rainfall" OR "slope" OR "erosion" OR "atmospheric volatilization" OR "surface water" OR "groundwater" OR "residence time" OR "reservoirs" OR " floodplains " OR "transport" OR "particulate nutrient ") AND "freshwater"	*22 of 22*	*38 of 38*
	Search string 4: "nutrient" AND "anthropogenic " AND "great barrier reef" AND ("fertiliser" OR "irrigation" OR "rainfall" OR "slope" OR "erosion" OR "atmospheric volatilization" OR "surface water" OR "groundwater" OR "residence time" OR "reservoirs" OR "floodplains" OR "transport " OR "particulate nutrient ") AND "freshwater"	*6 of 6*	*5 of 5*
	Totals from academic databases (initial screening)	*73*	*136*
B) Search engine (Google Scholar)			
	Search string 1: "nutrient" AND "great barrier reef" AND "freshwater"	*40 of 16,400 (first 130)*	
	Search string 2: "nutrient" AND "anthropogenic" AND "great barrier reef" AND "freshwater"	*45 of 9,540 (first 130)*	
	Search string 3: "nutrient" AND "great barrier reef" AND ("fertiliser" OR "rainfall" OR "hillslope" OR "erosion" OR "surface runoff" OR "groundwater" OR "residence time" OR "reservoirs" OR "floodplains" OR "transport" OR "particulate nutrient") AND "freshwater"	*39 of 15,800 (first 130)*	
	Search string 4: "nutrient" AND "anthropogenic" AND "great barrier reef" AND ("fertiliser" OR "rainfall" OR "slope" OR "erosion" OR "surface runoff" OR "groundwater" OR "residence" OR "floodplains" OR "transport" OR "particulate nutrient") AND "freshwater"	*35 of 9,070 (first 130)*	
	Total items online searches	***729 (95.9 %)***	

C) Manual search		
Date	Source	Number of items added
	Author personal collection	*12 of 21*
	SCS literature submissions	*5*
	Cited in searched items	*5*
	Total items manual searches	***31 (4.1 %)***

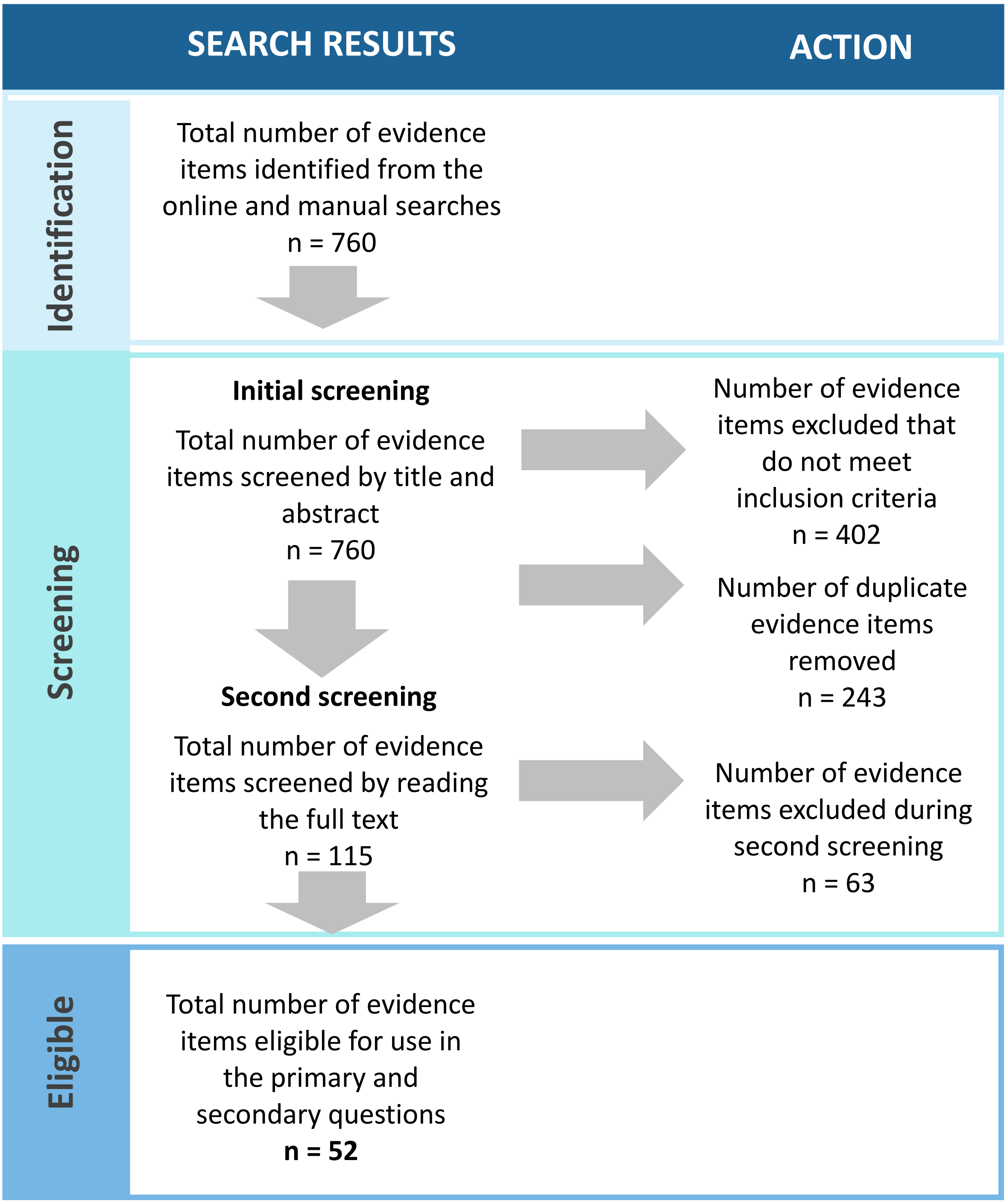


Figure 2. Flow chart of results of screening and assessing all search results for Question 4.5.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

A total of 52 eligible studies were used to address the primary and secondary questions (Figure 3). Of the 52 studies, 37 studies were classed as primary studies, including observational, experimental and modelled studies, and 13 were classed as secondary studies, including reviews or conceptual research. Two studies were classed as mixed (involving a mixture of observational, experimental and modelled or a mixture of observational and reviews). Fifty studies were relevant to the primary question 4.5 (What are the primary biophysical drivers of anthropogenic dissolved nutrient export to the Great Barrier Reef and how have these drivers changed over time?), 17 studies were relevant to the secondary question 4.5.1 (What proportion of nutrient is lost by surface and subsurface pathways?), and 17 papers were relevant to the secondary question 4.5.2 (How do nutrients transform during the transport and delivery to the GBR lagoon (e.g., bioavailability of particulate nutrients)?).

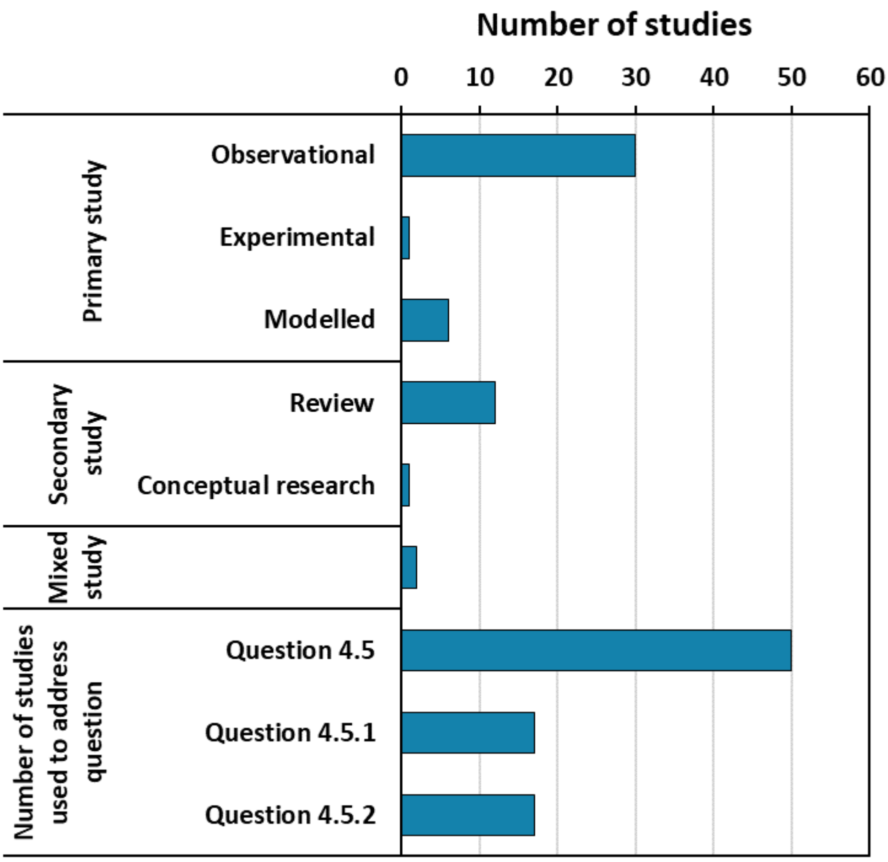


Figure 3. The number and type of studies used to address Questions 4.5, 4.5.1 and 4.5.2.

In terms of the biophysical drivers, such as fertiliser application, rainfall, erosion, surface runoff, groundwater and others, a total of 12 are selected in this literature (Figure 4). Of the 52 studies, 35 (~67%) discussed the impact of rainfall and rainfall intensity on anthropogenic dissolved nutrient export to the GBR, followed by fertiliser and application rates and methods (31 out of 52, ~60%) and erosion (27 out of 52, ~52%). A total of 20 and 17 studies noted the issue of anthropogenic dissolved nutrients delivered by surface and subsurface (groundwater) runoff, respectively. A total of 19 papers examined the impact of topography effects on particulate and dissolved nutrient concentrations, while 14 papers discussed dissolved nutrients on floodplains. Ten and nine studies discussed the influence of irrigation and in-stream processes on dissolved nutrient concentrations, respectively. Eight studies examined the impact of atmospheric deposition on dissolved nutrient concentrations. Six studies examined the impact of residence time and reservoir on dissolved nutrient concentrations.

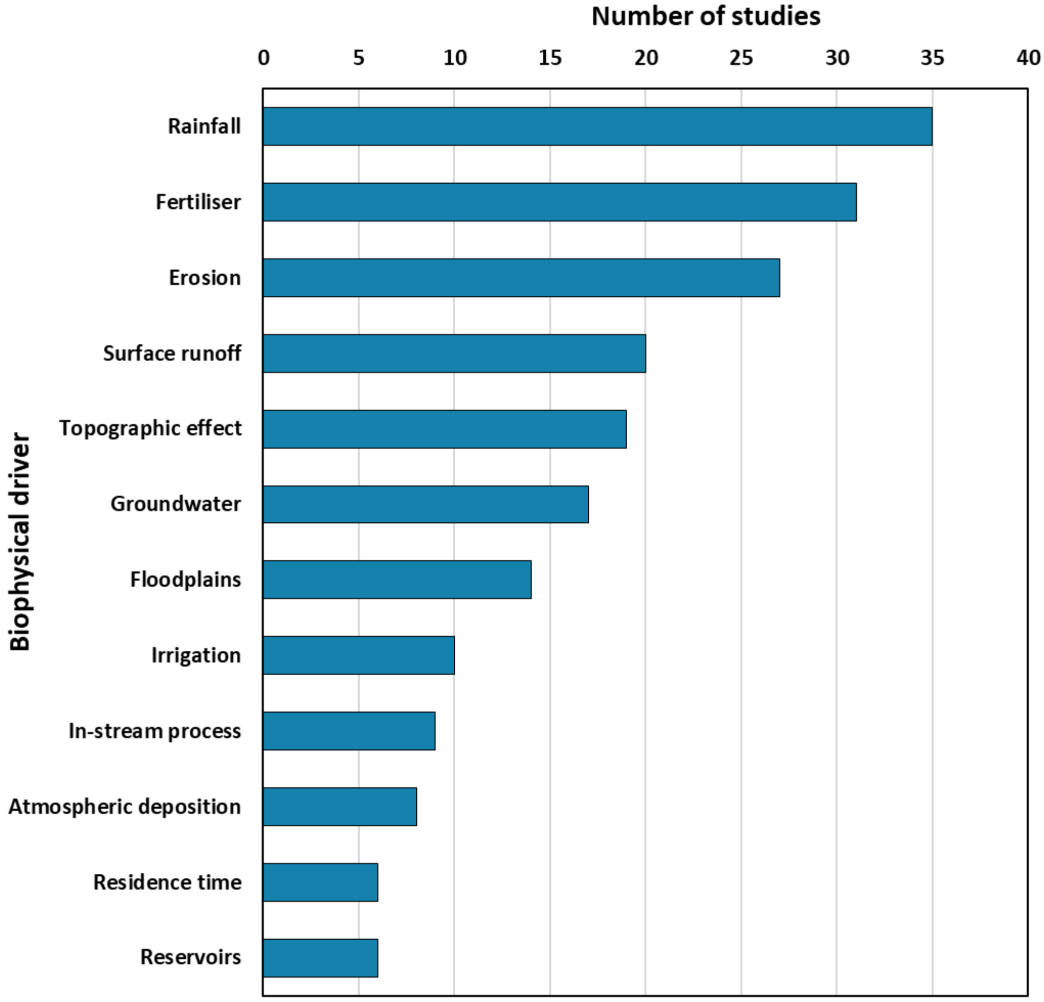


Figure 4. Number of studies by biophysical driver examined in Question 4.5.

Among various dominant land uses generating nutrients (Figure 5), sugarcane was discussed the most (42 studies, ~81%), followed by grazing/dairy (40 studies, 77%). A total of 25 studies examined nutrient concentrations associated with horticulture (mainly banana cultivation), followed by irrigated or dryland cropping (15 studies, 29%). There were 12 studies that described the relationship between nutrient concentrations and urban development. A total of eight studies discussed the influence of other non-agricultural land uses (such as roads, STPs and industry), and seven studies examined cotton/grains with respect to dissolved nutrient concentrations.

Among different regions and climate conditions, the Wet Tropics region was the most discussed (38 studies), followed by the Burdekin (34 studies) and Mackay Whitsunday regions (22 studies) (Figure 6). A total of 20 and 19 studies examined the Cape York and Fitzroy regions respectively, and 17 studies examined the Burnett Mary region. Many of the studies in the Burdekin and Fitzroy regions had a focus on the dry tropics. About 35 studies (67%) targeted rainfall events or were conducted during the wet season.

Among the dissolved nutrients identified from anthropogenic sources, nitrate/nitrite (NOx-N) and filtered reactive phosphate (FRP) (otherwise known as dissolved inorganic phosphorus (DIP)) were discussed in 26 and 25 studies, respectively (Figure 7). A total of 26 studies combined nitrate/nitrite and ammonium into an examination of DIN, followed by dissolved organic nitrogen (DON) (22 studies) and ammonium (NH_4-N, 21 studies). Dissolved organic phosphorus (DOP) was examined in 17 studies. Particulate nitrogen (PN) and particulate phosphorus (PP) were examined in 22 and 16 studies, respectively.

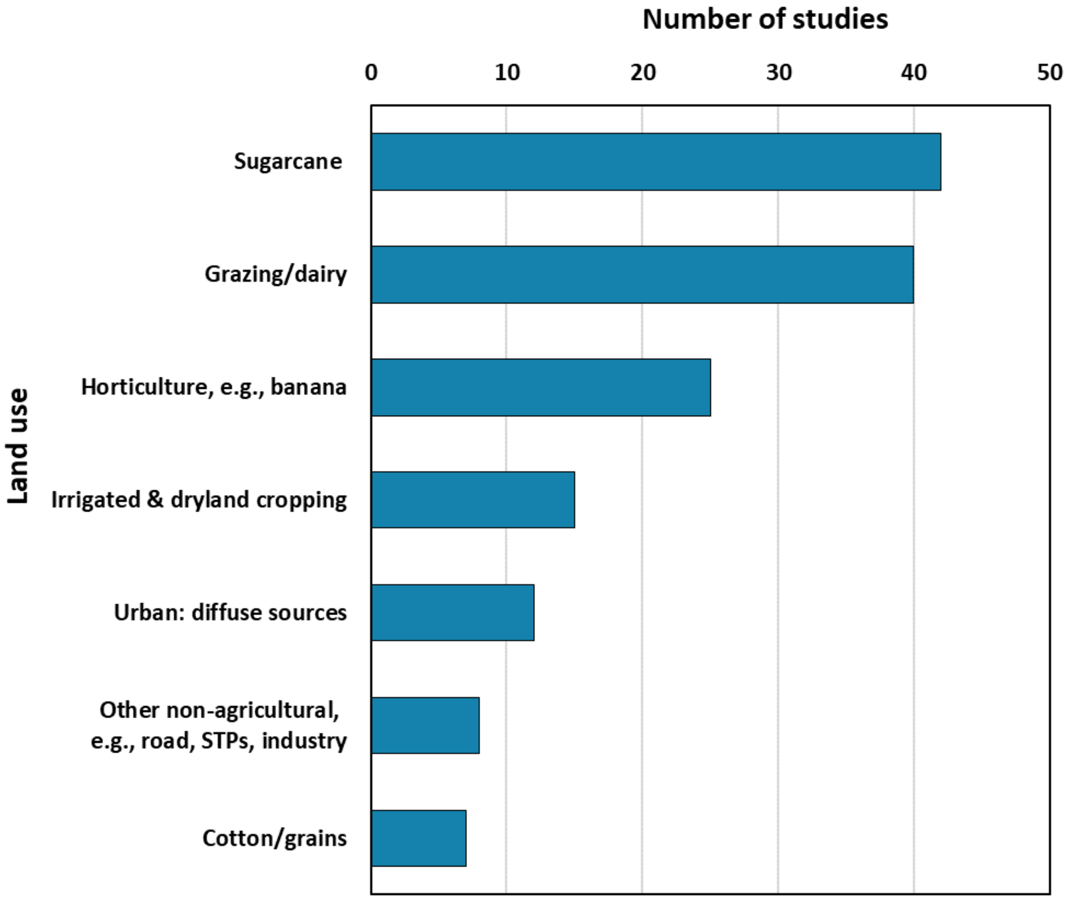


Figure 5. Number of studies by dominant nutrient generating land uses.

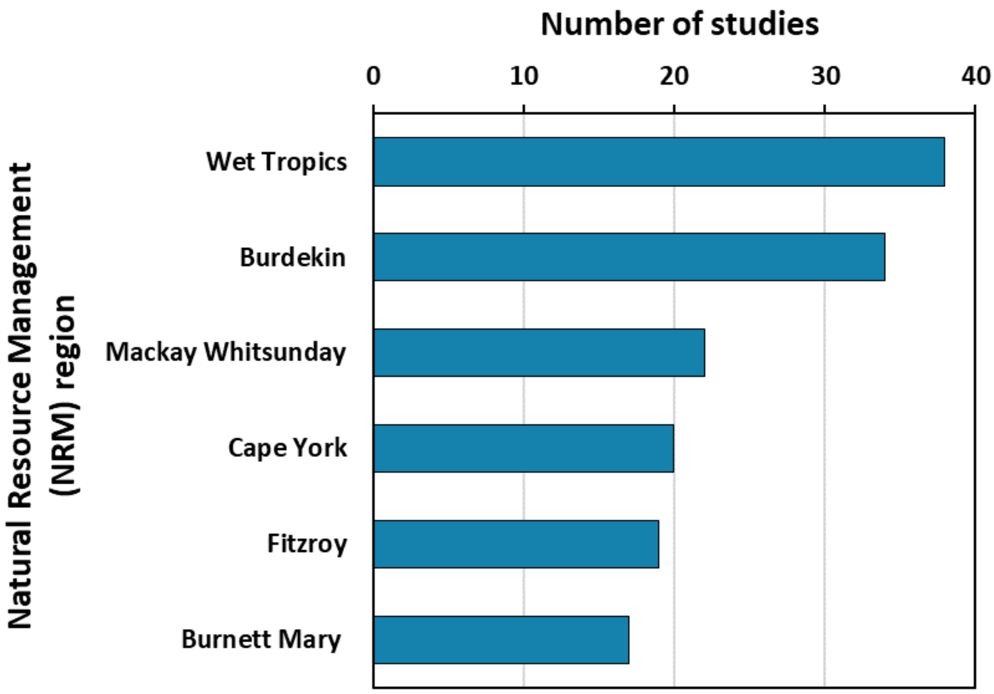


Figure 6. Number of studies by Natural Resource Management (NM) region.

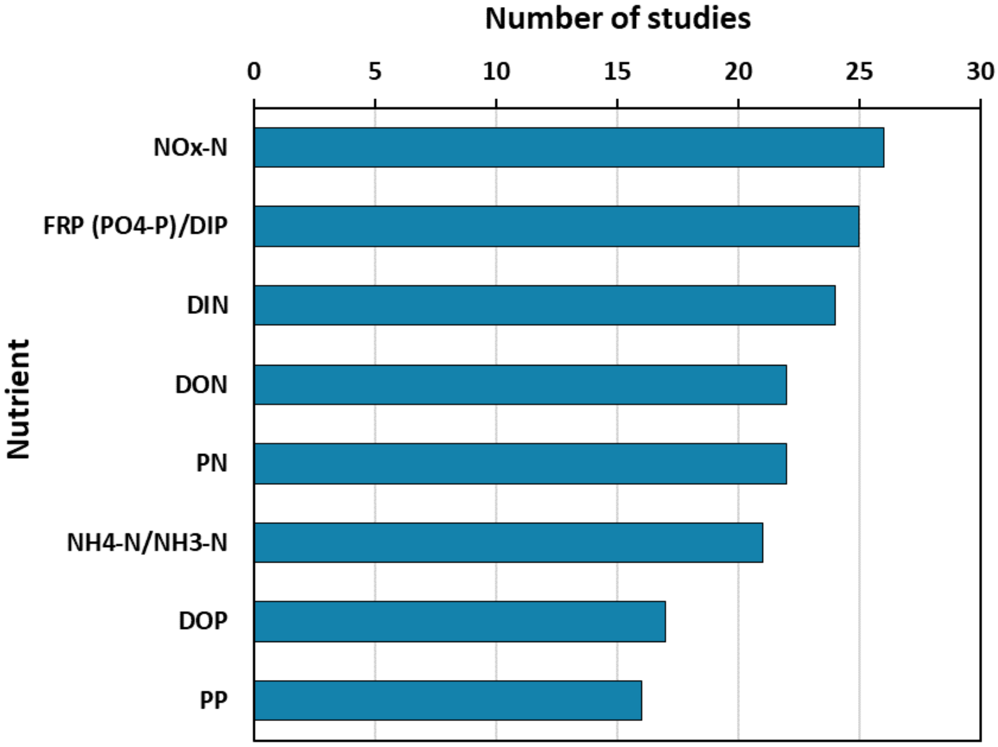


Figure 7. The summary of the nutrients that are measured in all studies (NOx-N = nitrate/nitrite, NH_4-N/NH_3-N = ammonium/ammonia, DIN = dissolved inorganic nitrogen, DON = dissolved organic nitrogen, FRP = filtered reactive phosphorus or DIP = dissolved inorganic phosphorus, DOP = Dissolved organic phosphorus, PP = particulate phosphorus).

4.1.1 Summary of evidence up to 2022

Nutrient transformation that occurs during the transport process in freshwaters can be influenced by a variety of biophysical drivers. Rainfall and associated surface runoff are one of the most important drivers of mobilisation of soluble nutrients within the catchments. This affects multiple factors including water residence time in rivers, the relative importance of surface and subsurface runoff, and interactions with floodplains, which in turn affect nutrient export to the GBR. Fertiliser inputs and erosion are also key drivers to anthropogenic nutrient export to the GBR. The scale of fertiliser inputs and erosion is affected by rainfall and runoff. In this review, 12 primary biophysical drivers were examined (see Figure 1): rainfall and rain intensity, fertiliser application rates and methods, direct release from erosion, irrigation, topography effect (catchment slope), delivery from surface and subsurface runoff, atmospheric deposition, water residence time, presence of reservoirs, interaction with floodplains, river transport and transformation from particulate to dissolved form. There is little or no information on inputs from nitrogen fixation in waterways, so this has not been included. The drivers cover agricultural management practices, environmental factors, catchment characteristics and catchment processes.

4.1.1.1 Rainfall and rain intensity

Rainfall, especially heavy rainfall, can increase nutrient export to the GBR through runoff. Rainfall is one of the most significant drivers of the timing, frequency, intensity and periodicity of water flows and nutrient mobilisation in the GBR catchment area (Adame et al., 2021; Furnas, 2003; Koci et al., 2020). Across the GBR catchment area, annual rainfall averages from <600 mm y^{-1} in some of the inland agricultural grazing districts to ~4,000 mm y^{-1} in some coastal areas, with high inter-annual variability (Furnas, 2003; Thorburn et al., 2013). Cyclones and other less intense low-pressure systems are common and bring large amounts of rainfall (e.g., >300 mm d^{-1}) (Thorburn et al., 2013). As with most tropical and subtropical catchments, mobilisation of dissolved nutrients within the catchments has been shown to occur largely during brief periods of intense rainfall when surface runoff into river systems predominates (Brodie et al., 2015; Furnas, 2003). This also includes particulate nutrients associated with suspended sediments (Bartley et al., 2014; Brodie et al., 2015; Haynes et al., 2007; Howley et al., 2018; 2021; Pearson et al., 2021). For instance, Howley et al. (2021) reported high concentrations of nutrients (NH_4-N, NO_x-N, FRP, PN and PP) and sediments in the upper catchment of the Normanby River during rainfall runoff events, while suspended sediment and nutrient concentrations were generally low across all freshwater sites during baseflow periods. In contrast, DOP and DON concentrations were not significantly different between baseflow or event conditions (Howley et al., 2021). In catchments where rainfall intensities are typically lower, such as the upper Burdekin River, O'Reagain et al. (2005) found that soil and nutrient export were relatively low across all animal grazing strategies.

The review from Adame et al. (2021) noted that catchments of the GBR with high rainfall typically have cropping land, and most of the N pollution is in the form of DIN due to fertiliser runoff. By contrast, in catchments with lower rainfall, land use is dominated by domestic animal grazing and natural vegetation. In these catchments, N exports are mostly in the form of particulate N, primarily due to erosion processes, and particularly gully erosion (Adame et al., 2021). Koci et al. (2020) reported that events with runoff >20 mm (16–25% of all events) generated 79–85% of the total runoff volume and 71–78% of the total suspended solids (TSS), TN, and TP loads. However, Koci et al. (2020) also found that at the event timescale, there were no clear differences in runoff, sediment and nutrient loads among the subcatchments in the Burdekin River system, attributable to variability in catchment conditions (e.g., antecedent soil moisture, rainfall intensity, vegetation) that occur within- and between events. Koci et al. (2020) concluded that recovery of degraded savanna rangelands following reduction in livestock grazing pressure would take decades and was strongly influenced by climate. They suggested that measuring water quality responses to land management change in variable climates requires nested spatial monitoring over long timescales that also include factors that can influence the response (e.g., climate, soil properties, vegetation and land use).

Other studies have also noted that PN and PP loads in wet and wet-dry tropical rivers were strongly correlated with suspended sediment concentrations, which, in turn, were generally correlated with discharge rate (rainfall, stream energy) and catchment erosion (vegetation cover, land use) (Brodie et al., 2015; Brodie & Mitchell, 2005; Tsatsaros et al., 2013). Moreover, sources of increased DON (excluding urea fertiliser) in catchments are associated with improved drainage and other hydrological modifications, fertilised soils and potentially changed rainfall intensities (Brodie et al., 2015).

Studies reported that rainfall contains DIN and contributed about 28% of the longer-term average annual DIN load to the entire GBR catchment area (Hunter & Walton, 2008; Packett, 2017). It is inferred from the studies that the anthropogenic drivers of DIN in rainfall can be attributed to fertiliser use, burning fossil fuels and industrial processes. The importance of domestic animal grazing lands for contributing DIN to rainfall is unknown. Packett (2017) suggested that nutrient data from rainfall would be useful for measuring future input trends for the GBR catchment area and would also be a valuable addition to the global database on atmospheric N pollution.

Lough (2011) presented data showing that since the late 19th century, average rainfall and its variability had increased significantly, with wet and dry extremes becoming more frequent than in earlier centuries. This suggests that a warming global climate may be associated with more variable rainfall in the Queensland tropics. More variable annual rainfall and increased cyclone intensity can increase the risk of nutrient export from crops into the GBR in runoff during intense rainfall events. However, Armour et al. (2022) showed that from 2009 until late 2020, there was significant variation in weather in drought conditions and extreme wet seasons, superimposed on the underlying climate trend to warmer conditions, and reduced rainfall and runoff . Clearly there are differences in prediction with respect to rainfall and runoff between studies and further work is needed.

4.1.1.2 Surface runoff

Surface runoff is one of the important drivers of nutrient export to the GBR. Riverine loads of nitrogen have been identified as the largest source to the GBR, with runoff delivering 900 (400–1,400) g ha^{-1} d^{-1} of DIN during rainfall events in intensively farmed areas (mostly in the form of NO_3-N) (Adame et al., 2021). Several studies reported that the dominant proportion of urea is exported almost entirely in the initial runoff event following application (Armour et al., 2022; Davis et al., 2016; Masters et al., 2017). Urea–N export (in terms of both loads and proportionate contribution to the DON export) occurring after these initial events was relatively minimal, suggesting that the period of substantial urea mobility in surface water runoff is intense but short (Davis et al., 2016). Armour et al. (2022) also showed that the dominant N species in runoff are determined by the period between application and initial runoff event with urea>ammonium>oxidised N from the Tully-Murray basins. The dominant form of N in surface runoff was DIN in the Herbert and Johnstone basins.

Several studies showed that vegetation clearing, and land use changes can increase surface runoff (Armour et al., 2022; Elledge & Thornton, 2017; Thorburn & Wilkinson, 2013; Thorburn et al., 2013). This runoff will have higher sediment and nutrients as shown in a study by Elledge and Thornton (2017). They reported that both the cropped and grazed catchments exported higher loads of sediment and P than the undisturbed Brigalow catchment area; however, the grazed catchment exported less total, oxidised and dissolved nitrogen than the Brigalow catchment. The cropped catchment exported higher loads of all nutrients compared to the grazed catchment. Armour et al. (2022) also reported that grazing and dryland cropping produced twice the runoff volume of native vegetation. Peak runoff rates increased by 96% for grazing and 47% for dryland cropping (Fitzroy grazing). In addition, heavy grazing (0.54 adult equivalent animals ha^{-1}) resulted in 3.6 times more total runoff and a 3.3 times greater average peak runoff rate compared to conservative grazing (0.17 adult equivalent animals ha^{-1}) (Fitzroy grazing). Pastures had lower nutrient export than crops. Event mean concentrations (EMCs) of both total and dissolved fractions of N, P, and TSS were lower from pasture than cropping (Fitzroy grazing). Masters et al. (2017) reported that the plant phase had greater concentrations of DIN in surface water than the ratoon phase for sugarcane. Armour et al. (2022) showed that bare inter-rows in banana cropping had greater runoff than grassed inter-rows, presumably due to the reduced soil infiltration associated with the lack of vegetative ground cover. The grassed inter-row had an average of 46% less runoff compared to the bare inter-rows (Wet Tropics bananas). Legume fallow break crops minimise the nutrients in runoff due to the increase in ground cover. This is also discussed further in Question 3.4 (Wilkinson et al., this SCS).

O'Reagain et al. (2005) showed that most runoff events occur later in the wet season when rain falls on soils with high antecedent soil moisture. In addition, O'Reagain et al. (2005) and Mitchell et al. (2001) reported that the export of sediment and nutrients from sites followed a typical pattern in all runoff events with concentrations being highest early in the event as runoff rates were increasing, but thereafter declined sharply as the event proceeded. This pattern arises from the flushing of accumulated soluble nutrients and sediment from disaggregated soil in the first flush flow.

Judy et al. (2018) demonstrated the importance of colloidal N and the inaccuracy of assuming N <0.45 µm is dissolved N in the sampled areas, as well as providing an alternate explanation for the large amounts of what has previously been defined as dissolved N in runoff from non-fertilised grazing land. Judy et al. (2018) suggested that soil-borne colloids may play an important role in the transport of N within the catchments that discharge into the GBR marine zone, and future studies examining colloid-associated N in surface waters within the Burdekin basin, as well as in the lagoon itself, are necessary.

Armour et al. (2022) reported that export of P in runoff was up to eight times higher in mill mud treatments (127 kg P ha^{-1} applied; 8.5kg ha^{-1} export) compared with treatments of P fertiliser applied at the Six Easy Steps (6ES) recommended application rates (20 kg P ha^{-1} applied; 1.1 kg ha^{-1} export), based on one year of monitoring (Mackay sugarcane). Higher P concentrations in surface soil resulted in greater P runoff export, presumably due to historical mill mud applications (Marian site, Mackay sugarcane).

4.1.1.3 Water residence time

In aquatic systems, water residence time is one of the most important factors affecting the degree to which nutrient transformations can occur in freshwater systems. Water residence time is affected by hydrological regime within each river system and as a result of rainfall and runoff inputs. The GBR catchment area is no different, as Brodie et al. (2015) identified. Brodie and Mitchell (2005) showed that flow events in northern Australian rivers (e.g., the Burdekin) are typically short and energetic, with very short water residence time, with flood-pulse periods typically less than one month and water residence time in rivers approximately one week, ranging from about ten days maximum to only one or two days for the smaller coastal rivers. Several other studies have also identified short residence time during major events in GBR catchments (Connolly et al., 2015; Pearson et al., 2021; Thorburn et al., 2013; Tsatsaros et al., 2013).

Nutrient transformation processes are likely to be limited within the water residence timeframes of high flow events (Brodie & Mitchell, 2005; Connolly et al., 2015; McKergow et al., 2005; Thorburn & Wilkinson, 2013; Thorburn et al., 2013; Tsatsaros et al., 2013). Additionally, nutrient loads, in dissolved and particulate forms, increase significantly in rivers during rainfall events. This coupled with the short water residence time during events, means that the majority of nutrient loads generated in catchments will end up in the GBR, putting significant pressure on coastal ecosystems (Brodie & Mitchell, 2005; Brodie et al., 2015) (also refer to Questions 4.6, Thorburn et al., and 4.7, Waltham et al., this SCS).

4.1.1.4 Fertiliser application rates and methods

A key source of anthropogenic nutrients export to the GBR is driven by fertiliser application rates and methods. The total amount of fertiliser applied in northern Australia has increased rapidly since 1950 due to both the increased cultivation areas and increased rates of fertiliser application (Brodie & Mitchell, 2005; Furnas, 2003; Kroon et al., 2016) (also refer to Question 2.3, Lewis et al., this SCS). Studies reported that the increase of DIN in surface water runoff was largely related to the increased use of inorganic nitrogen fertiliser on crops, particularly sugarcane (Bainbridge et al., 2009; Brodie et al., 2015; Brodie & Mitchell, 2005; Burton et al., 2015; Fraser et al., 2017; Haynes et al., 2007; Kroon et al., 2016; Lewis et al., 2021; Masters et al., 2017; McCloskey et al., 2021a; Thorburn et al., 2013; Tsatsaros et al., 2013). Additionally, a strong positive relationship between both nitrate and DIN concentrations in rivers and streams, and fertiliser-added land use (FALU) has been described in several studies (Bainbridge et al., 2009; Connolly et al., 2015; Mitchell et al., 2009; Thorburn & Wilkinson, 2013). The results strongly indicate that most of the nitrate or DIN in streams with a high proportion of FALU land use is derived from nitrogen fertiliser. In contrast, the correlation between FRP and FALU was considerably weaker (Connolly et al., 2015; Mitchell et al., 2009). Additionally, a study by Bainbridge et al. (2009) in the Tully-Murray basin, found that the concentrations of all forms of P species were low across all land uses reflecting relatively low soil erosion. Phosphorus is typically strongly bound to soils (i.e., in the particulate form).

The N use efficiency (NUE) of fertiliser applied to crops was deemed to be low in a number of older studies, with an estimated 35–40% of the fertiliser applied to sugarcane being used by crops in the year of application (Haynes et al., 2007; Mitchell et al., 2009). As a result of this relatively low efficiency, a large fraction of the nitrogen lost has been shown to be transported into adjacent streams and rivers (Brodie & Mitchell, 2005; Haynes et al., 2007; Thorburn & Wilkinson, 2013). Fertiliser, such as urea, is often applied when rainfall is anticipated to ensure penetration into the soil. This further increases the likelihood that urea, or its dissociated product, ammonium, will be carried into local surface waters (Armour et al., 2022; Davis et al., 2016; Thorburn et al., 2013). Moreover, the nitrogen from fertiliser can be transported into groundwater during rain events (Armour et al., 2022; Brodie & Mitchell, 2005; Connolly et al., 2015; Haynes et al., 2007; Hunter, 2012; Rasiah et al., 2010; Thorburn et al., 2013). Several studies show that fertiliser was one of the main sources leading to elevated nitrate levels in deep drainage areas and groundwater (Armour et al., 2013; 2022; Brodie & Mitchell, 2005; Hunter, 2012; Rasiah et al., 2010; Shishaye et al., 2021).

Increased concentrations of urea (a form of DON) in waterways from urea-based fertilisers is also a concern, as urea constitutes a significant proportion of the nitrogen fertiliser within the GBR catchment area (Brodie et al., 2015; Davis et al., 2016). Appreciable concentrations of urea-N have been detected in freshwater systems adjacent to heavily fertilised cropping lands but this was based on a small number of measurements (Brodie et al., 2015; Davis et al., 2016). Urea typically constitutes a small proportion of DON in aquatic systems so it is unclear whether DON loads are measurably increasing as a result of increased urea loads across the GBR catchment area (Brodie et al., 2015). Management of urea fertiliser use is a priority as urea-N and ammonium, as disassociated urea, are readily bioavailable to phytoplankton and bacteria (Brodie et al., 2015; Davis et al., 2016).

The principles of managing nitrogen fertiliser to reduce nitrogen export from GBR cropping lands are well understood (Kroon et al., 2016; Thorburn & Wilkinson, 2013; Thorburn et al., 2013). Much of the focus of managing nitrogen fertiliser in cropping systems aims to increase nitrogen use efficiency by various management practices (Thorburn et al., 2013; Thorburn & Wilkinson, 2013). Studies have shown that nitrogen fertiliser inputs can be reduced while maintaining similar crop yields for sugarcane and banana production (Armour et al., 2022; Connolly et al., 2015; Kroon et al., 2016; McKergow et al., 2005; Thorburn & Wilkinson, 2013; Thorburn et al., 2013). Armour et al. (2022) showed that reduced fertiliser application rate reduced N export in runoff and deep drainage areas in sugarcane production areas (Wet Tropics sugarcane, Mackay sugarcane). Armour et al. (2022) also reported that N export from banana crops was driven by N fertiliser rate and application method. In ratoons, a lower N application rate at fortnightly intervals in fertigation (fertiliser application) water reduced DIN runoff, with no reduction in yields (Wet Tropics bananas). Fraser et al. (2017) found that runoff after liquid fertiliser applications had higher initial DIN concentrations, though these concentrations diminished more rapidly in comparison to granular fertiliser applications. Several studies mentioned that the timing of fertiliser application is critical to reducing nutrient concentrations in runoff, particularly relative to periods of rainfall and irrigation (Armour et al., 2022; Brodie et al., 2015; Fraser et al., 2017; Thorburn et al., 2013).

Several studies discussed the changes to fertiliser rates over time, although this review does not examine fertiliser use (see Question 4.6, Thorburn et al., this SCS). Mitchell et al. (2009) showed that fertiliser application rates on sugarcane crops in the Tully–Murray–Hull catchments have declined by 25% since 2000,and the fertiliser application rate for bananas has declined by 40% since 1995, with probable further declines during the overall 20-year period of sampling (1987–2007). Lewis et al. (2021) also suggested that the banana industry reduced N fertiliser rates during the 1990s and 2000s (industry average 520 kg ha^{-1} in the mid-1990s down to 298 kg ha^{-1} in 1997) while improvements in fertiliser application (fertigation) and the adoption of grassed inter-rows are reducing nutrient and sediment exports. However, Kroon et al. (2016) reported that total N fertiliser usage across the GBR catchment area increased significantly from 1910 to 2012–2013.

4.1.1.5 Crop irrigation

Irrigation for the production of crops is a driver of anthropogenic nutrient export. The 2013 SCS identified several mechanisms from irrigation that cause nutrient export. First, the higher the yields of irrigated crops, the higher the fertiliser application, leading to an increased chance of nutrient export. Additionally, application of irrigation water itself can exacerbate nutrient export processes. Lastly, low efficiency irrigation systems, such as furrow irrigation, can increase nutrient export through runoff, and deep drainage where the water moves below the root zone of plants. Deep drainage is a natural process that leads to the recharge of groundwaters and springs that may flow into creeks and rivers; however excess infiltration from irrigation can exacerbate the process and increase nutrient leaching and transport via subsurface pathways.

The review from Brodie and Mitchell (2005) showed that nutrient concentrations downstream of irrigated sugarcane lands in the Burdekin River were higher than those upstream, with the highest concentrations in sugarcane-growing areas. Bores used for irrigation in the Mackay and Burdekin regions had relatively high nitrate concentrations, and it was surmised that this was due to infiltration of nitrogen fertiliser application on crops (Brodie & Mitchell, 2005). Several studies noted that the highest nutrient exports were from lower Burdekin sugarcane farms that were furrow irrigated and associated with dry season furrow irrigation applied after fertiliser applications (Armour et al., 2022; Davis et al., 2014; Davis et al., 2016). The timing of rainfall and/or irrigation, and application of fertiliser has been shown consistently to be critical in affecting the proportion of those constituents that are found in runoff, deep drainage, plants, or via other pathways across the agricultural industries evaluated. Deep drainage was a more significant export pathway than runoff in many of the sugarcane and banana sites (Wet Tropics sugarcane and bananas, Burdekin Delta sugarcane and Bundaberg sugarcane by inference) and can be a significant export pathway for nutrients, depending on the soil type, rainfall intensity or irrigation frequency (Armour et al., 2022).

Thorburn et al. (2013) identified that crop irrigation was common in coastal floodplains in the GBR catchment area with low rainfall (less than 2,000 mm y^{-1}), and the combined amount of rainfall and irrigation in those regions, such as the Burdekin region, can be similar to rainfall in the wet tropics. However, some knowledge gaps remain in understanding the fate of nutrients associated with irrigated agriculture. These are given in Table 8.

4.1.1.6 Direct nutrient release from erosion

Domestic animal grazing (52%), riparian zones (30%) and conservation areas (14%, i.e., natural sources), are the major land uses contributing eroded soil to waterways, and increasing suspended sediment and particulate nutrient export to the GBR (Bainbridge et al., 2009; Bartley et al., 2014; Brodie et al., 2015; Brodie & Mitchell, 2005; Howley et al., 2018; 2021; Kroon et al., 2012; McCloskey et al., 2021b; Thorburn & Wilkinson, 2013; Thorburn et al., 2013) (also refer to Question 3.4, Wilkinson et al., this SCS). Brodie et al. (2015) reviewed the literature on erosive processes and found that relative contributions from surface and subsurface soils, and different soil types affect the amount of eroded PN. Fine particles derived from surface soils are typically higher in N than fine particles derived from subsurface soils. However, the quantity of soil eroded from a particular source also needs to be factored in when determining dominant source contributions (i.e., large quantity of subsurface soil at low concentration can contribute a higher load of N to the system than a smaller quantity of a higher concentration surface soil) (Brodie et al., 2015; Burton et al., 2015; Garzon-Garcia et al., 2018a; McCloskey et al., 2021b; McKergow et al., 2005). McCloskey et al. (2021b) also found a correlation between export of particulate nutrient loads and fine sediment loads, given that PN and PP can be adsorbed to sediment particles. The Burdekin and Fitzroy regions were the largest contributors of particulate nutrient loads to the GBR (Kroon et al., 2016; McCloskey et al., 2021b). In basins other than the Burdekin and Don, where gully erosion dominates, hillslope erosion (topography effect) was assessed as the greatest source per unit area of particulate nutrient loads across the GBR basins (McCloskey et al., 2021b; McKergow et al., 2005).

The contribution of particulate nutrients, particularly those associated with fine sediment loads, to the bioavailable nutrient pool in the GBR has been examined (Burton et al., 2015; Garzon-Garcia et al., 2018a; 2018b; 2021). Garzon-Garcia et al. (2021) found that microbial mineralisation transformed PN into bioavailable nitrogen (BAN), i.e., DIN, over relatively short timeframes. The degree to which particulate nutrients are bioavailable depends on the sediment characteristics, which will vary with soil type, land use and sediment source (Burton et al., 2015; Garzon-Garcia et al., 2018b). For instance, Burton et al. (2015) reported that fine (<10 µm) sediment from surface soil erosion processes was enriched in bioavailable N and P, relative to fine sediment of subsurface origin. Studies also reported that as PN and PP were mobilised in the water column, some chemical desorption of nutrient species, such as ammonium and phosphate, could occur, thereby increasing DIN and DIP concentrations (Brodie & Mitchell, 2005; Garzon-Garcia et al., 2021). Garzon-Garcia et al. (2021) also reported the desorption of ammonium as particulate inorganic nitrogen (PIN) from eroded soil when riverine sediment enters estuaries. Garzon-Garcia et al. (2018a) reported that modelled DIN generated from sediments eroded from grazing catchments (in this instance in the Burdekin) accounts for a significant proportion of the end-of-system DIN measured and modelled in these catchments. McCloskey et al. (2021b) suggested that particulate nutrient bioavailability, as well as fine sediment and dissolved nutrient hotspots, needs to be taken into account in terms of ecosystem effects of erosion. Garzon-Garcia et al. (2018a) suggested that PN and bioavailable nutrients from eroded soil need to be prioritised separately from sediment in all catchments, and DIN generation from erosion should be included when undertaking cost-benefit analysis of various management options for reducing DIN.

4.1.1.7 Subsurface (groundwater) inputs to rivers

Studies have found that groundwater that receives infiltration from agricultural activities can be a significant source of N, and subsurface input from groundwater to rivers can be one of the important drivers that leads to nutrient export to the GBR. However, there are very few studies of groundwater to date, and this warrants more studies.

Fertiliser N is lost through direct runoff of dissolved and soil-attached N, and through infiltration of dissolved N through the soil column into groundwater reserves, which has been discussed in the previous Section (4.1.1.4 Fertiliser application rates and methods). Several studies have reported that higher groundwater discharge to streams increased nitrate concentrations in rivers and streams (Brodie & Mitchell, 2005; Connolly et al., 2015; Furnas, 2003; Hunter, 2012; Hunter & Walton, 2008). Hunter (2012) showed that median nitrate concentrations in groundwater were significantly higher than the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC and ARMCANZ 2000) for surface waters in the Wet Tropics, Lower Burdekin, and Mackay Whitsunday regions. Of the three areas, the Wet Tropics had the highest proportion of groundwater discharge to rivers and creeks compared to coastal or submarine discharge, with the average annual total groundwater discharge generally <10% of average annual streamflow (Hunter, 2012). Hunter (2012) noted that around 40% of the samples collected from 409 bores on 313 farms across the lower Burdekin floodplain contained nitrate at concentrations >5 mg nitrate-N L^{-1}. Thorburn et al. (2013) also reported high N concentrations in groundwaters in the cropped coastal plains of the Burdekin, Mackay, Whitsunday, and Burnett Mary regions. Moreover, Brodie and Mitchell (2005) reported that high nitrate concentrations periodically detected in pristine areas may be due to the groundwater discharge to the stream, often after the main peak flow. Furnas (2003) reported that the highest nitrate concentrations occurred at the end of the dry season when high nitrate groundwater inputs make a larger relative contribution to water in the Herbert River. In addition, groundwater is an important source of nitrate in the wet tropics rivers (e.g., Herbert and Tully basins) where there is usually some rain throughout the year (Furnas, 2003). Shishaye et al. (2021) found that very high nitrate concentrations (~12 mg-N L^{-1}) were detected in 'younger' groundwater (~1-year) at greater depths (>25 m), below perched and locally confined systems. Increased groundwater age and decreased nutrient concentrations were detected in the unconfined aquifer, while old-groundwater (~160-years) and lower nitrate (<3 mg-N L^{-1}) concentrations were detected in the confined systems. These studies suggest that groundwater contribution to river base flow, particularly during the dry season, could potentially deliver a considerable amount of nitrate to streams (Brodie et al., 2015; Connolly et al., 2015; Hunter, 2012). A study also showed that in sugarcane growing areas of the Johnstone basin, groundwater levels can rise rapidly following major rainfall events with nitrate being supplied from all aquifers, contributing to the elevated stream nitrate levels (Hunter & Walton, 2008). The same study also reported that groundwater discharge to rivers may occur relatively rapidly (e.g., shallow discharge to drains), with groundwater-borne contaminants potentially entrained in receding floodwaters.

Thorburn et al. (2013) highlighted that knowledge of the interactions between N in groundwaters, and in streams and rivers was unclear. However, the research to date suggests that land use contribution of nutrients to groundwater with subsequent flow into waterways, could be substantial. Adame et al. (2021) also reported that there was limited knowledge on the role of groundwater in the total N budget of catchments.

4.1.1.8 Topography effects

Topography effects are also identified as a driver that influences nutrient export, particularly PN, to the GBR. Several studies highlighted the disproportionate contribution of hillslope erosion (a topography effect) to particulate (and potentially bioavailable) nutrient catchment export per unit mass of eroded sediment, when compared to subsurface erosion (gully and streambank) (Brodie et al., 2015; Burton et al., 2015; Garzon-Garcia et al., 2018a; McCloskey et al., 2021b; McKergow et al., 2005). This is because surface soils are generally richer in particulate nutrients compared to subsurface soils. In some circumstances, hillslope erosion may be a smaller contributor to the overall sediment load, but it may be a bigger contributor to the PN load (Brodie et al., 2015; McCloskey et al., 2021b). As PN is sourced from erosion, understanding the relative role of hillslope (and rill erosion), gully and streambank erosion is key to erosion management. However, there are knowledge gaps in the delivery mechanisms for particulate nutrients from different erosion sources (Brodie et al., 2015).

Brodie et al. (2015) reported that PN derived from erosion on agricultural grazing lands derives from all forms of erosion - gully, streambank and hillslope. However, other studies suggest that the proportion from channel erosion (gullies and streambanks) is much greater than hillslope sources (Garzon-Garcia et al., 2021; Hancock et al., 2014; Olley et al., 2013; Wilkinson et al., 2013) (also refer to Question 3.4, Wilkinson et al., this SCS).

The topography within catchments can also impact nutrient transport to waterways. Howley et al. (2021) noted that during flood events, suspended sediment and nutrient concentrations were significantly higher in freshwater sites in the steeper, upper Normanby catchment compared to the lower catchment floodplain. However, the effect of catchment slope could not be differentiated from a range of other factors, such as differences in stream power, soil type and anthropogenic soil disturbances. Bainbridge et al. (2009) also showed that lower suspended sediment concentrations were likely the result of more ground cover in the catchment from regular, year-long rainfall in the Tully–Murray basins. Davis et al. (2016) applied random forest models to examine the impact of various parameters including paddock slope (m/m), annual paddock runoff volume (mm), irrigation and rainfall on urea proportionate contribution to annual total dissolved nitrogen (TDN) exports. However, slope was ranked 10 out of 14, lower than interim rainfall and annual runoff, but higher than soil type, event volume, crop tillage system and crop residue treatment.

Koci et al. (2020) suggested that the time it took for sediment and nutrients generated via hillslope and gully erosion processes to reach stream channels varied depending upon the size and intensity of the rainfall event, time between successive events, and overall hydrological and sediment connectivity. Armour et al. (2022) found that cattle ramps and ramp trails (cattle trail leading to a cattle ramp) on streambanks resulted in increased hydraulic connectivity with surrounding hillslope areas via interception and concentration of runoff in the Fitzroy River basin. Alluvial gullies appeared to be initiated by cattle ramp trails intercepting and concentrating hillslope runoff onto streambank ramps. Armour et al. (2022) suggested that the potential increase in hydraulic connectivity between hillslope, floodplains and the stream network, via cattle ramps and ramp trails, required investigation. New technology such as mobile LiDAR or drone-photogrammetry data could be combined with topography software to more effectively map these impacts.

4.1.1.9 Reservoirs

The review from Brodie et al. (2015) showed that reservoirs increase water residence time in rivers, resulting in significant transformation of N, in addition to direct trapping of PN. This is consistent with findings of studies globally. The major forms of N transported during the inflow events into reservoirs were found to be DON, PN and nitrate. Phytoplankton rapidly assimilate nitrate. PN is sedimented and a proportion is subsequently remineralised by the microbial community to ammonium in the anoxic bottom waters. This source of ammonium can be used by the phytoplankton community, converted to nitrate by nitrifiers, or released in the outflow. Several studies reported that the reservoirs in the GBR basins, such as the Burnett, Pioneer, Burdekin, Tully and Barron, trapped a significant proportion of the TSS river loads, and by inference PN and PP loads (Bartley et al., 2014; Kroon et al., 2012; Lewis et al., 2013). McCloskey et al. (2021b) mentioned that trapping or storage of fine sediment in reservoirs was based on the storage capacity of the reservoir, the length (the longest impoundment length from the dam wall at full capacity) and discharge rate of the reservoir. In the study, particulate nutrient trapping was based on the same Lewis trapping models as that for fine sediment (McCloskey et al., 2021b). McKergow et al. (2005) incorporated nutrient export and exchange, including storage of all forms of nutrients, denitrification of DIN and the deposition of particulate nutrients, into GBR reservoirs in a catchment nutrient model.

Brodie and Mitchell (2005) reported that reservoirs, such as Teemburra Dam on the Pioneer River and Peter Faust Dam on the Proserpine River, export nitrate that has originally entered the reservoir as PN or DON, but was transformed to nitrate over time. Brodie et al. (2015) identified that the remineralisation of N which originally entered as other forms of N, in particular particulate forms, means that N released from impoundments is likely to be more bioavailable to promote algal blooms.

Brodie et al. (2015) also mentioned that reservoirs were very effective at retaining sediment and P, but far less effective at retaining N. Typically P is more closely associated with sediment, and a higher proportion is buried. This differential effect of reservoirs and other impoundments on retention of N and P means that the stoichiometry of outflow water may shift towards higher N relative to P. The effect on ecological processes and biological communities downstream is unclear.

4.1.1.10 Interaction with floodplains

Several studies showed that rivers and floodplains in the mid- and lower catchment can be a sink for sediments and nutrients (PN, PP, DON, NOx and FRP) (Howley et al., 2018; 2021; McKergow et al., 2005; Wallace et al., 2009). Load calculations for the Normanby basin showed nutrient and sediment load reductions of between 65 and 85% between the upper and mid-catchment regions, confirming that sediments and nutrients were settling out, or biologically used, in the central and lower Normanby floodplains (Howley et al., 2018; 2021). The sediment load reduction is also supported by modelling for pollutant load reductions due to improved management practices in the GBR, in which approximately half of the generated sediment in the Normanby basin was deposited mainly in the floodplain (McCloskey et al., 2016). Wallace et al. (2009) showed that in the Tully basin, a large proportion (up to 30%) of the total load of N and suspended sediment was present in waters in overbank flow on the floodplain. McKergow et al. (2005) suggested that floodplain and reservoir deposition of particulate nutrients are significant stores of nutrients, and these are most significant in the larger catchments.

In the Wet Tropics region, much of the floodplain area in the downstream parts of catchments is used for agriculture, with Connolly et al. (2015) recording chronic leaking of nutrients from the agricultural floodplain through subsurface flows. Hunter (2012) noted riparian sites, such as in the lower Burdekin floodplain, near areas of groundwater discharge to the Burdekin River and Barratta Creek, were shown to reduce nitrate concentrations. Furnas and Mitchell (2000) observed upstream–downstream differences between concentrations of nitrogen species in the lower Herbert River indicating that the floodplain was the major source of DIN, chiefly nitrate, exported from the Herbert basin. A portion of the DON generated in the upper catchment was biologically consumed or oxidised on the floodplain (Brodie et al., 2015) (also refer to Question 4.7, Waltham et al., this SCS). Davis et al. (2014) reported that higher in-stream nitrate concentrations were observed in lower Burdekin floodplain waterways during wet-season flood events compared to low flow conditions. The considerable inorganic nutrient loading was from tailwater runoff and groundwater leachate inputs sourced from local sugarcane farms. Nitrate concentrations in many surface water systems such as Barratta Creek are now consistently well above Australian and New Zealand Marine and Freshwater Water Quality Guidelines (ANZECC and ARMCANZ 2000) for ecosystem protection (Davis et al., 2014).

4.1.1.11 Atmospheric deposition

Hunter and Walton (2008) reported that rainwater contains very low levels of dissolved nutrients (the median total N and total P concentrations were 0.05 mg L^{-1} and 0.01 mg L^{-1}, respectively and ammonium and nitrate concentrations were 0.013 mg L^{-1} and 0.010 mg L^{-1}, respectively), but that increased ammonium concentrations were sometimes recorded in rainwater, which can be due to volatilisation of ammonia from animal excreta and surface-applied urea fertiliser. Based on the median concentration, estimated inputs of N in wet precipitation ranged from around 0.8 kg N ha^{-1} y^{-1} (upper catchment, mean annual precipitation 1,673 mm) to 1.8 kg N ha^{-1} y^{-1} (lower catchment, 3,545 mm), with corresponding P inputs of around 0.2–0.4 kg P ha^{-1} y^{-1}, respectively. They also reported that around 10% of P in rainwater was FRP and 90% was DOP. Packett (2017) collected rain samples for three years in the Fitzroy River and the Pioneer River, targeting various rain events, including storms, monsoons and cyclones. Results suggest rainfall contributed ~37% of the average annual DIN load from the Fitzroy River over three wet seasons but ranged from 5 to >100%. An estimate from the study, using measured and modelled data, indicated rainfall contributed about 28% of the longer-term average annual DIN load to the entire GBR catchment.

Several studies identified that the contribution of atmospheric deposition to DIN export from GBR catchments was relatively low compared to other more developed regions due to the lower human population density and associated industrial N emissions (Adame et al., 2021; Brodie & Mitchell, 2005; Furnas, 2003; Thorburn & Wilkinson, 2013). Projections on how climate change will impact N and P rainfall loads is needed for assessing catchment management outcomes, and regional trends in atmospheric deposition (Armour et al., 2022; Brodie & Mitchell, 2005; Packett, 2017).

4.1.1.12 In-stream processing

Reviews by Brodie and Mitchell (2005), and Brodie et al. (2015) identified that discharge of N to the GBR from rivers had increased alongside agricultural development and intensification in the GBR catchment area over the last 180 years. Adame et al. (2021) developed a conceptual model of nitrogen dynamics for the GBR catchment area, which was typical of the factors to be considered for most catchments globally. The study identified the need to consider that channels cross landscapes of different characteristics including varied geology, climate, landform, soil type, vegetation and land use. These characteristics impact N inputs through runoff and erosion, sediment transport and N processing. The high spatial and temporal variation in flows impacts these transformations.

High river flows occurring at a frequency of 0.25 y^{-1} (i.e., once every four years) have been identified for dry tropics rivers, including the Fitzroy and Burdekin, through to 3 flows per year for wet tropics rivers, such as the Tully (Brodie et al., 2015). During these high flow periods, more than 80% of the nutrient load can be discharged from the Tully River, and more than 98% of the nutrient load from the Burdekin River. First flush events at the beginning of the wet season can result in disproportionately high nutrient concentrations as outlined above.

A review by Brodie and Mitchell (2005) concluded that soil derived N and P both display minimal instream processing and high delivery to coastal waters during high flow events. Most N and N occurs in dissolved forms, particularly where derived from fertiliser applications, such as in the wet tropics, or associated with fine sediment fractions with very low settling velocities. Both these forms enhance transport in high flow events, while short residence time minimises in-stream processing, resulting in a high delivery ratio (proportion of nutrient source reaching the river mouth) to coastal waters.

Adame et al. (2021) summarised nutrient transformation processes that typically occurred in river systems globally, for example, nutrient removal by in-stream processes such as denitrification in sediments, uptake by aquatic plants, and sediment storage in rivers. The study did not find any published measurements on important processes such as denitrification in rivers, streams or in-channel lakes in the GBR catchment area. Thorburn and Wilkinson (2013) suggested that in-catchment N removal processes (such as in-stream denitrification) were unlikely to significantly impact export loads because water transport time across land and waterways were low during significant runoff events.

In the Normanby basin, sedimentation was shown to trap almost half of the particulate N load (Howley et al., 2018; 2021). Additionally, particulate and organic N can be mineralised by microorganisms, with the scale of this dependent on the characteristics of the sediment and litter (Garzon-Garcia et al., 2018b). Another study showed that there were three DIN generating processes from PN - solubilisation, and mineralisation of both DON and PON. Solubilisation was by far the greatest contributor compared to mineralisation (Garzon-Garcia et al., 2018a).

4.1.1.13 Transformation from particulate to dissolved forms

The study from Burton et al. (2015) showed that the proportion of surface and subsurface sediments in runoff would affect the scale of bioavailable nutrient loads at end-of-system. This study indicated that fine (<10 µm) sediment from surface soil erosion processes was enriched in bioavailable N and P, relative to fine sediment of subsurface origin. The enrichment varied depending on the bioavailable nutrient pool and soil type. In a basin such as the Burdekin, where the contribution of subsurface sediments can be high (~90%), although relatively low in bioavailable nutrients they are likely to be a significant source. In addition, Burton et al. (2015) reported that land use affected bioavailability of nutrients in fine sediments, with quantities increasing in the order: grazing<cane=bananas<dairy. Cattle tracks may be a source of sediments with elevated levels of bioavailable N. Garzon-Garcia et al. (2018a) reported that DIN generated from sediment yields (kg DIN generated kg^{-1} of eroded sediment ha y^{-1}) were much higher in the Johnstone basin than in the Bowen River catchment, and that large modelled yields of DIN from fertiliser dominated the DIN source to end-of-catchment in the Johnstone. However, sediment will likely continue to generate DIN from PON mineralisation as it is transported further in the estuary and the marine environment which may increase the importance of DIN generation from eroded soils in the Johnstone basin on the GBR. In the Johnstone basin, although conservation (i.e., natural sources of nutrients), and sugarcane dominated sediment export, and sugarcane alone dominated PN

export, modelling results indicated that dairy might be an important source of DIN generated from eroded sediment at the end-of-catchment (39% contribution) together with sugarcane (44% contribution) (Garzon-Garcia et al., 2018a).

A recent study from Garzon-Garcia et al. (2021) quantified the bioavailable nitrogen (BAN) contribution from the riverine plumes to GBR coastal environments (also refer to Question 4.1, Robson et al., this SCS). The results suggested that microbial mineralisation was an important source of BAN, and particulate inorganic nitrogen conversion to DIN was an important process in short timeframes (25% to 100% of the generated load). Additionally, the potential BAN from two dry tropics riverine plumes (Burdekin River) was considerable (9–30% added to the end-of-catchment DIN load). Another study from Garzon-Garcia et al. (2018b) also noted that sediments delivered to freshwater and marine environments could make important contributions to the aquatic bioavailable nutrient pool. Nutrients in sediment could promote phytoplankton growth, with nutrient bioavailability depending not only on sediment load, but also sediment characteristics associated with its parent soil. These characteristics varied with soil type, land use and erosion process. Adame et al. (2021) and McCloskey et al. (2021b) both highlight that mineralisation from sediments can account for a variable proportion of exported inorganic N.

Synthesis of secondary questions

4.5.1. What proportion of nutrient is lost by surface and subsurface pathways?

As identified above, there are limited studies on subsurface pathways for nutrient loss, and therefore estimating the proportion of nutrients lost by surface versus subsurface pathways is problematic. Several studies have examined or discussed nutrient export by surface and subsurface pathways, primarily focusing on agricultural areas (Armour et al., 2013; Bohl et al., 2000; Brodie & Mitchell, 2005; Haynes et al., 2007; Hunter, 2012; Masters et al., 2017; McCloskey et al., 2021a; Rasiah et al., 2010; 2011). The proportion of nutrients lost by surface and subsurface pathways can be affected by many factors such as soil types, land uses, vegetative ground cover, rainfall, fertiliser application and irrigation practices (Armour et al., 2013; 2022; Bohl et al., 2000; Masters et al., 2017; Rasiah et al., 2010). Considerable variability in nutrient export was measured between sites and years.

Nitrate export via subsurface flow were measured over two relatively wet years on a range of soil types in the Ripple Creek area of the lower Herbert catchment in the Wet Tropics, including export to groundwater (vertical deep drainage) and via lateral flows from shallow perched water tables (0–1 m depth) (Bohl et al., 2000). From an agronomic perspective, N export to groundwater (17 kg ha^{-1} y^{-1}) and drains (8 kg ha^{-1} y^{-1}) were relatively small. However, there was considerable variation between sites and years, for example, sandy soils on the riverbank showed export to groundwater of around 70 kg N ha^{-1} y^{-1}. Further, as noted by the authors, the timing of fertiliser application, relative to rainfall, may have been an important factor in the results (as may the timing of the monthly to bimonthly sampling).

Monitoring of subsurface drainage of nitrate under bananas in the Tully catchment was conducted annually over the 6-month wet season (December–May) from 2004 to 2006 (Rasiah et al., 2010). Mean nitrate concentrations were 5.3 mg nitrate-N L^{-1} in leachate at approximately 1 m depth in the soil profile; 2.0 mg nitrate-N L^{-1} in an adjacent drain at approximately 3 m depth; and 4.1 mg nitrate-N L^{-1} in groundwater across the three seasons. Wet-season nitrate concentrations at 1 m depth in this study were lower than those reported under fertilised bananas in the study by Armour et al. (2013), possibly due to the much lower rates of fertiliser application used in the more recent Tully study (300–450 kg N ha^{-1} y^{-1}).

Masters et al. (2017) reported N export through runoff, deep drainage and lateral interflow in sugarcane in the Wet Tropics region. The study showed that total N export in runoff ranged from 6–11 kg N ha^{-1} in the plant crop and 8–12 kg N ha^{-1} in the first ratoon, across a range of management options, with the proportion of total N in the form of DIN averaging 97% and 54%, respectively. Total N export in deep drainage ranged 0.3–16 kg N ha^{-1} per crop year with the majority of total N consisting of DIN (primarily as oxidised–N). Considerably higher export would be expected in average to above average rainfall years. DIN export in drainage was greatest in plant crops ranging from 5–16 kg N ha^{-1} across all treatments, compared to 0.3–5 kg N ha^{-1} in the first ratoon. This was despite greater rainfall and N application rates in the first ratoon, further reflecting the inefficiency of a developing root system to take up available N. In addition, Masters et al. (2017) indicated a portion of drainage leachate was rapidly moving laterally through the soil profile and into the neighbouring drainage channels. Although the amount of DIN moving laterally via interflow into the bordering channel was not quantified in this study (i.e., total load), it was suggested that it was likely to be a substantial proportion of the DIN measured in deep drainage (i.e., between 0.3–16 kg N ha^{-1}).

McCloskey et al. (2021a) found that in sugarcane and banana cropping areas, seepage was the dominant modelled DIN transport pathway across all associated GBR regions. In sugarcane crops, the contribution of modelled surface DIN loads (to export) was <30 y^{-1} (up to ~70 t y^{-1}) per subcatchment, compared to the seepage loads which were predominantly >30 t y^{-1} (up to 90 t y^{-1}) per subcatchment. Comparatively, in banana crops, the contribution of modelled surface DIN loads (to export) was <0.5 t y^{-1} (up to ~0.7 t y^{-1}) per subcatchment, compared to the seepage loads which were predominantly >3 t y^{-1} (up to 12 t y^{-1}) per subcatchment.

A recent study by Armour et al. (2022) reported that deep drainage (or subsurface flow) moving laterally into neighbouring drains or into groundwater, was the main pathway for off-site water movement at two monitoring sites in rain-fed sugarcane crops in the Tully-Murray. At these sites, deep drainage accounted for 23–42% of the annual water budget, while runoff accounted for 6–14% of the annual water budget. Deep drainage contained the greatest amount of N (primarily NO_X-N) lost offsite (up to 13 kg N ha^{-1} y^{-1}). Total N in runoff was 2–9 kg N ha^{-1} y^{-1}, of which DIN was <4 kg N ha^{-1} y^{-1}. In addition, Armour et al. (2022) suggested that deep drainage was a larger export pathway than runoff at many sugarcane and banana sites (Wet Tropics sugarcane and bananas, Burdekin Delta sugarcane and Bundaberg sugarcane by inference).

The review by Hunter (2012) found very few studies of P transport, transformation or reduction in subsurface environments beneath the plant root zone. There were two exceptions, both conducted in the Wet Tropics. In the Johnstone basin, a study of the P mass-balances of plant and ratoon crops of bananas and sugarcane found leaching export of P below 60 cm were negligible (Moody et al., 1996). This result was not unexpected, given the strongly P-sorbing Ferrosol soils on which the crops were grown. By contrast, however, monitoring of 24 bores in the Johnstone basin found inorganic P (FRP) to be present in groundwater, at median concentrations in the range of 0.005–0.22 mg P L^{-1} (Rasiah et al., 2011). Similarly, in the Tully basin, inorganic P was found in both groundwater (up to 0.16 mg P L^{-1}) and drains (up to 0.11 mg P L^{-1}). Organic P was also present in samples from both basins, and comprised on average 38% of the total dissolved P (Rasiah et al., 2011). These levels of P in groundwater were surprising given the expectation that P would be bound in soils via the high clay content in both study areas. It is possible that P transport into groundwater may have occurred via bypass flow, rather than through the soil matrix (Rasiah et al., 2011).

The limited studies comparing subsurface versus surface export pathways for nitrogen show that subsurface pathways may be important for export of N from soils to waterways, and in some cases, may be dominant. Subsurface transport processes are influenced by a range of factors including soil type, fertiliser application timing, rate and method, and crop stage (root development). Very few studies for P exist from which to draw conclusions.

4.5.2. How do nutrients transform during the transport and delivery to the Great Barrier Reef lagoon (e.g., bioavailability of particulate nutrients)?

For the question examining how nutrients transform during transport and delivery to the GBR lagoon, there were a total of nine relevant papers. All studies focused on N transformation. Studies showed that a range of processes transform N (Adame et al., 2021; Brodie et al., 2015; Brodie & Mitchell, 2005; Connolly et al., 2015; Garzon-Garcia et al., 2018b; 2021; McCloskey et al., 2021b). The processes, which are typical of those found in all aquatic systems, include: nitrification-denitrification which may remove N from the system; direct N uptake and storage by algae and aquatic plants; desorption of ammonium as PIN from eroded soil; microbial conversion of particulate nitrogen into more bioavailable forms, such as ammonium, which are then used by algae and aquatic plants; and photo-oxidative and microbial conversion of DON into more bioavailable forms, which may also be used by algae and aquatic plants (Adame et al., 2021; Brodie et al., 2015; Brodie & Mitchell, 2005; Connolly et al., 2015; Garzon-Garcia et al., 2018b; 2021; McCloskey et al., 2021b). Adame et al. (2021) quantified the denitrification rates from rivers (in-stream) and Garzon-Garcia et al. (2021) determined the potential mineralisation rates of organic N from riverine plume samples. Other processes include sedimentation and chemical binding of nutrients to particles (McKergow et al., 2005). All the studies from the current search ignore another significant microbial process, i.e., anaerobic ammonium oxidation (anammox), which converts ammonium and nitrate/nitrite to N gas in the absence of oxygen, and without the need for a carbon supply.

Most information in this section was covered in the previous sections, but a summary of the key findings is provided here.

- Removal of N via denitrification is limited in rivers due to short residence time as a result of rapid flow rates in coastal river systems draining the major areas of cropping.
- Adame et al. (2021) reviewed N processes including denitrification and did not find any studies in GBR catchment area but compared two studies in a wetland and a river in southeast Queensland and found that denitrification rates were higher than aquatic plant uptake (study in one river with invasive para grass). Another study showed that trees have low potential to remove N (Connolly et al., 2015).
- McKergow et al. (2005) reported that about a third of the dissolved inputs of P are predicted to become attached to sediment during transport and thus would be deposited on floodplains and in reservoirs.
- Sedimentation in floodplains can cause trapping of almost half of the particulate N load (Howley et al., 2018; 2021). In addition, wetlands and reservoirs trap not only a large amount of PN due to sedimentation (Adame et al., 2021; Brodie et al., 2015), but also result in significant transformations of N.
- Garzon-Garcia et al. (2021) reported the desorption of ammonium or PIN from eroded soil when riverine sediment enters estuaries.
- Garzon-Garcia et al. (2021) found potential DIN generation from suspended particulate matter in some riverine plumes that is likely to provide a considerable source of DIN to GBR coastal environments during plume conditions.

In addition, Brodie et al. (2015) reported that while N is generally considered the major limiting nutrient in marine waters, both globally and in the GBR, limitation among N, P and silica vary, even in marine waters, in time and space. Thus, it is quite possible that P can limit primary productivity at certain times in the GBR and at certain locations. As a result, P transformation processes should not be ignored.

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

Of the 52 studies, 21 (~40%) were published for the period 2016–2022, with 15 of these examining the impact of rainfall on nutrient concentrations and species, followed by erosion (13 studies), fertiliser contribution (12 studies), surface runoff (10 studies), particulate nutrient and topography effects (both 8 studies). Four studies examined in-stream processes, irrigation effects, floodplains and subsurface flow. Two studies examined atmospheric deposition. Only one study explicitly discussed water residence time.

In terms of the findings, recent studies continue to identify fertiliser inputs, erosion, surface runoff and rainfall as key factors affecting nutrients in freshwater. There was an increased number of studies on particulate nutrients, specifically on the transformation from particulate to dissolved form (termed bioavailable nutrients) in freshwater, reflecting an increased understanding the importance of this process. With the exception of studies on the importance of particulate nutrient transformations, there has been limited progress in our understanding of GBR freshwater systems in the last 5–6 years.

There are some significant findings, particularly in terms of land use effects, and management actions. Specifically, studies have shown that:

- Reducing the fertiliser application rate reduced N export in runoff and deep drainage areas in sugarcane fields (Wet Tropics sugarcane, Mackay sugarcane).

- The period between N application and first runoff determined the dominant N species (urea>ammonium>nitrate) in runoff and to a large extent, the total N export (Wet Tropics sugarcane, Mackay sugarcane).
- Subsurface application of N fertiliser reduced runoff export compared to surface application with no decrease in sugarcane yield. However, the effects on deep drainage export to waterways were not examined (RainSim).
- Particulate N may be the dominant species in runoff where sediment export is high and conversely dissolved export has been minimised through optimised application rates and timing (e.g., during plant and fallow stages) (Mackay sugarcane).
- N export from banana crops is driven by N fertiliser rate and application method. In ratoons (a new shoot that grows from near the root or crown of crop plants), a lower N application rate at fortnightly intervals in fertigation water (also resulting in a lower total N rate per crop cycle) reduced DIN export in runoff, with no reduction in yields (Wet Tropics bananas).
- Export of P in runoff was up to eight times higher in treatments with mill mud applications (127 kg P ha^{-1} applied) compared with treatments applied with the Six Easy Steps (6ES) recommended application rates (20 kg P ha^{-1}). This was based on one year of monitoring. (Mackay sugarcane).
- Higher P concentrations in surface soil resulted in greater P runoff loss, presumably from historical mill mud applications (Marian site, Mackay sugarcane).
- Pastures had lower nutrient export than crops. Event mean concentrations (EMCs) of both total and dissolved fractions of N and P, and TSS, were lower from pasture than cropping land use (Fitzroy grazing).
- A recent study also demonstrated that definitions of particulate and dissolved N may be inaccurate as colloidal N passes through filters typically used in monitoring and research studies. This may provide an alternative explanation for the significant concentrations that have previously been defined as DIN N in runoff from non-fertilised grazing land.
- Floodplains can be a significant sink for nutrients.

4.1.3 Key conclusions

Key conclusions from the body of evidence are that:

- Increased rates of fertiliser application, increased cultivation area, low efficiency irrigation systems and heavy rainfall can lead to increased nutrient export, especially nitrogen, in surface runoff, deep drainage and groundwater. Considerable variation in nutrient export can occur between sites and years.
- Rainfall and subsequent runoff events can lead to substantial increase in nitrogen loads (in dissolved and particulate form) in GBR rivers. Highly variable flow regimes range from extended periods of low rainfall, through to extreme rainfall events causing extensive flooding. This spatial and temporal variation leads to high levels of uncertainty in generalising about nutrient loads, forms and their transformations.
- Subsurface inputs of nutrients to freshwater systems (such as via groundwater movement) are increasingly being recognised as important sources of nutrient delivery to the GBR, but in the few studies reviewed, the contribution of subsurface inputs relative to inputs from surface runoff was highly variable. Deep drainage was a larger export pathway than surface runoff from many of the sugarcane and banana sites in the Wet Tropics basins, Burdekin Delta and Bundaberg. Studies have shown potentially high nitrogen loadings to groundwater and have inferred a significant contribution of subsurface nitrogen to dissolved inorganic nitrogen loads in streams. However, there is limited quantification of the spatial and temporal contribution of groundwater in the context of the total nitrogen budget of basins.
- The proportion of nutrients exported by surface and subsurface pathways has not been quantified but can be affected by many factors such as soil type, land uses and management, vegetative ground cover, rainfall, fertiliser application and irrigation practices.
- In several studies undertaken in the Wet Tropics and Mackay Whitsunday Natural Resource Management regions, matching nitrogen supply to crop nitrogen requirements, better

application methods (subsurface application or different fertiliser forms) and the timing of rainfall and/or irrigation contributed to reduced nitrogen export in runoff while maintaining similar crop yields.
- Increased residence time in rivers during periods of low flow can allow for further in-stream processes which transform, store or remove nutrients, e.g., denitrification in sediments, uptake by aquatic plants and sediment storage in the rivers. However, the relative importance of different processes for nutrient export requires further study.
- Floodplains typically act as a sink for sediment and nutrients (both particulate and dissolved) and therefore effective management of floodplains is important for reducing nutrient (and sediment) loads at the end-of-catchments.
- Microbial mineralisation and chemical processes in freshwaters have been shown to make nitrogen more bioavailable, particularly conversion of particulate nitrogen to dissolved inorganic nitrogen. Bioavailability depends on sediment characteristics such as soil type, land use and sediment source (surface or subsurface). The few studies investigating these processes have been conducted in the Burdekin and Wet Tropics regions, and very little research into nutrient transformation has been conducted in other regions, including the source of land-based dissolved inorganic nitrogen from the Fitzroy region.
- Studies showed that reservoirs in the GBR catchment area are responsible for significant trapping and transformation of nutrients, particularly phosphorus, due to their increased water residence time. Remineralisation processes within reservoirs typically increase the proportion of bioavailable nutrients which has the potential to promote algal growth both within reservoirs and impact rivers downstream. These findings support those of other studies globally.
- More studies focus on nitrogen compared to phosphorus. This is, in part, because nitrogen is generally considered the major limiting nutrient in marine waters, both globally and in the GBR. Additionally, phosphorus is typically strongly bound to soils. However, it is possible that phosphorus can limit primary productivity in rivers and the GBR at times and at certain locations. As a result, phosphorus transformation processes should not be ignored and the impact of anthropogenic phosphorus discharges to rivers/streams should be determined.

4.1.4 Significance of findings for policy, management and practice

This review examined the primary biophysical drivers that influence anthropogenic dissolved nutrient export to the GBR, and how these drivers change over time. In addition, this review aimed to determine the proportion of nutrients that is lost by surface and subsurface pathways and understand the transformation of nutrients during the transport and delivery to the GBR lagoon, but with a focus on freshwater. It is clear that since the 2017 SCS, there has been little change in our understanding of the dominant sources and transformations of nutrients in GBR catchment area. Much of the research has broadened our knowledge across time and over a greater area, has consolidated previous findings. However, in terms of nutrient transformations, there are relatively few novel studies, with the exception being that soil-derived particulate nutrients are a more important source of bioavailable nutrients in freshwaters (and marine waters) than previously considered.

The main drivers of anthropogenic nutrient loss have been identified as fertiliser, erosion, rainfall and rainfall intensity, surface runoff and instream process, and groundwater. Managing N fertiliser to reduce N export, and erosion to reduce fine sediment and particulate nutrients is well understood. For example, studies have shown reducing the fertiliser application rate reduced N export in runoff and deep drainage in sugarcane. Typically, studies have not examined the relative importance of these drivers or their linkages in detail; however, in terms of management of the GBR catchment area, it is important that such linkages and their interacting effects are considered. Additionally, climate variability, including droughts and extreme rainfall events can lead to a variability on the export of N from the land to waterways. This also impacts the capacity of rivers and streams to transform nitrogen.

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

- Many studies related to nutrient export by surface and subsurface pathways focus on agricultural areas, in particular nitrogen export from sugarcane of the Wet Tropics. Therefore, investigation of other crops, such as banana and other horticulture, is required.
- Export of DON from urea-based fertiliser used in grain cropping and livestock grazing.
- Improved quantification of deep drainage export and linkages to loads entering the GBR.
- Greater understanding of the interactions between N in groundwaters and in streams and rivers, and the role of groundwater in the total N budget of catchments.
- Information on nutrient transformations and their role in assimilating nutrients in rivers is still very limited. For instance, the origin and fate of refractory DON are unclear, including whether it is mineralised or consumed by bacteria, and the role of organic carbon inputs in stimulating this.
- Nitrogen mineralisation in rivers and the effect on ammonium (NH_4-N) exports is poorly understood.
- Managing for particulate nutrient bioavailability, as well as fine sediment and dissolved nutrient hotspots, is becoming a higher priority and requires more information about where hotspots of nutrients are located in the catchments.
- Spatial knowledge of bioavailable N (BAN), especially for high priority catchments with the highest sediment loads, such as the Fitzroy, Herbert and Mary River basins.
- The impact of anthropogenic phosphorus discharges to rivers and streams.
- The function of floodplains and their effect on nutrient transformation and assimilation.

4.1.5 Key uncertainties and/or limitations

- The majority of studies included are from sugarcane land use. There were only a few studies on other agricultural crops or relating to urban sources.
- There are studies relating to nutrient export by surface and subsurface pathways. However, most studies focus on agricultural areas and N (not P). The proportion of nutrients lost by surface and subsurface pathways can be affected by many factors such as soil type, vegetative ground cover, climatic condition, fertiliser application and irrigation practices. Considerable variability in nutrient exports can be found between sites and years.
- There are few studies which examine the transformation processes of nutrients in soil and water in detail, and it is often difficult to generalise within and across the GBR catchment area. Additionally, the importance of various transformation processes will vary over different hydrological states within each catchment system. Therefore, there is a high level of uncertainty in the links between hydrological states and transformations which makes it difficult to assess and predict the effectiveness of management actions.
- There is some limited coverage of understanding in some regions from the GBR (e.g., DIN from the Fitzroy region is poorly understood).

4.2 Contextual variables influencing outcomes

Twelve biophysical factors were selected in this literature review to discuss their influence on anthropogenic dissolved nutrients export to the GBR. The detail information is discussed in section 4.1.1 (Summary of evidence up to 2022).

Table 7. Summary of contextual variables for Question 4.5.

Contextual variables	Influence on question outcome or relationships as per conceptual model
Land uses	• Cattle grazing, sugarcane and broad-acre cropping Excess river sediment and nutrient loads to the GBR lagoon are derived from: i) surface and subsurface erosion, predominantly in rangeland cattle grazing settings; and ii) fertiliser applications in sugarcane and broad-acre cropping (Brodie et al., 2015; Elledge & Thornton, 2017; Furnas & Mitchell, 2000; Furnas,

Contextual variables	Influence on question outcome or relationships as per conceptual model
	2003; Hunter & Walton, 2008; Joo et al., 2012; Kroon et al., 2012; 2016; Mitchell et al., 2009; Thorburn et al., 2013; Tsatsaros et al., 2013).
Rainfall	• Rainfall intensity Rainfall intensity affects nutrient loss. Particulate and dissolved nutrient concentrations in streams and rivers substantially increased following heavy rainfall (Bartley et al., 2014; Brodie et al., 2015; Haynes et al., 2007; Howley et al., 2018; 2021; Pearson et al., 2021). Soil and nutrient exports were relatively low across all livestock grazing strategies due to a combination of significant ground cover, low slope topography and low rainfall intensities in the upper Burdekin River catchment (O'Reagain et al., 2005).
Fertiliser	• Rates of fertiliser application • Fertiliser-additive land use areas • The N use efficiency of applied fertiliser The increased rates of fertiliser application, increased cultivation areas and low nutrient use efficiency can lead to increased nutrients, especially N loss which can subsequently reach adjacent streams and rivers (Bainbridge et al., 2009; Brodie & Mitchell, 2005; Connolly et al., 2015; Haynes et al., 2007; Kroon et al., 2012; 2016; Mitchell et al., 2009; Thorburn & Wilkinson, 2013; Thorburn et al., 2013). • The types of fertiliser The increase of DIN in rivers and groundwater is largely related to the increased use of inorganic N fertiliser in crops (Bainbridge et al., 2009; Brodie et al., 2015; Brodie & Mitchell, 2005; Burton et al., 2015; Fraser et al., 2017; Haynes et al., 2007; Kroon et al., 2016; Lewis et al., 2021; Masters et al., 2017; McCloskey et al., 2021a; Thorburn et al., 2013; Tsatsaros et al., 2013). However, a concern is that urea-based fertilisers constitute a significant proportion of the fertiliser N applied within the GBR catchment area (Brodie et al., 2015). Armour et al. (2022) also reported that N export from banana crops was driven by N fertiliser rate and application method. In ratoons, a lower N application rate at fortnightly intervals in fertigation (fertiliser application) water reduced DIN export in runoff, with no reduction in yields (Wet Tropics bananas). Fraser et al. (2017) found that runoff after liquid fertiliser applications had higher initial DIN concentrations. • The timing of fertiliser application The timing of fertiliser application is critical to reducing nutrient concentrations in runoff, particularly relative to rainfall and irrigation (Armour et al., 2022; Brodie et al., 2015; Fraser et al., 2017; Thorburn et al., 2013).
Erosion	• Rangelands with animal grazing, riparian zones and conservation (i.e., natural sources) areas are the major land uses contributing eroded soil to waterways, increasing suspended sediment and particulate nutrient export to the GBR (Bainbridge et al., 2009; Brodie et al., 2015; Brodie & Mitchell, 2005; Howley et al., 2018; 2021; Kroon et al., 2012; McCloskey et al., 2021b; Thorburn & Wilkinson, 2013; Thorburn et al., 2013). • Erosion rates, rainfall, soil type, land use and sediment source can affect the total sediment load and also the nutrient bioavailability (Brodie et al., 2015; Garzon-Garcia et al., 2018b; 2021; McCloskey et al., 2021b; McKergow et al., 2005).
Surface runoff	• Rainfall, clearing and land use changes can increase surface runoff (Armour et al., 2022; Elledge & Thornton, 2017; Thorburn & Wilkinson, 2013; Thorburn et al., 2013).

Contextual variables	Influence on question outcome or relationships as per conceptual model
Groundwater	• Land use, irrigation, rainfall, groundwater age and depth can affect the nutrients in groundwater discharge to rivers (Brodie et al., 2015; Hunter, 2012; Shishaye et al., 2021; Thorburn & Wilkinson, 2013; Thorburn et al., 2013).
In stream process	• Geology, climate, landform, soil type, vegetation and land use can impact N inputs through runoff and erosion, sediment transport and N processing in rivers (Adame et al., 2021).
Hillslope	• Hillslope erosion (topography effect) is considered the major source of particulate nutrients across the GBR catchment area (Brodie et al., 2015; Burton et al., 2015; McCloskey et al., 2021b; McKergow et al., 2005).
Irrigation	• The timing of rainfall and/or irrigation The timing of fertiliser application is critical to reducing nutrient concentrations in runoff, particularly relative to rainfall and irrigation (Armour et al., 2022; Brodie et al., 2015; Thorburn et al., 2013). • Irrigation frequency/type/efficiency Irrigation frequency can affect nutrient export through deep drainage which is a significant export pathway for nutrients (Armour et al., 2022).
Residence time	• Nutrient transformation mediated by bacterial action and denitrification requires considerable time. However, those processes may be limited for rivers with short residence time during major runoff events (Brodie & Mitchell, 2005; Connolly et al., 2015; McKergow et al., 2005; Thorburn & Wilkinson, 2013; Thorburn et al., 2013; Tsatsaros et al., 2013).
Reservoirs	• Reservoirs typically increase water residence time in river, resulting in significant transformation of N and P, in addition to direct trapping of PN and PP (Bartley et al., 2014; Brodie et al., 2015; Kroon et al., 2012; Lewis et al., 2013).
Floodplains	• Floodplains can be a sink for sediments and nutrients (PN, PP, DON, NOx and FRP) (Howley et al., 2018; 2021; McKergow et al., 2005; Wallace et al., 2009).

4.3 Evidence appraisal

Relevance

The overall relevance of the body of evidence to the primary question was rated as Moderate. The spatial and temporal relevance of the body of evidence to the question were both rated as Moderate. A total of 38% (20 out of 52) and 42% (22 out 52) of the studies were given a High or Moderate score respectively for the relevance of the study approach and reporting of results relevant to the question. Approximately 31% (16 out of 52) and 42% (21 out of 52) of the studies had a High or Moderate spatial relevance score, respectively. Approximately 27% (14 out of 52) and 35% (18 out of 52) of the studies were given a High and Moderate temporal relevance score, respectively. The scores were given based on several factors described below.

- The relevance of the study approach and study results was assessed as *High* in which 37 studies were primary studies, including observational, experimental, modelled information. A total of 13 studies were secondary studies, including reviews and conceptual frameworks. Two studies were mixed studies, including a mixture of observational, experimental and modelled or a mixture of observational and reviews. The study approach and results are relevant to the primary or the secondary questions and the study design directly addresses the question. Most studies considered more than one form of dissolved inorganic nutrient, as well as land use. Most studies examined more than one primary biophysical driver.

- The relevance or generalisability of the spatial scale of studies was Moderate. All studies were within the GBR catchment area with 50% (26 out of 52) of studies covering at least two of the six NRM regions. Several studies, especially for modelling, covered all the 35 GBR basins. For studies only covering one region, several locations were selected for study and comparisons. As discussed in the section on summary of study characteristics (Table 1), the selected studies covered different land uses and climate conditions of the GBR.
- Relevance or generalisability of the temporal scale of studies was Moderate. Most of the primary studies were carried out over two years, with multiple measurements conducted during that period. A total of 35 studies (67%) targeted rainfall events, and more than two rainfall events were captured. For several modelling studies, the models were run for a fixed 28-year climate period (1986–2014) to normalise the effects of climate variability on constituent loads being exported to the GBR.

Most selected studies were relevant to the conceptual model (Figure 1). However, there was one study by Judy et al. (2018) which provided important new information. It demonstrated the importance of colloid-associated N as a component of dissolved N and could provide an alternate explanation as to how non-fertilised grazing land can contribute substantial amounts of N to aquatic environments. Several studies discussed the impact of policy and agricultural management practices on nutrient and sediment loads.

Consistency, Quantity and Diversity

The consistency for the overall body of evidence was Moderate for the primary question. Findings across the primary and secondary studies were generally consistent, reporting similar conclusions on the impacts of primary biophysical drivers on the forms and loads of dissolved nutrients. For example, several studies reported that increased rates of fertiliser application, increased cultivation areas and low nutrient use efficiency could lead to increased nutrient, especially N, export into adjacent streams and rivers. Additionally, studies discussed the impact of rainfall intensity on nutrient loss. There was a high degree of consistency between studies that particulate and dissolved nutrients, and suspended sediment concentrations in streams or rivers increased substantially following heavy rainfall.

A total of 52 studies is considered to be a Moderate representation of evidence used to answer the question, explained below. There were three different study types used in the review: 1) primary studies (experimental, observational or modelled); 2) secondary studies (reviews or Systematic Reviews); and 3) mixed studies (a mixture of observational, experimental and modelled or a mixture of observational and reviews). Of these, 37 studies (71%) were classed as primary studies, 13 (25%) were secondary studies and two (4%) were mixed studies. For the primary studies, 81% were observational,3% were laboratory experiments and 16% were modelling studies. A High rating was therefore given to the diversity of studies.

A number of studies were excluded using pre-defined exclusion criteria and quality appraisal. This was because:

- The study did not examine primary biophysical drivers.
- The study did not examine anthropogenic dissolved nutrients (dissolved inorganic nitrogen and phosphate) in freshwater.
- The study did not examine agriculture (sugarcane, horticulture, banana, irrigated and dryland crops, and grazing), urban (diffuse sources) and other non-agricultural land uses (roads, STPs and industry).
- The study location was outside Australia.

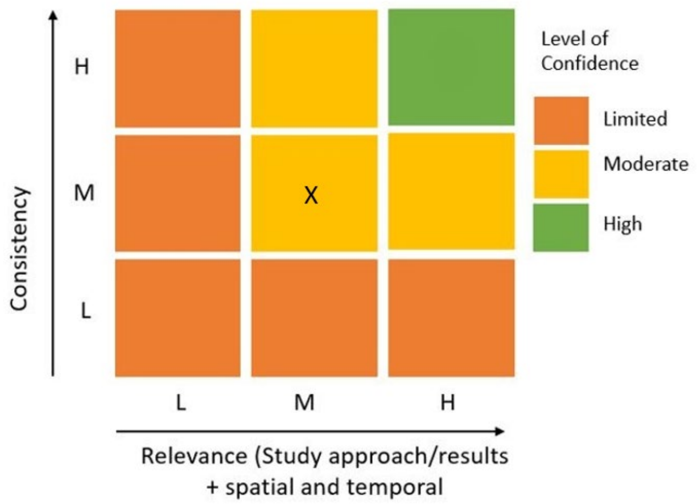
Overall, the pool of evidence (n=52) used for this review was assessed as Moderate due to:

1) Consideration of the inclusion/exclusion criteria used for the question.
2) The number of studies used by similar reviews or other synthesis.
3) The frequency of duplicate returns during the search process across multiple academic databases.

Confidence

The Confidence rating for the primary question based on the overall relevance rating and Consistency was Moderate as shown in Table 8 below. As discussed above, Consistency for the overall body of evidence was Moderate as findings across 35 studies were generally consistent. The Relevance rating for the body of evidence was determined to be High. The Moderate Confidence rating was also influenced by the authors' views that a moderate number of eligible studies were used in the synthesis with generally consistent findings based on evidence from observational, experimental modelled and secondary studies.

Table 8. Summary of results for the evidence appraisal of the whole body of evidence used in addressing Question 4.5. 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	High	
-Spatial	Moderate	
-Temporal	Moderate	
Consistency	Moderate	
Quantity	Moderate (52 items)	
Diversity	High (71% primary (81% observational, 3% laboratory experiment, 16% modelled), 25% secondary and 4% mixed studies)	

4.4 Indigenous engagement/participation within the body of evidence

A low degree (1 of 52 studies, 1.9%) of Indigenous engagement or direct participation was found in the body of evidence for Question 4.5. Only Howley et al. (2021) reported Indigenous engagement in their study.

4.5 Knowledge gaps

Table 9. Summary of knowledge gaps for Question 4.5.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or M&E question to be addressed	Potential outcome or Impact for management if addressed
1. A majority of the studies included are from sugarcane, and investigation of other cropping land uses, such as	How do other cropping activities, such as bananas, contribute to the nutrient export to the GBR?	Provide better management strategies on other cropping activities to reduce nutrient loss.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or M&E question to be addressed	Potential outcome or Impact for management if addressed
bananas, and urban runoff is required.		
2. Export of DON from urea-based fertiliser in grain cropping and grazing requires further investigation.	How much DON export occurs from urea-based fertiliser application on grain cropping and grazing?	Provide better management strategies on the application of urea-based fertiliser to reduce nutrient loss.
3. Deep drainage export and linkages to loads entering the GBR is needed.	What is the contribution of dissolved nutrients from deep drainage export to the GBR?	This information will be useful for environmental modellers to improve their nutrient models of the GBR. Better management strategies can be developed and applied to reduce nutrient export from deep drainage.
4. Information about nutrient transformation in rivers is still limited. For instance, the origin and fate of refractory DON are also unclear, including whether it is mineralised or consumed by bacteria. Also, more research is needed on the role of mineralisation in rivers and their potential ammonium exports.	How are nutrients transformed in rivers?	This detailed information will be useful to environmental modellers to improve their nutrient dynamics models and mitigation strategies can also be developed.
5. Managing for particulate nutrient bioavailability, as well as fine sediment and dissolved nutrient hotspots, is becoming a higher priority. This requires more information about where hotspots are.	Where are the particulate nutrient bioavailability, fine sediment and dissolved nutrient hotspots and how should these hotspots be managed?	Provide better management strategies for reducing nutrient export from hotspots.
6. Impact of anthropogenic P discharges to the GBR through rivers and streams.	How much anthropogenic P discharges to the GBR through rivers and streams?	This detailed information will be useful to environmental modellers to improve their nutrient dynamics models and mitigation strategies can be also developed.
7. Need to understand the interactions between N in groundwaters and in streams and rivers. More knowledge is required on the role of groundwater in the total N budget of catchments.	What are the interactions between N in groundwaters and in streams and rivers, and what is the contribution of groundwater to the total N budget of catchments?	Provide better management strategies for reducing nutrient export from groundwater to rivers and streams. This information will be useful to environmental modellers to improve their nutrient models of GBR.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or M&E question to be addressed	Potential outcome or Impact for management if addressed
8. Limited studies on nutrient export by surface and subsurface pathway for land uses other than sugarcane and bananas, outside of the Wet Tropics, and on nutrients other than nitrogen.	What is the nutrient export by surface and subsurface pathways on other land uses and regions?	Provide better management strategies on other land uses and regions to reduce nutrient loss.
9. The spatial knowledge of bioavailable nitrogen (BAN) requires further investigation especially for high priority sediment basins such as the Burdekin, Fitzroy, Herbert and Mary.	What is the occurrence and spatial extent of bioavailable nitrogen in the GBR catchment area?	This information will be useful to environmental modellers to improve their nutrient models of GBR.
10. Limited research on water residence time and the function of floodplains on nutrient transformation.	How does water residence time and how do floodplains influence nutrient transformation?	Provide better management strategies for floodplain management and the role of residence times in nutrient transformation.

5. Evidence Statement

The synthesis of the evidence for **Question 4.5** was based on 52 studies undertaken in the Great Barrier Reef and published between 1990 and 2022. The synthesis includes a *High* diversity of study types (58% observational, 25% reviews, 12% modelling and 5% mixed/other), and has a *Moderate* confidence rating (based on *Moderate* consistency and *Moderate* overall relevance of studies).

Summary of findings relevant to policy or management action

Consistent with knowledge of freshwater systems globally, anthropogenic dissolved nutrients generated in the Great Barrier Reef catchment area from multiple land uses, including agricultural and urban areas, are transported to waterways by surface and subsurface runoff. Rainfall (and associated surface and subsurface runoff) is one of the most important natural biophysical drivers of the mobilisation of soluble nutrients within the Great Barrier Reef catchment area. Anthropogenic biophysical drivers include fertiliser application, altered catchment hydrology leading to changed (typically shorter) water residence time in rivers and reduced interaction of surface and subsurface runoff with floodplains and erosion. The drivers are interlinked and thus, management actions should consider those drivers simultaneously. During river transport, nutrients can be transformed by a range of processes such as denitrification, desorption of nutrients from soil particles, plant uptake and burial. Notwithstanding this, the majority of nutrient loads are delivered from the source to the Great Barrier Reef, potentially putting pressure on receiving ecosystems. However, to fully understand the implications, improved quantification of nutrient transformation pathways, processes and the assimilative capacity of rivers is needed.

Supporting points

- Nutrients are delivered from land-based sources in the Great Barrier Reef catchment area to rivers by two primary mechanisms: surface and subsurface runoff. Most studies assessing the export pathways have focused on agricultural areas, with the highest number of studies looking at sugarcane in the Wet Tropics basins.
- Rainfall and subsequent runoff events can lead to substantial increase in nitrogen loads (in dissolved and particulate form) in Great Barrier Reef rivers. Highly variable flow regimes range from extended periods of low rainfall, through to extreme rainfall events causing extensive flooding. This spatial and temporal variation leads to high levels of uncertainty in generalising about nutrient loads, forms and their transformations.
- Subsurface inputs of nutrients to freshwater systems (such as via groundwater movement) are increasingly being recognised as important sources of nutrient delivery to the Great Barrier Reef, but in the few studies reviewed, the contribution of subsurface inputs relative to inputs from surface runoff was highly variable. Deep drainage was a larger export pathway than surface runoff from many of the sugarcane and banana sites in the Wet Tropics basins, Burdekin Delta and Bundaberg. Studies have shown potentially high nitrogen loadings to groundwater and have inferred a significant contribution of subsurface nitrogen to dissolved inorganic nitrogen loads in streams. However, there is limited quantification of the spatial and temporal contribution of groundwater in the context of the total nitrogen budget of basins.
- The proportion of nutrients exported by surface and subsurface pathways has not been quantified but can be affected by many factors such as soil type, land uses and management, vegetative ground cover, rainfall, fertiliser application and irrigation practices.
- Increased rates of fertiliser application, increased cultivation area, low efficiency irrigation systems and heavy rainfall can lead to increased nutrient export, especially nitrogen, in surface runoff, deep drainage and groundwater.
- In several studies undertaken in the Wet Tropics and Mackay Whitsunday Natural Resource Management regions, matching nitrogen supply to crop nitrogen requirements, better application methods (subsurface application or different fertiliser forms) and the timing of rainfall and/or irrigation contributed to reduced nitrogen export in runoff while maintaining similar crop yields.

- Increased residence time in rivers during periods of low flow can allow for further in-stream processes which transform, store or remove nutrients, e.g., denitrification in sediments, uptake by aquatic plants and sediment storage in the rivers. However, the relative importance of different processes for nutrient export requires further study.
- Floodplains typically act as a sink for sediment and nutrients (both particulate and dissolved) and therefore effective management of floodplains is important for reducing nutrient (and sediment) loads at the end-of-catchments.
- Microbial mineralisation and chemical processes in freshwaters have been shown to make nitrogen more bioavailable, particularly conversion of particulate nitrogen to dissolved inorganic nitrogen. Bioavailability depends on sediment characteristics such as soil type, land use and sediment source (surface or subsurface). The few studies investigating these processes have been conducted in the Burdekin and Wet Tropics regions, and very little research into nutrient transformation has been conducted in other regions, including the source of land-based dissolved inorganic nitrogen from the Fitzroy region.
- Studies showed that reservoirs in the Great Barrier Reef catchment area are responsible for significant trapping and transformation of nutrients, particularly phosphorus, due to their increased water residence time. Remineralisation processes within reservoirs typically increase the proportion of bioavailable nutrients which has the potential to promote algal growth both within reservoirs and impact rivers downstream. These findings support those of other studies globally.
- More studies focus on nitrogen compared to phosphorus. This is, in part, because nitrogen is generally considered the major limiting nutrient in marine waters, both globally and in the Great Barrier Reef. Additionally, phosphorus is typically strongly bound to soils. However, it is possible that phosphorus can limit primary productivity in rivers and the Great Barrier Reef at times and at certain locations. As a result, phosphorus transformation processes should not be ignored and the impact of anthropogenic phosphorus discharges to rivers/streams should be determined.

6. References

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

Body of Evidence

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

Armour, J. D., Elledge, A. E., Packett, B., Bosomworth, B., Masters, B. L., Thornton, C. M., Rogusz, D., Orr, G. L., Shrestha, K., Rohde, K. W., Silburn, D. M., Eyles, M., Tahir, N., & Donaldson, S. (2022). Effect of agricultural management practices on water quality. Paddock monitoring of the Paddock to Reef program, 2009-2020. A synopsis. *Paddock monitoring for the Paddock to Reef program*. *Department of Environment and Science, Queensland*. https://nla.gov.au/nla.obj-3092715942/view

Armour, J. D., Nelson, P. N., Daniells, J. W., Rasiah, V., & Inman-Bamber, N. G. (2013). Nitrogen leaching from the root zone of sugarcane and bananas in the humid tropics of Australia. *Agriculture, Ecosystems & Environment*, *180*, 68–78. https://doi.org/10.1016/j.agee.2012.05.007

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

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

Bohl, H. P., Mitchell, D. C., Penny, R. S., & Roth, C. H. (2000). Nitrogen losses via subsurface flow from sugar cane on floodplain soils in the Australian wet tropics. *Proceedings of the Australian Society of Sugar Cane Technologists*, *22*, 302–307.

Brodie, J. E., Burford, M. A., Davis, A., de Silva, E., Devlin, M. J., Furnas, M. J., Kroon, F. J., Lewis, S. E., Lønborg, C., O'Brian, D., Schaffelke, B., & Bainbridge, Z. T. (2015). The relative risks to water quality from particulate nitrogen discharged from rivers to the Great Barrier Reef in comparison to other forms of nitrogen. *Centre for Tropical Water & Aquatic Ecosystem Research, James Cook University*.

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

Brodie, J. E., Schroeder, T., Rohde, K. W., Faithful, J. W., Masters, B. L., Dekker, A. G., Brando, V. E., & Maughan, M. (2010). Dispersal of suspended sediments and nutrients in the Great Barrier Reef lagoon during river-discharge events: Conclusions from satellite remote sensing and concurrent flood-plume sampling. *Marine and Freshwater Research*, *61*(6), 651–664. https://doi.org/10.1071/MF08030

Burton, J. M., Moody, P. W., DeHayr, R., & Chen, C. C. M. (2015). Sources of bioavailable particulate nutrients: Phase 1 (RP128G). *Department of Science, Information Technology and Innovation*. https://www.publications.qld.gov.au/dataset/35b3d675-af86-47f3-965a-32834f7f6bec/resource/dbb8a587-ef94-45fe-90bf-f4640be44c47/download/sourcesofbioavailableparticulatenutrientsphase1rp128gfinal.pdf

Connolly, N. M., Pearson, R. G., Loong, D., Maughan, M., & Brodie, J. E. (2015). Water quality variation along streams with similar agricultural development but contrasting riparian vegetation. *Agriculture, Ecosystems & Environment*, *213*, 11–20. https://doi.org/10.1016/j.agee.2015.07.007

Davis, A. M., Lewis, S. E., O'Brien, D. S., Bainbridge, Z. T., Bentley, C., Müller, J. F., & Brodie, J. E. (2013). Water resource development and high value coastal wetlands on the Lower Burdekin floodplain, Australia. In E. Wolanski (Ed.), *Estuaries of Australia in 2050 and beyond* (pp. 223–245). *Springer*. https://doi.org/10.1007/978-94-007-7019-5_13

Davis, A. M., Tink, M., Rohde, K. W., & Brodie, J. E. (2016). Urea contributions to dissolved 'organic' nitrogen losses from intensive, fertilised agriculture. *Agriculture, Ecosystems & Environment*, *223*, 190–196. https://doi.org/10.1016/j.agee.2016.03.006

Elledge, A. E., & Thornton, C. M. (2017). Effect of changing land use from virgin brigalow (*Acacia harpophylla*) woodland to a crop or pasture system on sediment, nitrogen and phosphorus in runoff over 25 years in subtropical Australia. *Agriculture, Ecosystems & Environment*, *239*, 119–131. https://doi.org/10.1016/j.agee.2016.12.031

Fraser, G. W., Rohde, K. W., & Silburn, D. M. (2017). Fertiliser management effects on dissolved inorganic nitrogen in runoff from Australian sugarcane farms. *Environmental Monitoring and Assessment*, *189*(8), 409. https://doi.org/10.1007/s10661-017-6115-z

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

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

Garzon-Garcia, A., Burton, J. M., Ellis, R. J., Askildsen, M., Finn, L., Moody, P. W., & DeHayr, R. (2018a). Sediment particle size and contribution of eroded soils to dissolved inorganic nitrogen export in Great Barrier Reef catchments. Report to the Office of the Great Barrier Reef. *Brisbane: Department of Environment and Science, Queensland Government.* https://www.qld.gov.au/__data/assets/pdf_file/0029/92963/rp178a-particle-size-contribution-eroded-soils.pdf

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

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

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

Haynes, D., Brodie, J. E., Waterhouse, J., Bainbridge, Z. T., Bass, D. K., & Hart, B. T. (2007). Assessment of the water quality and ecosystem health of the Great Barrier Reef (Australia): Conceptual models. *Environmental Management*, *40*(6), 993–1003. https://doi.org/10.1007/s00267-007-9009-y

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

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

Hunter, H. M. (2012). Nutrients and herbicides in groundwater flows to the Great Barrier Reef lagoon: Processes, fluxes and links to on-farm management. *Queensland Government*. https://www.qld.gov.au/__data/assets/pdf_file/0027/69066/rp51c-grounderwater-synthesis-great-barrier-reef.pdf

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

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

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

Koci, J., Sidle, R. C., Kinsey-Henderson, A. E., Bartley, R., Wilkinson, S. N., Hawdon, A. A., Jarihani, B., Roth, C. H., & Hogarth, L. (2020). Effect of reduced grazing pressure on sediment and nutrient yields in savanna rangeland streams draining to the Great Barrier Reef. *Journal of Hydrology*, *582*, 124520. https://doi.org/10.1016/j.jhydrol.2019.124520

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

Kroon, F. J., Thorburn, P. J., Schaffelke, B., & Whitten, S. M. (2016). Towards protecting the Great Barrier Reef from land-based pollution. *Global Change Biology*, *22*(6), 1985–2002. https://doi.org/10.1111/gcb.13262

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

Lough, J. M. (2011). Great Barrier Reef coral luminescence reveals rainfall variability over northeastern Australia since the 17th century. *Paleoceanography*, *26*(2). https://doi.org/10.1029/2010PA002050

Masters, B. L., Mortimore, C., Tahir, N., Fries, J., Armour, J. D., & Enderlin, N. (2017). Paddock scale water quality monitoring of nitrogen fertiliser management practices in sugarcane cropping: 2014-2016. Technical report. *Department of Natural Resources and Mines.*

McCloskey, G. L., Baheerathan, R., Dougall, C., Ellis, R. J., Bennett, F. R., Waters, D. K., Darr, S., Fentie, B., Hateley, L. R., & Askildsen, M. (2021a). Modelled estimates of dissolved inorganic nitrogen exported to the Great Barrier Reef lagoon. *Marine Pollution Bulletin*, *171*, 112655. https://doi.org/10.1016/j.marpolbul.2021.112655

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

McCloskey, G. L., Walters, D., Baheerathan, R., Hateley, L. R., Fentie, B., Dougall, C., Ellis, A., & Askildsen, M. (2016). Modelling pollutant load reductions due to improved management practices in the Great Barrier Reef catchments: Updated methodology and results. Technical Report for Reef

Report Card. https://nla.gov.au/nla.obj-1649393788/view. *Department of Natural Resources, Mines and Energy.*

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

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

Mitchell, A. W., Reghenzani, J. R., & Furnas, M. J. (2001). Nitrogen levels in the Tully River - a long-term view. *Water Science and Technology*, *43*(9), 99–105. https://doi.org/10.2166/wst.2001.0516

O'Reagain, P. J., Brodie, J. E., Fraser, G. W., Bushell, J. J., Holloway, C. H., Faithful, J. W., & Haynes, D. (2005). Nutrient loss and water quality under extensive grazing in the upper Burdekin river catchment, North Queensland. *Marine Pollution Bulletin*, *51*(1–4), 37–50. https://doi.org/10.1016/j.marpolbul.2004.10.023

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

Packett, R. (2017). Rainfall contributes ~ 30% of the dissolved inorganic nitrogen exported from a southern Great Barrier Reef river basin. *Marine Pollution Bulletin*, *121*(1–2), 16–31. https://doi.org/10.1016/j.marpolbul.2017.05.008

Pearson, R. G., Connolly, N. M., Davis, A. M., & Brodie, J. E. (2021). Fresh waters and estuaries of the Great Barrier Reef catchment: Effects and management of anthropogenic disturbance on biodiversity, ecology and connectivity. *Marine Pollution Bulletin*, *166*, 112194. https://doi.org/10.1016/j.marpolbul.2021.112194

Rasiah, V., Armour, J. D., Cogle, A. L., & Florentine, S. K. (2010). Nitrate import - export dynamics in groundwater interacting with surface-water in a wet-tropical environment. *Soil Research*, *48*(4), 361–370. https://doi.org/10.1071/SR09120

Rasiah, V., Moody, P. W., & Armour, J. D. (2011). Soluble phosphate in fluctuating groundwater under cropping in the north-eastern wet tropics of Australia. *Soil Research*, *49*(4), 329–342. https://doi.org/10.1071/SR10167

Shishaye, H. A., Tait, D. R., Maher, D. T., Befus, K. M., Erler, D. V, Jeffrey, L. C., Reading, M. J., Morgenstern, U., Kaserzon, S. L., Müller, J. F., & De Verelle-Hill, W. (2021). The legacy and drivers of groundwater nutrients and pesticides in an agriculturally impacted Quaternary aquifer system. *Science of the Total Environment*, *753*, 142010. https://doi.org/10.1016/j.scitotenv.2020.142010

Thorburn, P. J., & Wilkinson, S. N. (2013). Conceptual frameworks for estimating the water quality benefits of improved agricultural management practices in large catchments. *Agriculture, Ecosystems & Environment*, *180*, 192–209. https://doi.org/10.1016/j.agee.2011.12.021

Thorburn, P. J., Wilkinson, S. N., & Silburn, D. M. (2013). Water quality in agricultural lands draining to the Great Barrier Reef: A review of causes, management and priorities. *Agriculture, Ecosystems & Environment*, *180*, 4–20. https://doi.org/10.1016/j.agee.2013.07.006

Tsatsaros, J. H., Brodie, J. E., Bohnet, I. C., & Valentine, P. S. (2013). Water quality degradation of coastal waterways in the Wet Tropics, Australia. *Water, Air, & Soil Pollution*, *224*(3), 1443. https://doi.org/10.1007/s11270-013-1443-2

Wallace, J. F., Stewart, L. K., Hawdon, A. A., Keen, R. J., Karim, F., & Kemei, J. (2009). Flood water quality and marine sediment and nutrient loads from the Tully and Murray catchments in north

Queensland, Australia. *Marine and Freshwater Research*, *60*(11), 1123–1311. https://doi.org/10.1071/MF08356

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

Supporting References

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

Moody, P. W., Reghenzani, J. R., Armour, J. D., Prove, B. G., & McShane, T. J. (1996). Nutrient balances and transport at farm scale - Johnstone River Catchment. In *Downstream Effects of Land Use - Technical Report*. *Department of Natural Resources*.

Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 4.5

Theme 4: Dissolved nutrients – catchment to reef

Primary Question 4.5 What are the primary biophysical drivers of anthropogenic dissolved nutrient export to the Great Barrier Reef and how have these drivers changed over time?

Secondary Question 4.5.1 What proportion of nutrient is lost by surface and subsurface pathways?

Secondary Question 4.5.2 How do nutrients transform during the transport and delivery to the Great Barrier Reef lagoon (e.g., bioavailability of particulate nutrients)?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Michele Burford	Griffith University	Nutrient biogeochemistry	Lead Author	All Sections
2.Jianyin (Leslie) Huang	Griffith University	Nutrient biogeochemistry	Contributor	All Sections
3. Zoe Bainbridge	James Cook University	Water quality and sediment transport processes	Contributor	All Sections
4. Joanne Burton	Queensland Department of Environment and Science	Catchment and Riverine Processes	Contributor	All Sections
5. Mohammad Bahadori	Queensland Department of Environment and Science	Sediment and nutrient tracing	Contributor	All Sections
6. Gillian McCloskey	Queensland Department of Environment and Science	Water quality modelling	Contributor	All Sections
7. Michael Newham	Queensland Department of Environment and Science	Nutrient processes	Contributor	All Sections