2022 Scientific Consensus Statement

Question 4.4 How much anthropogenic dissolved nutrient (nitrogen and phosphorus species) is exported from Great Barrier Reef catchments?

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Explanatory Notes for readers of the 2022 SCS Syntheses of Evidence

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

What is the Scientific Consensus Statement?

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

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

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

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

Method used to address the 2022 SCS Questions

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

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

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

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

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

Two methods were developed for the 2022 SCS:

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

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

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

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

[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

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Executive Summary

Question

Question 4.4 How much anthropogenic dissolved nutrient (nitrogen and phosphorus species) is exported from Great Barrier Reef catchments (including the spatial and temporal variation in export), what are the most important characteristics of anthropogenic dissolved nutrients, and what are the primary sources?

Background

Rivers are a link between catchment land uses and marine impacts in the Great Barrier Reef (GBR). This question addresses the degree to which increased dissolved nutrient loss (nitrogen (N) and phosphorus (P)) from catchment land use (Question 4.5, Burford et al., this SCS) results in higher than natural exports of nutrients to marine environments. Knowledge about nutrient exports from the GBR catchment area will help in understanding the patterns of impact on marine ecosystems (Question 4.2, Diaz-Pulido et al., this SCS) and how catchment management can reduce these impacts (Questions 4.6, Thorburn et al., and 4.7, Waltham et al., this SCS). This question is closely tied to the parallel question on exports of suspended sediments and particulate nutrients (Question 3.3, Prosser and Wilkinson, this SCS).

Methods

- A formal Rapid Review approach was used for the 2022 Scientific Consensus Statement (SCS) synthesis of evidence. Rapid reviews are a systematic review with a simplification or omission of some steps to accommodate the time and resources available[5]. For the SCS, this applies to the search effort, quality appraisal of evidence and the amount of data extracted. The process has well-defined steps enabling fit-for-purpose evidence to be searched, retrieved, assessed and synthesised into final products to inform policy. For this question, an Evidence Summary method was used.
- Search locations were Web of Science, Scopus, and Google Scholar.
- Main source of evidence: studies conducted within the GBR, as evidence from outside the GBR has very limited relevance to this question.
- More than 300 studies were identified through online searches for peer reviewed and published literature from the initial keyword search. Ten studies were added manually from citations in online search publications and personal collections, which represented 12% of the total evidence. Following full-text screening, 61 studies were eligible for inclusion in the synthesis of evidence. All studies were accessible.

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 two academic databases were searched.
- Only GBR derived studies were included.
- The review was predominantly restricted to peer reviewed journal publications as well as publications from the major government programs.
- Only studies published post 1990 were included.

In the authors' professional opinion the review included the vast majority of peer reviewed research findings on the topic.

[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

Key Findings

Summary of evidence to 2022

Overall, there is a strong body of evidence on GBR catchment exports of dissolved inorganic nitrogen (DIN) being a dissolved nutrient with considerable anthropogenic increases in export, attributable largely to sugarcane and banana land uses. There is evidence of anthropogenic exports of dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP) and dissolved organic phosphorus (DOP) as well but they remain less well investigated with uncertain sources. Of the 61 GBR publications used in this Evidence Summary, the majority (33) included observations or measurements pertinent to understanding exports; 14 were modelling studies, of which 4 were statistical models of measured exports; 7 combined observations with models; and 7 were review studies which contain some new data or findings. All the papers that directly address dissolved nutrients considered N and DIN. Fewer papers considered P (29) and in many this was quite incidental, either making no conclusions about P transport or concluding that exports were low and not of concern.

There were 38 studies which had a GBR wide scope. The Wet Tropics region was the focus of 15 studies reflecting the early identification of that region as a source of anthropogenic DIN loads. Regarding elements of the question, 42 studies helped inform spatial patterns; 26 addressed sources of material; 13 described the nutrient characteristics; and 16 contained information on temporal patterns, including the differences between pre-development and current exports.

Key conclusions from the body of evidence are that:

- In 11 of the 35 GBR basins the current total dissolved inorganic nitrogen exports are estimated to be over double the pre-development rate. These basins are in the Wet Tropics, Burdekin, Mackay Whitsunday and Burnett Mary regions.
- Monitoring and modelling show that the Herbert, Burdekin, Fitzroy, Johnstone, Mulgrave-Russell, Tully and Haughton basins are the largest exporters of total dissolved inorganic nitrogen to the GBR, each exporting an annual average load of over 500 tonnes per year.
- There is strong and consistent evidence of high anthropogenic dissolved inorganic nitrogen exports from basins in the Wet Tropics, Burdekin and Mackay Whitsunday regions. These basins have substantial areas of fertiliser-adding land use. Sugarcane is the biggest fertiliser-adding land use in the GBR catchments, but bananas and other horticulture can be locally important. Basins in the Burnett Mary region also show high anthropogenic exports per unit area, with sugarcane a major land use, although the total anthropogenic loads are not as high as other regions.
- Sugarcane contributes 42% of total dissolved inorganic nitrogen export despite it occupying just 1.2% of the GBR catchment area, whereas urban land use contributes 7% from 0.7% of the area and bananas 1% from <0.1% of the area. Grazing lands contribute 22% of the total dissolved inorganic nitrogen export from 73% of the GBR catchment area, and conservation land contributes 24% from 15% of the area, but the latter is natural not anthropogenic export. Anthropogenic load contributions of agricultural and urban land uses are much higher than those of conservation areas.
- Most export occurs in the wet season, with chronic and continuously high exports in wet tropical catchments.
- Groundwater is an important transport pathway in addition to surface runoff, although the proportion of total transport is rarely quantified. Groundwater transport means that dissolved exports are not closely correlated to large events and there can be both continual background chronic export, and acute export in large events. The detailed temporal pattern is also correlated to timing of fertiliser addition and loss.
- The Reef Water Quality Report Card 2020 estimates that ‘Moderate’ overall progress has been made toward meeting the dissolved inorganic nitrogen load reduction targets. The monitoring program should be able to start detecting improvements to export loads where long records and no compounding factors are present. For some management actions it may be several years until the benefits of management are fully realised.

- The focus of nutrient export research and management has been on dissolved inorganic nitrogen and is linked to knowledge in the marine systems where there is greater clarity of the impacts of dissolved inorganic nutrient forms. However other nutrients may be important for GBR ecosystems. For example, dissolved organic and particulate nitrogen may also be adding to increased nutrient concentrations in the GBR. There is also evidence for substantially increased phosphorus exports from the GBR catchment area overall, and while most phosphorus is in the particulate form, it can become bioavailable in freshwater and marine environments. The impacts of these nutrient forms on GBR ecosystems are poorly understood, as is detailed knowledge of their anthropogenic sources.

Recent findings 2016-2022

Approximately 19 of the 61 (32%) papers included in this synthesis have been published since the 2017 SCS. The strongest themes in the recent publications are:

- Improved modelling, whether that be statistical modelling of exports or improvements to SedNet, and its full documentation in the peer reviewed literature. There is now closer agreement between modelling and observations of DIN which strengthens the confidence about sources, priorities, and export patterns that were reported in the 2017 SCS.
- Better understanding of N species other than DIN, showing that some nutrients assessed as dissolved are fine colloidal materials and that dry tropic catchments may be more important contributors of bioavailable nutrients than previously thought because of transformation of particulate N to dissolved species.

In addition, since 2017 there has been an expansion in the export monitoring program, including more sites and longer records of consistent measurement providing a better primary dataset for analysis and to inform models and increase understanding.

Significance for policy, practice, and research

The systematic literature review confirms the substantial anthropogenic exports of DIN, which is immediately bioavailable in freshwater and marine environments, and supports the focus on DIN in basin management programs. Many studies show that anthropogenic DIN is largely the result of fertiliser adding land uses, the largest of which is sugarcane, but any intense source of dissolved N should be considered for management. The research consistently points to the Wet Tropics, Mackay Whitsunday and Burnett Mary regions as places with the greatest acceleration of DIN exports, and this is reflected in management priorities.

Progress towards meeting DIN targets has been assessed by modelling, which predicts that substantial reductions in DIN exports have been achieved in some basins. The modelling makes several assumptions about nutrient exports and the effects of improved management, so the export reductions remain as predicted rather than demonstrated. It should be possible to start detecting the reduced exports of DIN by statistical analysis of water quality data in catchments where there is a good history of monitoring and where substantial reduction in exports are expected. This should be a priority to test the assumptions of the modelling and the management programs and properly test our understanding of dissolved nutrient processes. The increase in exports with expansion of fertiliser use was detectable so the corresponding reduction could be detectable as well in places, and efforts to do so will improve our understanding of progress and what further actions need to be taken.

DIN may not be the only dissolved nutrient worthy of attention. Further assessment is needed on DON and P, particularly in the large dry tropic catchments where DIN is not of concern as there is some evidence that exports may have accelerated in association with erosion and that at least some of this material is bioavailable. There is concern that the patterns of other bioavailable nutrient export may not just mirror overall patterns for sediment and DIN. The first test would be to better understand if DON and P are likely to be having marine impacts in addition to DIN. If so then the sources, types of DON and P, and transformations would need to be better understood to determine whether these nutrients need to be managed specifically instead of as a complimentary benefit of reducing erosion and DIN loss.

Both the export monitoring program and modelling programs have been improved in recent years. These programs are linked to policy and management. Continued focus on both of these and continued improvements are needed to increase confidence in the patterns of exports and their link to marine impacts, confidently assess management progress, and to monitor a wider range of conditions and provide warnings of any unforeseen patterns in exports.

Key uncertainties and/or limitations

Predictions that DIN targets have been largely met in some basins need to be tested against measurements of river exports and DIN losses to rivers to understand what changes have actually occurred.

Modelling of marine impacts of DIN uses daily DIN export concentrations from the SedNet model which are poorly predicted at present so they may not be accurately simulating DIN or other nutrient impacts.

Apart from DIN, there is a poor understanding of the anthropogenic acceleration, bioavailability and sources of other forms of nutrients but these may contribute to impacts so should be further assessed.

Field investigations of nutrient processes have focused on catchments in the Wet Tropics region with extrapolation of that knowledge to other regions. Exports are monitored in other regions but the processes that drive those should be verified to confirm they are the same as the Wet Tropics.

Evidence appraisal

The overall relevance of the body of evidence was rated as High. The export of dissolved nutrients has been the topic of many studies of GBR rivers for a long time. Individual studies have focused on the areas with the most intensive land use which covers the vast majority of total export so there is a high level of spatial coverage. Basins without specific measurements are covered by several GBR-wide assessments and modelling studies of exports. Many studies examine current exports but several also address pre-development exports, acceleration of exports over pre-development rates, variability with flood intensity, and changes with land use over time. There are now over 20 years of published catchment export monitoring data.

A strong diversity of approaches are taken including: direct measurements of discharge and constituent concentrations, annual export calculations from these, modelling of exports from all GBR basins, modelling and proxy records. There is consistency between independent types of studies. In addition to the internal consistency of findings within the export studies, they are consistent with upstream work on the drivers of catchment nutrients (Question 4.5, Burford et al., this SCS) and downstream work on marine distributions (Question 4.1, Robson et al., this SCS).

1. Background

Rivers are a link between catchment land uses and marine impacts in the Great Barrier Reef (GBR). This question addresses the degree to which increased dissolved nutrient loss (nitrogen (N) and phosphorus (P)) from catchment land use (Question 4.5, Burford et al., this Scientific Consensus Statement (SCS)) results in higher than pre-development exports of nutrients to marine environments. Knowledge about catchment nutrient exports will help increase understanding of the patterns of impact on marine ecosystems (Question 4.2, Diaz-Pulido et al., this SCS) and how catchment management can reduce these impacts (Questions 4.6, Thorburn et al., and 4.7, Waltham et al., this SCS). This question is closely tied to the parallel question on exports of suspended sediments and particulate nutrients (Question 3.3, Prosser & Wilkinson, this SCS).

As described in Chapter 2 of the 2017 SCS[6], nutrients are essential to supporting freshwater and marine ecosystems and they are naturally exported from catchments. However, there is general agreement that excessive nutrient export is impacting on the ecological health of the GBR. Priority basins for management have been identified, export reduction targets set, land management programs implemented to reduce nutrient loss at source, and progress is reported on how well export targets are being met. Catchment nutrient exports are thus an integral part of GBR management.

To support GBR water quality management the following knowledge about catchment nutrient exports is needed:

- Estimates of total exports coming from the land to the GBR to assess if the land is a significant source compared to marine sources.
- Which rivers have the greatest influence on GBR ecosystems through the size of their flood plumes and concentrations of nutrients.
- Which nutrient species in their current export rates cause problems in the marine environment, and how much lower would export loads or concentrations need to be to remove the impacts (target setting).
- Temporal trends of exports with past changes to land use and climate and thus how they might change in future.
- Which major land uses contribute to anthropogenic exports so that they can be prioritised for management.
- How effective land management to date has been at reducing exports and meeting targets.

Sometimes the research focus has been on how accurately the mean annual load of dissolved nutrient in each catchment is able to be calculated, but the point of outlining the needs above is that the absolute value of the mean annual load has little bearing on these questions. More often it is only necessary to know relativities: which basins pose the worst problems, at what times, which types of material, in which concentrations, and from which major parts of large complex basins. Another point to emerge from the questions above is that there is no single measure of exports that can answer all the questions. It is not just the total load exported, the concentrations, the size of catchment, how many times greater than pre-development the export is; or the bioavailability of nutrients. It is a combination of all these factors that matter to marine impacts, and it is only by understanding the marine impacts that appropriate export targets and management can be put in place.

[6] Bartley, R., et al., (2017). Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 2: Sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef. State of Queensland, 2017

1.1 Question

Primary question	**Q4.4** How much anthropogenic dissolved nutrient (nitrogen and phosphorus species) is exported from Great Barrier Reef catchments (including the spatial and temporal variation in export), what are the most important characteristics of anthropogenic dissolved nutrients, and what are the primary sources?

The question is interpreted in the following context. This section is not referenced but further explanation is included in the Key Findings and in addressing other SCS Questions (particularly Questions 2.3, 4.1, 4.2, 4.5, 4.6 and 4.7).

All rivers export nutrients (dissolved N and P) from their catchments as a result of nutrient cycling in terrestrial ecosystems even under pristine natural conditions. This export of nutrients is often increased several fold under current land uses causing problems for marine ecosystems (see Question 4.2, Diaz-Pulido et al., this SCS). The difference between current loads and those under natural (or pre-development) conditions is the anthropogenic load, and it is the component that potentially causes problems through eutrophication. Anthropogenic load cannot be measured directly so is calculated from the difference between pre-development and current loads so this question considers evidence for these two components.

There are 35 river basins (also called catchments) as defined by the Australian Water Resources Management Committee that drain to the GBR ecosystems (Figure 1). These span from the Jacky Jacky River at the northern end of Cape York to the Mary River north of Brisbane). The defined river basins may be individual large rivers (such as the Burdekin River) but may include several small separate rivers. Measurements of the discharge and load of nutrients are made in some but not all catchments using river gauging. Those measurements are used to extrapolate to the ungauged catchments using various catchment modelling techniques. The different measurements and models are reviewed as multiple lines of evidence as they all have strengths and weaknesses. The review looks at the pattern of exports among the 35 river basins.

The anthropogenic loads of nutrients exported from basins can be attributed to different land uses. The contribution of a particular land use to river nutrient exports is a function of the area of land use, the intensity of nutrient loss in water from that land use, and whether any of the transported nutrient is lost to transformations, terrestrial ecosystems or the atmosphere before it reaches the catchment mouth. Details of losses and transformations during river transport are the scope of Question 4.5 (Burford et al., this SCS). One type of ecosystem that could store and process dissolved nutrients, preventing them from being exported, is wetlands which is the scope of Question 4.7 (Waltham et al., this SCS).

The volumes of water discharged from basins and also the export of nutrients is highly variable over time. The majority of transport occurs during floods when rainfall, overland flow and accentuated groundwater flow entrains nutrients and transports them downstream. In general, bigger floods export disproportionately bigger loads of nutrients but if dissolved nutrient export is limited by supply to rivers from the land, rather than by the ability of rivers to transport them, then export will be supply limited and dictated by patterns of supply from the land, such as timing of fertiliser addition and groundwater discharge, rather than by timing of floods.

Over time the export of nutrients may vary with climate change. Rainfall drives runoff, groundwater flow and the volume of floods so changes to rainfall over time (see Question 2.2, Fabricius et al., this SCS) may change the export rates of nutrients. Similarly, land use and land use practices change over time (see Question 2.3, Lewis et al., this SCS). The implications for these changes on nutrient exports will be considered.

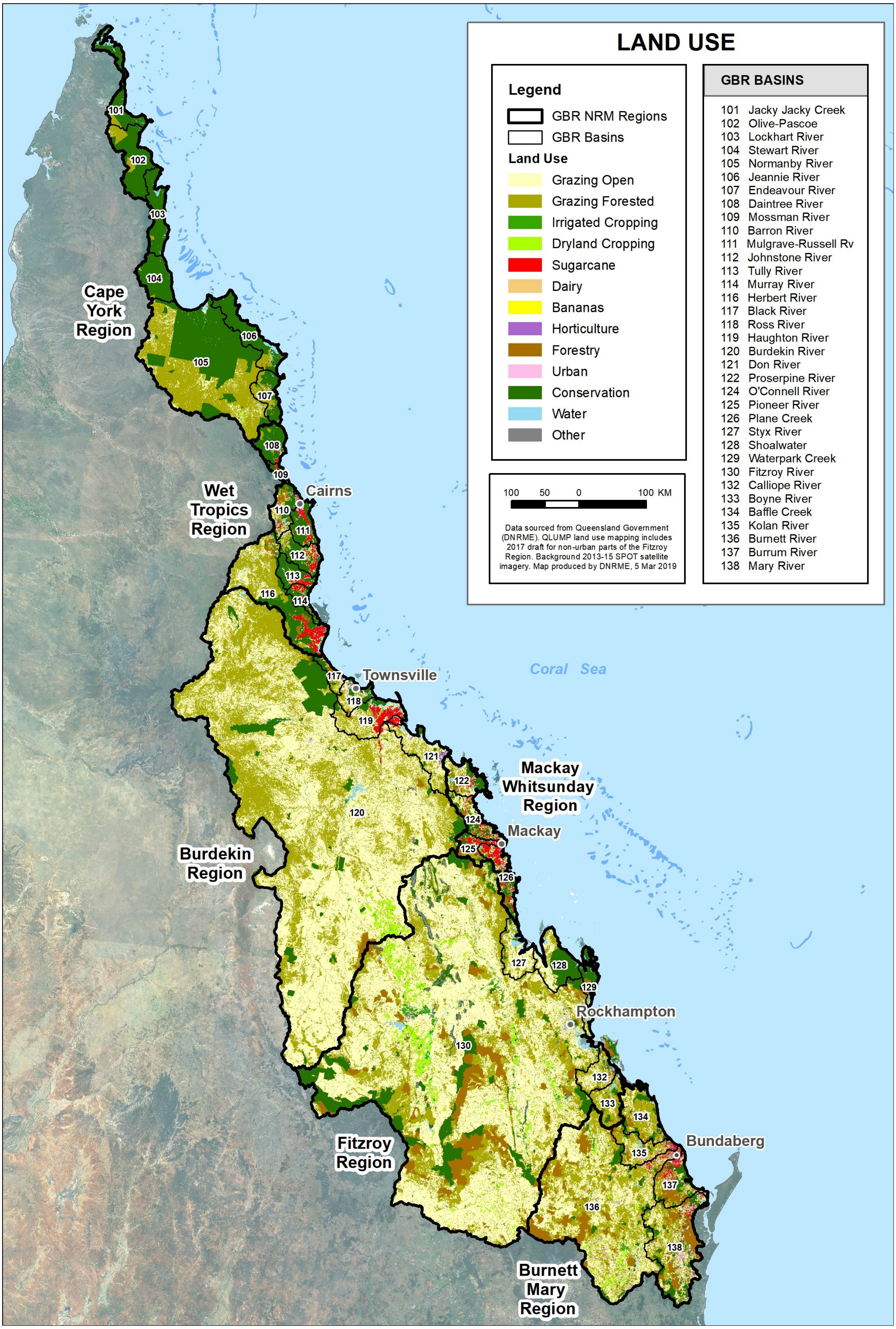


Figure 1. Natural Resource Management (NRM) regions, Australian Water Resources Management Committee river basins and land uses of the GBR (map provided by G. McCloskey from McCloskey et al. 2021).

1.2 Conceptual diagram

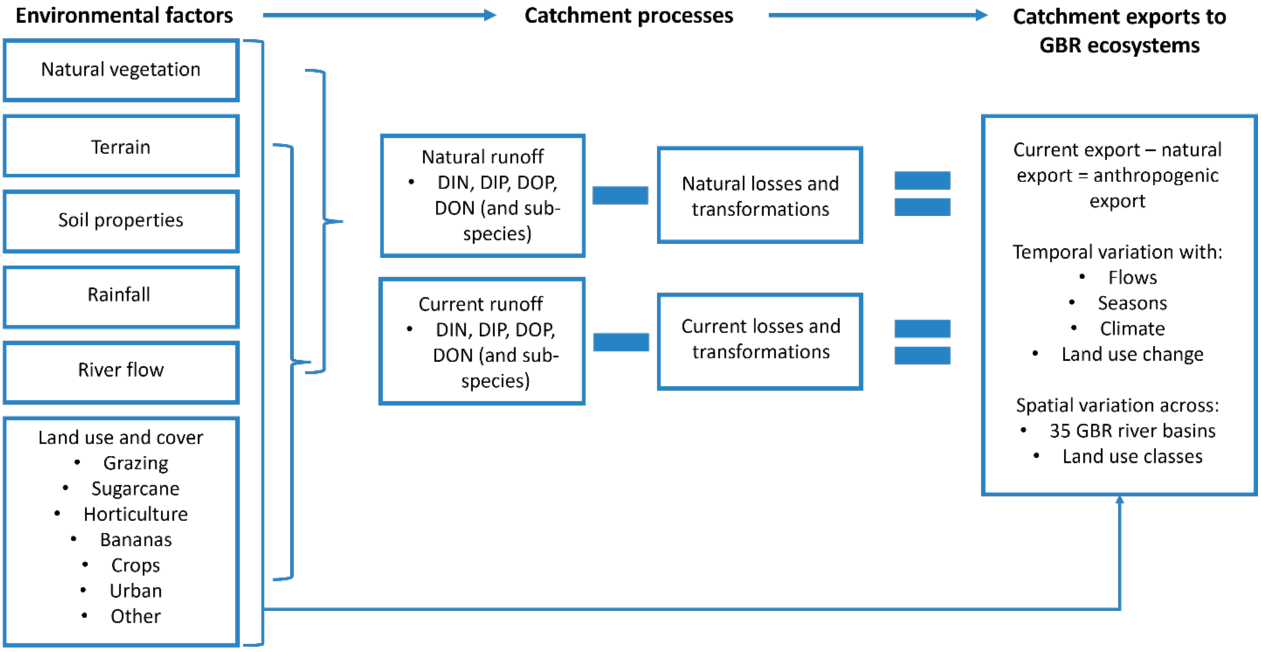


Figure 2. Conceptual diagram of catchment dissolved nutrient exports showing from left to right: the drivers for differences in export intensity across catchments; that anthropogenic exports are the difference between pre-development and current exports; and the reported temporal and spatial variations in exports.

1.3 Links to other questions

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

Links to other related questions	**Q2.3** What evidence is there for increases in land-based runoff from pre-development estimates in the Great Barrier Reef? (Provides a review of evidence of changes in nutrient exports to the GBR over time.) **Q4.5** What are the primary biophysical drivers of anthropogenic dissolved nutrient loss to the Great Barrier Reef and how have these drivers changed over time? (Covers the catchment nutrient processes and their drivers in detail.) Q4.6 and 4.7 cover management of GBR catchments and wetlands to reduce dissolved nutrient exports. **Q4.6** What are the most effective management practices for reducing dissolved nutrient losses (all land uses) from the Great Barrier Reef catchments, and do these vary spatially or in different climatic conditions? What are the costs of the practices, and cost-effectiveness of these practices, and does this vary spatially or in different climatic conditions? What are the production outcomes of these practices? **Q4.7** What is the efficacy of natural/near natural wetlands, restored, treatment (constructed) wetlands and other treatment systems in Great Barrier Reef catchments in improving water quality (nutrients, fine sediments and pesticides)?

	Q4.1 and Q4.2 deal with how the exported nutrient is distributed in the GBR marine environment and the impacts of that. **Q4.1** What is the spatial and temporal distribution of nutrients and associated indicators within the Great Barrier Reef? **Q4.2** What are the measured impacts of nutrients on Great Barrier Reef ecosystems, what are the mechanism(s) for those impacts and where is there evidence of this occurring in the Great Barrier Reef? Q3.3 covers exports of suspended sediment and particulate nutrients from GBR catchments. Particulate nutrients may transform to dissolved nutrients under certain conditions. **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?

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

2.1 Primary question elements and description

The primary question is: ***How much anthropogenic dissolved nutrient (nitrogen and phosphorus species) is exported from Great Barrier Reef catchments (including the spatial and temporal variation in export), what are the most important characteristics of anthropogenic dissolved nutrients, and what are the primary sources?***

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

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

Table 1. Description of primary question elements for Question 4.4.

Question S/PICO elements	Question term	Description
Subject/Population	Dissolved nutrients (nitrogen and phosphorus species)	Nutrients of nitrogen and phosphorus dissolved in river waters and derived from land uses. It concerns the loads of those constituents carried by rivers.
Intervention, exposure & qualifiers	Delivery of anthropogenic nutrients	The concern is over anthropogenic increases to catchment loads. These are the amount by which current and historical loads are greater than the pre-development loads of the catchments prior to European settlement of Australia and thus may cause problems of marine pollution through eutrophication.
Comparator	Spatial and temporal variation in export	Compare loads among the 35 river basins that drain to the GBR environments. Are loads likely to change with future climate and with changes to land use over time.

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

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

Question S/PICO elements	Question term	Description
Outcome & outcome qualifiers	Exported from the GBR catchment area The most important characteristics of anthropogenic dissolved nutrients Primary sources	Measures of loads at the mouth of the rivers, where they discharge to the sea. The characteristics of the dissolved nutrient loads may be important for GBR ecological impacts. There is a need to understand the species of nitrogen and phosphorus that are carried in solution as they influence bioavailability and susceptibility to transformations. To help reduce the anthropogenic loads, there is a need to know which land uses contribute most to them.

Table 2. Definitions for terms used in Question 4.4.

Definitions	
GBR catchments	The 35 river basins that span from Jacky Jacky River at the northern end of Cape York to the Mary River north of Brisbane. These river basins are described in the Bureau of Meteorology (BoM) Geofabric using boundaries defined by the Australian Water Resources Management Committee.
Anthropogenic load	The additional load of nutrients carried by rivers in current and historical times compared to the load carried prior to European settlement.
Dissolved nutrient	Species of nitrogen and phosphorus that are carried in solution by river waters and which contribute to ecosystem impacts of eutrophication when concentrations are well above pre-development levels. This includes dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP) and dissolved organic phosphorus (DOP). Carbon is outside of the scope of this question.
Land uses	Includes grazing, sugarcane, horticulture, banana, cropping and urban.

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:

- Web of Science
- Scopus
- Google Scholar (for technical reports and similar).

b) Search terms

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

Table 3. Search terms for S/PICO elements of Question 4.4.

Question element	Search terms
Subject/Population	Dissolved nutrients, load, nitrogen, phosphorus, Great Barrier Reef, catchment, river, basin
Exposure	Anthropogenic, historical, natural, pre-development, Pre-European
Comparator	(not relevant)
Outcome	Land uses, loads

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 4.4.

Search strings
TS=("Great Barrier Reef" AND (catchment OR river OR basin) AND (dissolved OR solution) AND (nutrient* OR nitrogen OR phosphor*) AND (load* OR concentration) AND ("land use*" OR anthropogenic OR historical OR natural OR pre-development OR Pre-European))

d) Inclusion and exclusion criteria

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

Table 5. Inclusion and exclusion criteria applied to the search returns for Question 4.4.

Question element	Inclusion	Exclusion
Subject/ Population	The catchment dissolved nutrient load or concentration (N or P) at the coast where it is exported to estuarine and marine environments or major catchments for the largest river basins. Specific dissolved nutrient species of N and P.	Small subcatchment or on land dissolved nutrient loads or concentrations. Research on drivers of nutrient processes within catchments (which are considered in other questions). Loads of sediment, and particulate nitrogen and phosphorus (which are considered in other questions).
Exposure or Intervention	Great Barrier Reef catchment area	All other catchments
Comparator	Calculations of anthropogenic dissolved nutrient loads or concentrations including changes over time and under pre-development conditions prior to European settlement.	Not anthropogenic, pre-development, current, historical exports or future exports.
Outcome	The contribution of land uses to the dissolved nutrient loads or concentrations.	Actions to reduce dissolved nutrient loads (considered in other questions).
Language	English	Other languages
Study type	Published 1990 and after, peer reviewed journal papers with original data, methods or results. Peer reviewed technical reports where findings are not covered by journal papers.	Conference papers, opinion pieces, commentary and public fact sheets. Any other publications not presenting new unpublished data, methods, or comprehensive reviews.

3. Search Results

Over 300 studies were identified through online searches for peer reviewed and published literature. Ten studies were identified manually through expert contact and personal collections, which represented 12% of the total evidence. Following second screening which involved reading the full-text, 61 studies were eligible for inclusion in the synthesis of evidence (Table 6) (Figure 3). All studies were accessible.

Table 6. Search results table, separated by A) Academic databases, B) Search engines (i.e. Google Scholar) and C) Manual searches. The search results 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
15/12/2022	*"Great Barrier Reef" AND (catchment OR river OR basin) AND (dissolved OR solution) AND (nutrient* OR nitrogen OR phosphor*) AND (load* OR concentration) AND ("land use*" OR anthropogenic OR historical OR natural OR pre-development OR Pre-European)*	*23 of 35*	*13 (10) of 46*
B) Google Scholar			
16/12/2022	*"Great Barrier Reef" AND (catchment OR river OR basin) AND (dissolved OR solution) AND (nutrient* OR nitrogen OR phosphor*) AND (load* OR concentration) AND ("land use*" OR anthropogenic OR historical OR natural OR pre-development OR Pre-European)*	*38 of 8,400 (first 250)*	
	Total items online searches	***331 (97 %)***	
C) Manual search			
Date/time	Source	Number of items added	
	Author personal knowledge and citations in papers from database search	*10*	
	Total items manual searches	***10 (3 %)***	

All of the academic database search returns used to answer the question met the inclusion criteria, notably that they were peer reviewed scientific journal papers on GBR catchments. This strict inclusion criteria still resulted in 74 potential papers on the topic and 61 of these were retained after screening of the full text, showing the depth of peer reviewed published research on the topic considering its narrow scope on exports from GBR rivers. Papers that just examined nutrient losses from land uses or flood plumes in the marine environment were excluded as they are considered elsewhere. Exceptions to including just journal papers were made for the book by Furnas (2003) on the early AIMS export monitoring program and the annual river monitoring technical reports of the government's Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef Program). These contain the most comprehensive record and analysis of measured exported nutrients. They are the most significant primary data source on exports. The earlier Science Consensus Statement reports were also included to show how knowledge has progressed over time.

Ten papers were added manually. Six of these were journal papers not identified by the database search but were cited by others and found to contain substantial relevant findings. Two were book chapters that were later excluded as they contained no new unpublished data or findings. Two were technical reports that contained comprehensive analysis of the issues of nutrient export. One was from a large expert workshop and the other a government commissioned review.

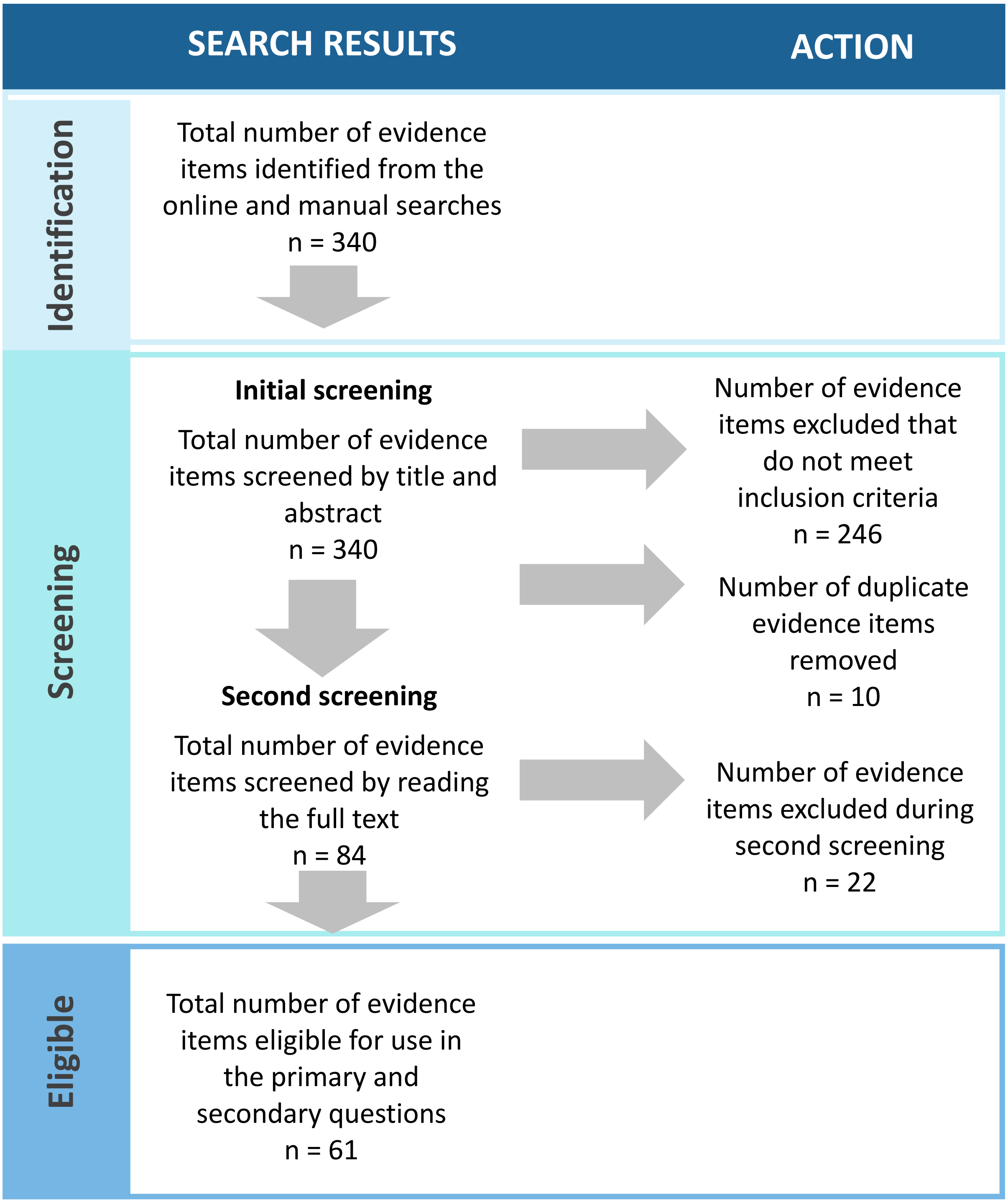


Figure 3. Flow chart of results of screening and assessing all search results for Question 4.4.

4. Key Findings

4.1 Narrative synthesis

4.1.0 Summary of study characteristics

Overall, 61 studies were used to answer elements of the question. All of these studies included GBR basins and the vast majority were exclusively about one or more GBR basins. Given the large number of studies on exports from GBR basins, only directly relevant high-quality studies were included which is reflected in the rating of the body of evidence. The majority of papers were peer reviewed international journal papers published since 1990, and most have been published since 2000. Excluded papers included reviews which did not contain original data or findings, conference papers, and most technical reports and book chapters (because of concerns over quality or presence of peer review). Most of the excluded material is superseded by later journal publication and none of the excluded material contained findings that conflict with the body of evidence.

The majority of papers (33) included observations or measurements pertinent to understanding exports; 14 were modelling studies, of which 4 were statistical models of measured exports; 7 combined observations with models; and 7 were review studies which contain some new data or findings. The distinction between observational and modelling studies is a matter of relative emphasis as exports are not measured directly but are calculated from statistical interpolation of flow and concentration. Similarly, all the modelling studies are founded on quite extensive observed data inputs on which to make predictions.

All the papers that directly address dissolved nutrients considered forms of N and specifically DIN. Fewer papers considered P (n=29) and many fairly incidentally either making no conclusions about P transport or concluding that exports were low and not of concern.

There were 38 studies which had a GBR wide scope. These were largely the Paddock to Reef Program and modelling studies where observations were extrapolated across catchments and/or basins. At a regional scale the geographical spread of studies among GBR regions reflects early understanding of marine impacts and anthropogenic increases (see earlier SCS reports). The Wet Tropics region was the focus of 15 studies reflecting the early evidence there about anthropogenic DIN loads. Only one study specifically focused on the Mackay Whitsunday region and none on the Burnett Mary region despite these being regions of high concern over anthropogenic DIN exports. These regions were covered by GBR wide studies including observations and modelling. The two largest regions, Burdekin and Fitzroy were the focus of three and two studies and Cape York was the topic of a further three studies.

Regarding elements of the question, 38 studies helped inform the spatial patterns of exports, 26 addressed aspects of sources of material, 13 described the characteristics of nutrients, and 16 contained information on the temporal patterns of exports, including the differences between pre-development and current exports.

Overall, there is a strong body of evidence on GBR catchment exports of DIN being a dissolved nutrient with considerable anthropogenic increases in export, attributable largely to sugarcane and banana land uses. There is evidence of anthropogenic exports of DON, DIP and DOP as well but they remain less well investigated with uncertain marine consequences (Question 4.2, Diaz-Pulido et al., this SCS) and uncertain sources.

4.1.1 Summary of evidence to 2022

Forms of nutrients

The types of dissolved nutrient fluxes considered are: dissolved inorganic nitrogen (DIN); dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP) and dissolved organic phosphorus (DOP). DIN in river waters is mainly nitrate (NO_3-) but can include nitrite (NO_2-), and ammonium (NH_4^+). Adame et al. (2021) explain the forms of nitrogen in GBR catchments. Nitrite is a short-term intermediate form of oxidised N. Ammonium is the preferred source of N for aquatic plants and algae and thus is quickly taken up and transformed. Dissolved organic nitrogen includes any dissolved nitrogen in a form compounded with carbon, ranging from highly bioreactive substances such as urea fertiliser to unreactive substances. Because of the way it is measured, DON and DIN can include colloidal nitrogen finer than 0.45 µm which can make up quite a large proportion of the measured amount but not behave as dissolved fractions (Judy et al., 2018).

DOP is analogous to DON, being part of many of the same organic compounds. DIP is mainly phosphate (PO_4^{3-}) most of which is tightly bound to clays and transported in particulate form. For phosphorus, often what is measured is filterable reactive P (FRP) which is DIP and the highly reactive parts of DOP, and considered the most bioavailable fraction of P.

Dissolved N is far more studied in GBR exports than dissolved P as it has far greater marine impacts, because there are larger marine sources of P than the river terrestrial sources, and the GBR system is considered to be 'nitrogen limited' (Furnas, 2003). The most studied N species is nitrate as it is the major component of DIN, has experienced the greatest increase in export compared to pre-development values and is bioavailable so has been the species most implicated in marine impacts (Furnas, 2003).

The forms of N and P can change from soil through river transport and in marine waters through biological processing and chemical reactions (Garzon-Garcia et al., 2018; 2021; Pailles & Moody, 1992).

Is there anthropogenic acceleration of exports?

The first consideration is whether there is evidence that current exports are substantially greater than pre-development exports, with the difference being the anthropogenic export. There are large differences in area, climate and terrain among GBR basins so a large range in pre-development exports between basins is expected. Thus, large exports from particular basins do not necessarily reflect large increases or eutrophication problems for GBR ecosystems. This has long been recognised (Brodie & Mitchell, 2005; Furnas, 2003; Hunter & Walton, 2008) so one research focus has been to examine if there is evidence for changes of exports over pre-development levels. This framework is better than assuming all exports are a problem but it raises the additional challenge of estimating pre-development exports.

For sediment and particulate nutrients there are surrogate geochemical measures of pre-development export but this is not the case for dissolved exports. Instead pre-development export rates are estimated by examining the mean concentrations of dissolved nutrients coming from subcatchments left in largely natural conditions and scaling those up to estimate what exports would be if the whole catchment had natural vegetation cover. The search found 12 papers that present evidence directly relevant to estimating pre-development exports or the acceleration of exports.

Dissolved nutrient loads from Queensland rainforest streams are dominated by organic compounds for both N and P (Bainbridge et al., 2009; Brodie et al., 2015; Brodie & Mitchell, 2005; Davies & Eyre, 2005; Hunter & Walton, 2008; Mitchell et al., 2009). Dissolved N often represents about half or more of total N transport (Brodie et al., 2015) and a bit less for P transport (Brodie & Mitchell, 2005). Nitrate concentrations are usually higher than ammonium concentrations and dissolved P loads are low. These patterns are consistent with those in wet natural catchments elsewhere in the world (Brodie & Mitchell, 2005). Drier savannah landscapes were found to have lower nitrate concentrations and higher DIP (Brodie & Mitchell, 2005).

There is strong field evidence that nitrate exports have accelerated dramatically wherever there are land uses that have added excess nitrogen through fertiliser. Sugarcane is the biggest fertiliser adding land use but bananas and other horticulture can be locally important (Bainbridge et al., 2009; Brodie et al., 2015; Furnas, 2003; Mitchell et al., 2005; Thorburn et al., 2013; Thorburn & Wilkinson, 2013). Mitchell et al. (2009) found conversion of natural rainforest to fertiliser adding land uses results in 26–35-fold increases in NO_x concentrations. In a broader compilation of nutrient concentration data by land use that included sites from across Australia as well as GBR basins (Bartley et al., 2012), forests had higher DIN concentrations and lower DON concentrations than quoted above but sugarcane still had seven times the DIN concentration of forests. Hunter and Walton (2008) calculate an acceleration of six times compared to pre-development in nitrate export from the Johnstone River as a result of sugarcane, and Bainbridge et al. (2009) records a ten times acceleration in the Tully-Murray for sugarcane.

Thorburn and Wilkinson (2013) estimate exports of DIN have increased over tenfold in most GBR regions. Several studies have shown strong positive correlations between nitrate exports and the proportion of fertiliser adding land uses in the basins (Brodie et al., 2015; Liu et al., 2018; Mitchell et al., 2009; Thorburn et al., 2013; Thorburn & Wilkinson, 2013) providing further evidence that fertiliser addition is the main cause of anthropogenic exports of DIN.

Other forms of dissolved nutrients seem to have increased by less and are of less concern. Several studies have shown some anthropogenic increase in DON exports (Bainbridge et al., 2009; Brodie et al., 2015; Mitchell et al., 2005; 2009) while the Johnstone River work did not reveal an anthropogenic increase in DON (Hunter & Walton, 2008) and Bell et al. (2016) question whether DON has increased because of land use. Brodie et al. (2015) suggest that acceleration of DON in grazing catchments may reflect a urea influence, although Judy et al (2018) suggest it may be fine colloidal material. FRP (analogous to DIP) has been found to be low from all land uses with little in-catchment evidence for anthropogenic acceleration (e.g., Bainbridge et al., 2009; Hunter & Walton, 2008). In contrast, Mallela et al. (2013) record an eightfold increase in P in corals off the mouth of the Tully River coinciding with the expansion of sugarcane (refer also to Question 2.3, Lewis et al., this SCS).

All the studies of anthropogenic acceleration of DIN identified in the GBR catchment area involve scaling up concentrations found in natural subcatchments to calculate what the export rates would be from the whole basin if it was all covered in natural vegetation. Similarly exports and acceleration factors are calculated by applying mean concentrations from each major land use to the extent of those land uses over the whole basin. The most sophisticated and widely used of these calculations is the DIN application of the SedNet model (McCloskey et al., 2021). This applies the sediment budget principles to DIN sources and exports. It includes point sources, baseflow and event flow concentrations, and in intense cropping land uses it uses nutrient loss results from agronomy models. The GBR wide patterns of SedNet modelling match the observational studies of mean annual exports well and conforms with the other evidence that most anthropogenic export comes from sugarcane. Thus there is confidence that the scaling up to the whole GBR is true to the pattern of observations. The total anthropogenic export across the GBR is predicted to be 1.9 times pre-development. Acceleration factors in wet tropic basins with intensive land uses range from 1.5 to 2.7; all Mackay Whitsunday basins have values of 3.8 to 5.4 and most Burnett Mary region basins have values above 5 (Figure 4).

Overall there is high confidence from both observations and model results that export of DIN to the marine environment has approximately doubled over pre-development exports. This is overwhelmingly the result of fertiliser added N being lost to rivers, and sugarcane is by far the largest fertiliser adding land use. Exports of DIN have more than doubled in 11 of the 35 river basins (McCloskey et al., 2021). These are all priority basins for reducing DIN exports under the Reef 2050 Water Quality Improvement Plan. There could be additional acceleration of DON loads but to a lesser degree and these are less well understood. There is some evidence of substantial anthropogenic DIP export and if DON loads are accelerated then DOP loads will be as well. It is not clear yet whether the acceleration of dissolved P exports is a concern for GBR ecosystems (see Question 4.2, Diaz-Pulido et al., this SCS).

Exported loads

The most comprehensive monitoring of exports of dissolved nutrients is the Great Barrier Reef Catchment Loads Monitoring Program (GBRCLMP). It measures samples for DIN, DON, NO_x, ammonium, DIP and DOP at end of catchment or major subcatchment locations. The samples have been used to estimate annual loads since 2006 and over the years the number of rivers monitored has increased and expanded to include major subcatchment monitoring. The 2017 SCS compiled the data to 2015 (Garzon-Garcia et al., 2016; Joo et al., 2012; Turner et al., 2012; 2013; Wallace et al., 2014; 2015; 2016) to estimate current mean annual loads (Bartley et al., 2017). Early years of monitoring results are published in Joo et al. (2014) and were used to compare to the baseline modelling as part of the same program (see below). More recent annual summaries (Huggins et al., 2017) and data are available on the program's website but have not been compiled to examine patterns over multiple years (https://www.reefplan.qld.gov.au/tracking-progress/paddock-to-reef/modelling-and-monitoring).

The Bartley et al. (2017) and Joo et al. (2014) compilations show NO_x always makes up the majority of DIN exports and wherever DIN yields are high NO_x makes up about 90% of DIN. The monitoring results (Bartley et al., 2017) also confirm that DON exports exceed DIN in basins without significant extent of fertilising land uses but NO_x and DIN dominate exports where fertiliser addition is significant. Dissolved N makes up between 33 and 73% of total N measured as exported from basins.

The Bartley et al. (2017) and Joo et al. (2014) compilations show DIP exports are fairly low, only exceeding 100 t/y in the Burdekin and Fitzroy basins and dissolved P constitutes just 14 to 52% of total P exports. DIP makes up 26 to 83% of dissolved exports with the higher values occurring in the dry basins and the lower values in the wet tropic basins where a lot of dissolved organic matter is exported. Furnas (2003) provides comprehensive reporting of the earlier Australian Institute of Marine Science (AIMS) river monitoring program which showed the same patterns as the current monitoring, particularly that DIN dominates N exports where there is fertiliser added and that nitrate makes up most of the DIN in those places, but elsewhere in Wet Tropics basins DON is the main constituent. Furnas (2003) also recorded low dissolved P exports as both a proportion of total P and as concentrations.

Other earlier catchment monitoring studies show the same patterns. Hunter and Walton (2008) reported on monitoring of the Johnstone River, where NO_x exports were found to exceed DON and dissolved N exports were comparable to particulate N exports. Dissolved P exports were low. Mitchell et al. (2009) found the same for Tully River exports. In the Fitzroy River, Packett et al. (2009) found that about half the nitrogen load was dissolved and that DIN made up half of the dissolved load, which is quite a bit more than recorded in Bartley et al. (2017) but the overall loads recorded were lower than the later more comprehensive monitoring. In the Normanby River, NO_x and ammonium exports are low and well exceeded by DON and both FRP and DOP have low exports (Howley et al., 2018; 2021).

The sampling programs rely on interpolating or extrapolating from sampled times across the full flow record. Limited sampling for laboratory analysis can affect export calculations (Novic et al., 2018) but could be overcome with continuous *in situ* monitoring of turbidity, conductivity and river level. These provide a richer temporal pattern of exports when linked to measured concentrations (Leigh et al., 2019) which helps estimate particulate loads but does not improve estimates of NO_x exports because of a lack of simple relationships between NO_x and flow conditions. Similarly, statistical techniques that improve particulate export calculations (Wang et al., 2011) do not improve export calculations for NO_x. Wallace et al. (2008; 2009; 2012) show that the monitoring results may underestimate overbank flows because these are poorly gauged, underestimating discharge by as much as 15% in large events. They show which rivers this is likely to be a problem for and suggest from measured nutrient concentrations that it may lead to quite large underestimates of DON export.

Modelling is used to extend from monitored rivers to calculations of total dissolved nutrient export to the GBR marine environment and extend to longer term or unmonitored conditions. The analysis of monitoring data in Bartley et al. (2017) show that the measured loads are from 12 of the 35 basins but that these basins cover 85% of the GBR catchment area. Much of the remaining area is small basins, or relatively undisturbed basins on Cape York, both of which are likely to have lower than typical impacts on GBR ecosystems because of small flood plumes and low intensity land use. However, in some basins s such as in the Wet Tropics region, a lot of the sugarcane land use is on the coastal floodplain below the gauging stations and thus not captured by monitored loads, but it is captured in the modelling. Modelled catchment exports are used in the eReefs marine model (Baird et al., 2021; Steven et al., 2019) to examine whether flood plumes are impacting marine environments and the results have been used to set the targets for reductions to loads (Brodie et al., 2009; 2017; Wooldridge et al., 2015).

The most widely used model of nutrient exports is SedNet and its subsequent developments. It is the model used by the Paddock to Reef Program (McCloskey et al., 2021). It takes a material budget approach, estimating nutrient exports from modelled spatial patterns of sources and losses within the basins. There are now over 20 years of development, use and improvement to the model in the GBR.

Modelled DIN exports (McCloskey et al., 2021) are shown in Figure 4 together with the monitored exports (Bartley et al., 2017). Much of the mismatch between the two sets of data is due to very high year to year variability and different periods being represented in each dataset as well as some contributing land use being missed by the monitoring (see above). When the same years and areal extent are compared (McCloskey et al., 2021) the two datasets agree to within 20% at over 50% of sites. The modelled results confirm the findings of the export monitoring and other river measurements which show that DIN exports per unit area are highest in the Wet Tropics basins, Haughton basin and to a lesser extent, the Mackay Whitsunday basins, where there are significant areas of fertiliser adding land uses and thus where the anthropogenic component of the export is highest (Figure 4). Monitoring and modelling show that the Herbert, Burdekin, Fitzroy, Johnstone, Mulgrave-Russell, Tully and Haughton basins are the largest exporters of total DIN, each exporting over 500 t/y (Figure 4).

The model estimates are considerably lower than previous estimates using earlier versions of the model or other calculations (Furnas, 2003; Kroon et al., 2012; McKergow et al., 2005) largely as a result of more accurate modelling of source concentrations and better export monitoring data for model calibration. This is especially true for the Cape York region because previously there was little data to inform the model. The earlier model results, despite their poorer accuracy, still showed that the Wet Tropics and Mackay Whitsunday regions had the highest DIN exports considering catchment size and highest anthropogenic exports. An investigation to classify monitored basins on their DIN exports also found that the Wet Tropics and Mackay Whitsunday could be separated as having distinctive DIN export behaviour (O'Sullivan et al., 2022), consistent with the nutrient budget modelling.

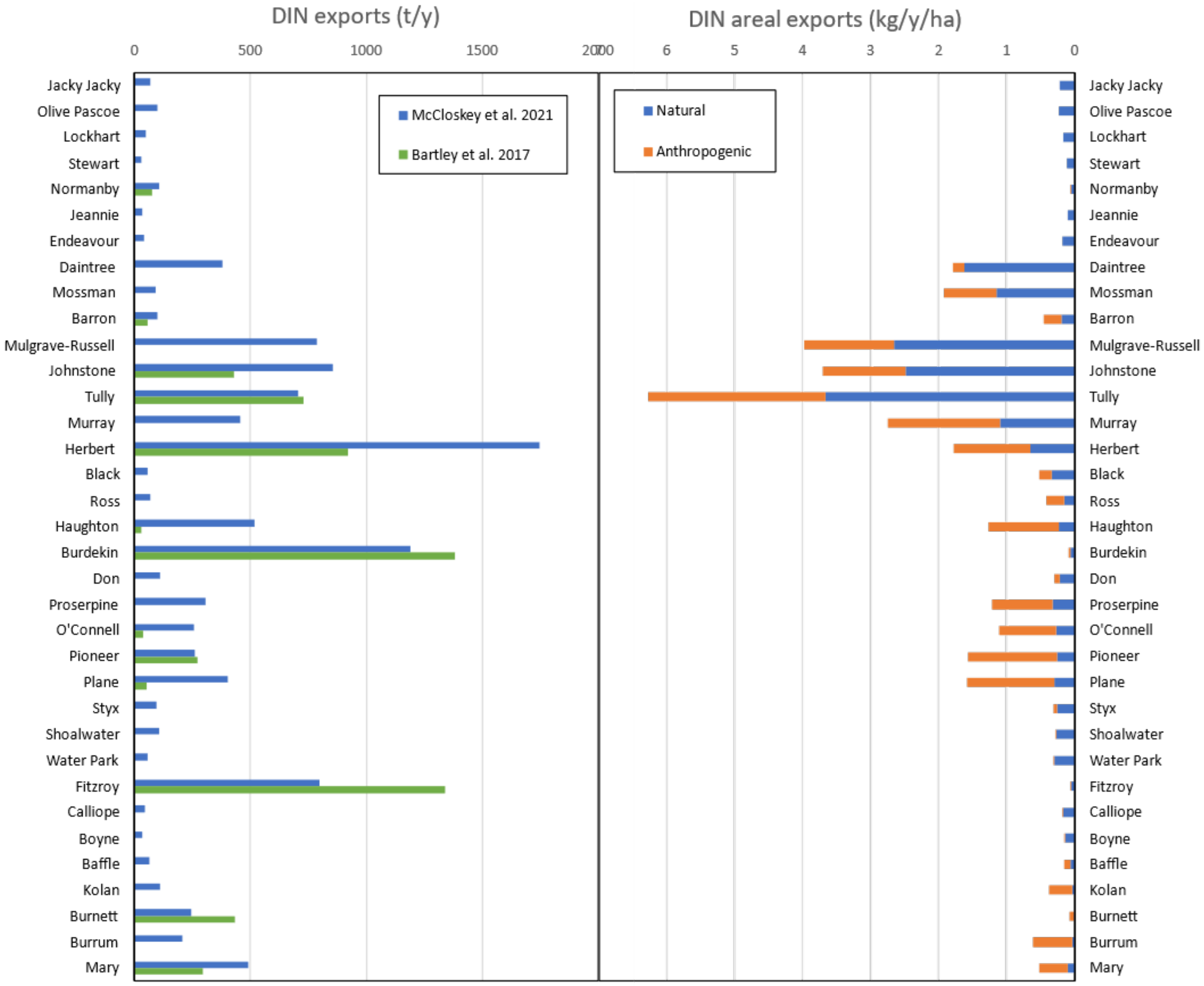


Figure 4. Left: modelled (McCloskey et al., 2021) and measured (Bartley et al., 2017) total DIN exports. The measured and modelled periods are both short and cover different times, partly explaining the differences. McCloskey et al. (2021) compare modelling with measurements for the same baseline period showing a better comparison. The Bartley et al. (2017) results are shown here because they are a larger and more recent dataset. Right: modelled pre-development and anthropogenic exports per ha of catchment area (McCloskey et al., 2021).

While the modelled DIN exports match the measured exports well overall, they typically perform poorly against observations at the monthly level (McCloskey et al., 2021). This is because much of the DIN comes from sugarcane farms and that source input comes from a paddock scale crop model (APSIM) which models a stylised typical farming enterprise which may not perfectly match the actual fertiliser applications made by individual farmers (McCloskey et al., 2021). The eReefs marine modelling (e.g., Baird et al., 2021) uses daily exports from SedNet which would be even more uncertain. It is not known whether high uncertainties in predictions of daily exports has a big impact on the conclusions gained from the eReefs model or not, compared with other uncertainties and variabilities.

The Paddock to Reef Program SedNet model is used to predict exports of other dissolved constituents but they receive less attention as they are not the focus of catchment management and have not been the focus of publications. The supplementary material of Baird et al. (2021) contains graphs of SedNet exports for other constituents. They show the same patterns as the monitoring results. Exports of DON are greater than DIN exports in unfertilised basins and DIP concentrations are low, exceeded by DOP and particulate P.

There is strong and consistent evidence for high anthropogenic DIN exports from the Wet Tropic, Burdekin and Mackay Whitsunday regions. These are regions with substantial areas of fertiliser adding sugarcane land use. Modelling and export monitoring show that Burnett Mary region has similar problems of high anthropogenic exports per unit area, and sugarcane is a substantial presence in that region as well. It is less certain whether monitored and modelled exports of DON, DIP and DOP are largely anthropogenic or not and whether that causes additional problems to the large increases in DIN export for the marine environment.

Sources of dissolved nutrients a) land uses and regions

As described in the sub-section above on evidence for anthropogenic exports, there is strong observational evidence for significant loads of anthropogenic DIN that is derived from fertilising land uses (Bainbridge et al., 2009; Bartley et al., 2012; Brodie et al., 2015; Brodie & Mitchell, 2005; Connolly et al., 2015; Furnas, 2003; Hunter & Walton, 2008; Liu et al., 2018; Mitchell et al., 2005; 2009; Thorburn et al., 2013; Thorburn & Wilkinson, 2013). This section expands that to scaling up sources to GBR wide and regional patterns.

Thorburn and Wilkinson (2013) scaled up the relationship between surplus N applied as fertiliser and DIN river loads to predict DIN export from each GBR region. The exports predicted were 20% less than those predicted by SedNet and river modelling at the time (Kroon et al, 2012) and would be even closer to the more recent results (Bartley et al., 2017; McCloskey et al., 2021).

The latest published DIN model results (McCloskey et al., 2021) predict that 42% of total DIN export comes from sugarcane land use despite it occupying just 1.2% of the GBR catchment area. Urban areas (including sewage treatment plants) contribute 7% of exports from 0.7% of the catchment area, confirming similar earlier estimates (Furnas, 2003; Hunter & Walton, 2008) and bananas contribute 1% of exports from <0.1% of the catchment area. Grazing lands contribute 22% of total DIN export from 73% of catchment area, and conservation land contributes 24% of DIN export from 15% of the catchment area, but the latter is natural not anthropogenic export. A catchment application of the SedNet model to the Tully and Murray basins showed that sugarcane produced 77% of the total DIN export (Armour et al., 2009). The highest areal concentrations are produced by sugarcane and bananas. A breakdown of modelled exports by region and land use is given in Figure 5 from earlier modelling (Bartley et al., 2017) showing the importance of the Wet Tropics, Burdekin and Mackay Whitsunday regions which produce large amounts of anthropogenic DIN from sugarcane. The Wet Tropics and Mackay Whitsunday regions are relatively small (5% and 2% of the total area respectively) and all of the Burdekin region sugarcane is on a similarly small area on the coastal floodplain. Supporting this, multi-factor statistical modelling of spatial patterns of nitrate and DIP across the GBR basins show strong positive correlations with sugarcane land use (Liu et al., 2021b).

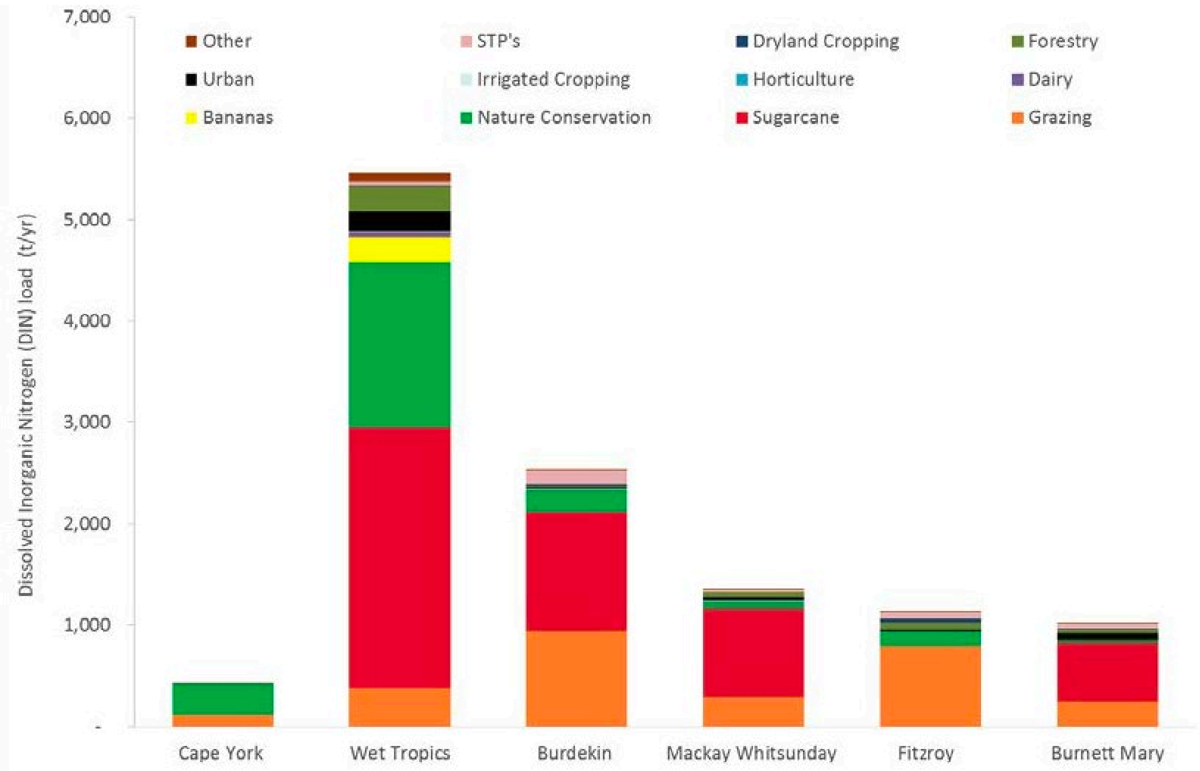


Figure 5. Modelled contribution of main land uses to DIN export for each region. 'STP's' represent sewage treatment plant. Reproduced from Bartley et al. (2017).

Grazing is an important land use source of DIN in dry tropic basins such as the Fitzroy and Burdekin basins. This is supported further by statistical modelling which shows that temporal patterns of dissolved N and P exports from the Fitzroy basin can be predicted far better by including which tributaries are contributing flow, especially contributions from the Nogoa catchment which is dominated by grazing land use, whereas some other tributaries are dominated by cropping (Robson & Dourdet, 2015). The Nogoa catchment also significant gully erosion and it is possible that much of what is analysed as dissolved nutrient is actually very fine colloidal material associated with dispersible clays (Judy et al., 2018).

Sources of dissolved nutrients b) surface runoff versus groundwater

Subsurface groundwater transport rather than surface runoff is an important source distinction for dissolved nutrients, especially nitrate. Much soil nitrate from fertiliser is leached from the soil (Thorburn et al., 2013) so one expects groundwater transport of that nitrate to be an important transport pathway. Groundwaters of the coastal plains of the Burdekin, Mackay Whitsunday and Burnett Mary regions have high nitrate concentrations but they are lower in the Wet Tropics (Hunter & Walton, 2008; Thorburn et al., 2003). Lower concentrations in wet tropics groundwaters may be a result of biological processing under anerobic conditions (Stanley & Reading, 2020). The isotopic signature of groundwater nitrate shows a fertiliser source in most cases (Thorburn et al., 2003). Connolly et al. (2015) show NO_x loads increasing downstream as a result of groundwater discharge during a period of low surface overland flow. Rasiah et al. (2013) estimate about half of nitrate transport in a wet tropics floodplain creek comes from groundwater, and (Liu et al., 2021a) model temporal patterns of nitrate export using temporal variables of baseflow, soil wetness and vegetation cover rather than of river discharge, which they interpret as indicating a substantial groundwater source.

The Paddock to Reef Program SedNet model separates quickflow (surface runoff) from slowflow (including groundwater discharge) and the model shows that in sugarcane and banana cropping areas leached DIN delivered via shallow groundwater is the dominant pathway (McCloskey et al. 2021).

The importance of groundwater as a source of dissolved nutrients raises the prospect that some nutrients are delivered to the sea directly through marine groundwater discharge rather than through rivers. Hunter (2012) investigated this and found that groundwater discharged directly to the coast is a small proportion of total groundwater discharge and that in each case studied, total groundwater discharge is less than 10% of total river discharge. Therefore, marine groundwater discharge is likely to be a very small component of nutrient export to marine environments. Where there are larger coastal aquifers such as in the lower Burdekin and Mackay Whitsunday regions, marine groundwater discharge may make up around 40% of aquifer discharge but that is still small compared to river export (Hunter, 2012).

Nutrient transformations

The species of dissolved nutrients can change from source to export during river transport. Major changes in nutrient form and bioavailability also occur in estuarine and marine environments (see Question 4.1, Robson et al., this SCS). Particulate and dissolved organic nitrogen could partially transform to DIN during transport through biological processing by bacteria (Adame et al., 2021) but that is a process that operates over timescales of days (Garzon-Garcia et al., 2018). Nitrate may also be lost to the atmosphere through denitrifying bacteria (Adame et al., 2021). Thorburn and Wilkinson (2013) concluded that in-catchment nitrogen loss processes like denitrification and mineralisation may be minimal for the anthropogenic DIN associated with coastal floodplain sugarcane production due to short residence times. However, this may not be the case for nitrogen losses from the more distant inland grazing areas or where residence times are increased by reservoir storage. The amount of nutrient transformation during transport is poorly understood. Denitrification and P exchange was originally including in the nutrient budget modelling (McKergow et al., 2005) but has been removed from the latest model versions (McCloskey et al., 2021) presumably because of concern over its accuracy and significance to budgets.

Changes over time, including climate change

Land use has intensified over time in the GBR catchment area so it would be expected that this could influence dissolved nutrient exports (refer also to Question 2.3, Lewis et al., this SCS). The area of sugarcane cultivation has quadrupled since 1930, with most of the change occurring since 1950, and banana growing has expanded in the Wet Tropics since 1970 (Brodie et al., 2001; Lewis et al., 2021) accompanied by a continuing increase in total N and P added in fertiliser until the record ends in 2000 (Brodie et al., 2001; Mallela et al., 2013). Improved farming practices may have compensated for some of the increases in land use intensity (Lewis et al., 2021). At the same time, wetland and riparian forest extent have decreased in the Herbert River (Brodie et al., 2001). Rising groundwater levels have been observed in the lower Burdekin River and could be occurring elsewhere (Hunter, 2012) which may increase nitrate discharge to rivers. The human population resident in the GBR catchment area has increased continually through time (Lewis et al., 2021) so perhaps urban contributions to dissolved nutrients have increased but improved sewage treatment might offset that (Lewis et al., 2021). Because many of these land use changes are gradual, occurring over much longer timescales than the consistent monitoring of exports, and because of the very high inter-annual variability of exports (Bartley et al., 2017) it is hard to detect trends in water quality parameters over time. Nevertheless, Furnas (2003) shows that expansion of bananas and sugarcane in the Tully River led to linearly increasing baseflow concentrations of nitrate and phosphate from 1993 to the end of the record in 2000. The increased phosphate exports are recorded offshore as increasing P/Calcium (Ca) ratios in coral skeletons (Mallela et al., 2013). Model results show a similar steady increase in DIN exports from the Tully and Murray basins since the 1960's (Bartley et al., 2017). The current modelling and monitoring of exports can be viewed as representing land use and land use practices of the last decade or so. The Paddock to Reef Program SedNet model (McCloskey et al., 2021) is updated with the latest Queensland Government land use mapping data.

The Paddock to Reef Program SedNet model is also used to model progress towards meeting export targets for DIN. It models the expected impacts from land use change to fertiliser practices in priority basins. The results show overall 'Moderate' progress towards meeting the targets (28% reduction achieved against a target 60% reduction across the whole GBR) with some basins close to meeting targets while others lag behind (Figure 6). Given the substantial reductions being achieved and lower annual variability in DIN with discharge than for particulate exports, it might be possible to start detecting reductions in observed exports for some basins in future years with sophisticated statistical analysis. This relies on there being only a short lag between management action and nutrient export, sufficient sampling and predictable short-term variability in concentrations, which may not be the case (e.g., Hunter, 2012; Khan et al., 2020; Leigh et al., 2019; Novic et al., 2018).

No studies were found of future climate change as a temporal driver of dissolved nutrients exports. However, Webster et al. (2009) found that climate change was likely to have little impact on the future viability of sugarcane or nitrate losses from production compared to the scale of changes that can come from fertiliser management practice change. Other drivers of land use change are likely to be more important than direct impacts of climate change. Climate change in the GBR catchment area could lead to greater variability in floods and increased frequency of very large floods even though mean annual rainfall may decline in future, but these changes may be small compared to the interannual variability of floods which will still dominate (Alluvium, 2019). Anthropogenic dissolved nutrient export is not as closely tied to discharge volume as particulate export (Khan et al., 2020; Liu et al., 2021a; Robson & Dourdet, 2015; Wang et al., 2011). It is more closely tied to the supply rate of nutrients to rivers from excess fertiliser addition (Brodie et al., 2015; Thorburn & Wilkinson, 2013), further suggesting that climate change will have a small role on exports compared to future land management.

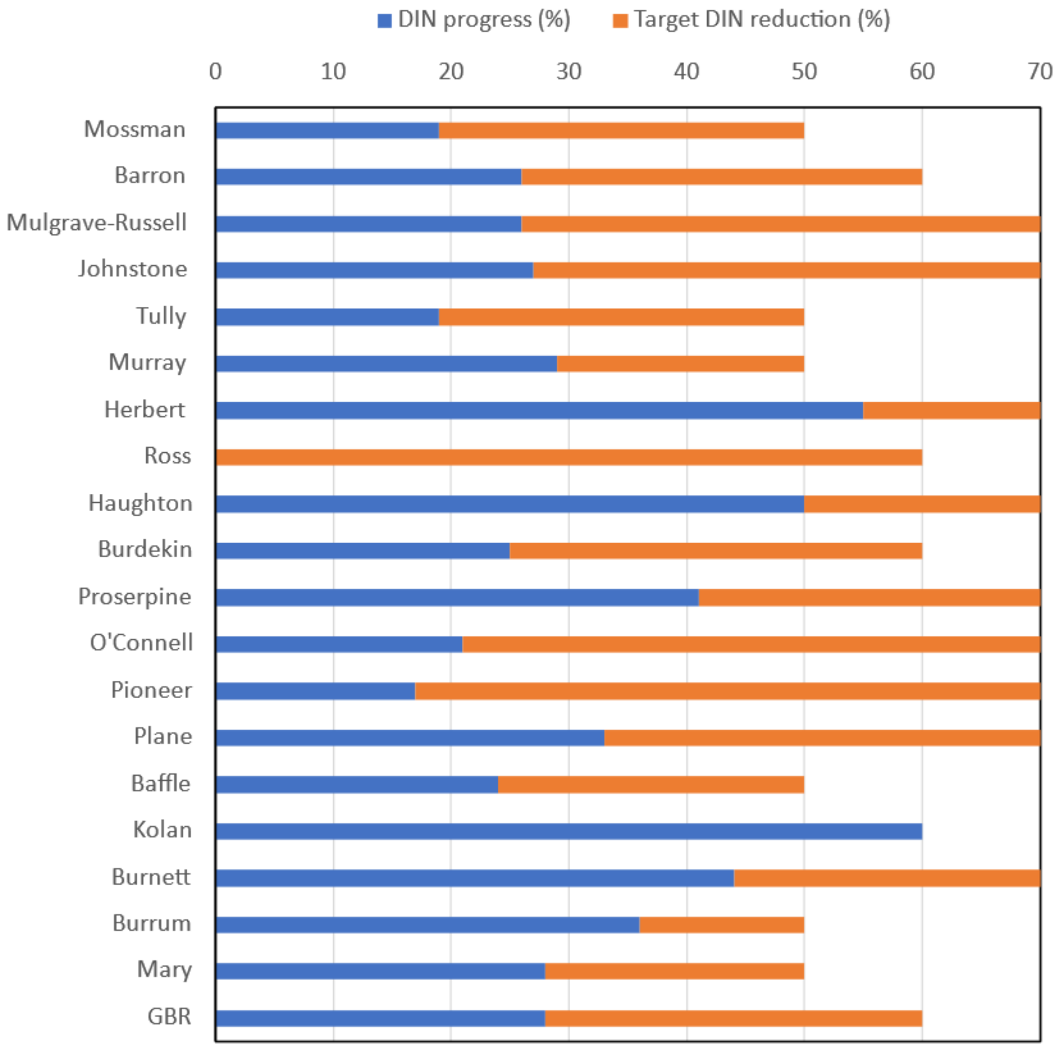


Figure 6. 2025 DIN annual load export reduction targets and progress toward meeting them from 2016–2020. Data from: https://www.reefplan.qld.gov.au/tracking-progress/reef-report-card/2020.

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

Approximately 19 of the 61 papers reviewed above (30%) have been published since the 2017 SCS. The strongest themes in the recent publications are:

1. Improved modelling whether that be statistical modelling of exports or improvements to SedNet and its full documentation in the peer reviewed literature. There is now closer agreement between modelling and observations of DIN which strengthens the confidence about sources, priorities, and export patterns that were reported in the 2017 SCS.
2. Better understanding of N species other than DIN, showing that some nutrients assessed as dissolved are fine colloidal materials and that dry tropic basins may be more important contributors of bioavailable nutrients than previously thought because of transformation of particulate N to dissolved species.

In addition, since 2017 there has been an expansion in the export monitoring program, including more sites and longer records of consistent measurement providing a better primary dataset for analysis and to inform models and increase understanding.

4.1.3 Key conclusions

- In 11 of the 35 GBR basins the current total dissolved inorganic nitrogen exports are estimated to be over double the pre-development rate. These basins are in the Wet Tropics, Burdekin, Mackay Whitsunday and Burnett Mary regions.
- Monitoring and modelling show that the Herbert, Burdekin, Fitzroy, Johnstone, Mulgrave-Russell, Tully and Haughton basins are the largest exporters of total dissolved inorganic nitrogen to the GBR, each exporting an annual average load of over 500 tonnes per year.
- There is strong and consistent evidence of high anthropogenic dissolved inorganic nitrogen exports from basins in the Wet Tropics, Burdekin and Mackay Whitsunday regions. These basins have substantial areas of fertiliser-adding land use. Sugarcane is the biggest fertiliser-adding land use in the GBR catchments, but bananas and other horticulture can be locally important. Basins in the Burnett Mary region also show high anthropogenic exports per unit area, with sugarcane a major land use, although the total anthropogenic loads are not as high as other regions.
- Sugarcane contributes 42% of total dissolved inorganic nitrogen export despite it occupying just 1.2% of the GBR catchment area, whereas urban land use contributes 7% from 0.7% of the area and bananas 1% from <0.1% of the area. Grazing lands contribute 22% of the total dissolved inorganic nitrogen export from 73% of the GBR catchment area, and conservation land contributes 24% from 15% of the area, but the latter is natural not anthropogenic export. Anthropogenic load contributions of agricultural and urban land uses are much higher than those of conservation areas.
- Most export occurs in the wet season, with chronic and continuously high exports in wet tropical catchments.
- Groundwater is an important transport pathway in addition to surface runoff, although the proportion of total transport is rarely quantified. Groundwater transport means that dissolved exports are not closely correlated to large events and there can be both continual background chronic export, and acute export in large events. The detailed temporal pattern is also correlated to timing of fertiliser addition and loss.
- The Reef Water Quality Report Card 2020 estimates that 'Moderate' overall progress has been made toward meeting the dissolved inorganic nitrogen load reduction targets. The monitoring program should be able to start detecting improvements to export loads where long records and no compounding factors are present. For some management actions it may be several years until the benefits of management are fully realised.
- The focus of nutrient export research and management has been on dissolved inorganic nitrogen and is linked to knowledge in the marine systems where there is greater clarity of the impacts of dissolved inorganic nutrient forms. However other nutrients may be important for GBR ecosystems. For example, dissolved organic and particulate nitrogen may also be adding to

increased nutrient concentrations in the GBR. There is also evidence for substantially increased phosphorus exports from the GBR catchment area overall, and while most phosphorus is in the particulate form, it can become bioavailable in freshwater and marine environments. The impacts of these nutrient forms on GBR ecosystems are poorly understood, as is detailed knowledge of their anthropogenic sources.

4.1.4 Significance of findings for policy, management and practice

The systematic literature review confirms the substantial anthropogenic exports of DIN, which is immediately bioavailable in freshwater and marine environments and supports the focus on DIN in land management programs. Many studies show that anthropogenic DIN is largely the result of fertiliser adding land uses the largest of which is sugarcane, but any intense source of dissolved N should be considered for management. The research consistently points to the Wet Tropics, Mackay Whitsunday and Burnett Mary regions as places with the greatest acceleration of DIN exports, and this is reflected in management priorities.

Progress towards meeting DIN targets has been assessed by modelling which predicts that substantial reductions in DIN exports have been achieved in some basins. The modelling makes several assumptions about nutrient exports and the effects of improved management so the export reductions remain as predicted rather than demonstrated. It should be possible to start detecting the reduced exports of DIN by statistical analysis of water quality data in basins where there is a good history of monitoring and where substantial reductions in exports are expected. This should be a priority to test the assumptions of the modelling and the management programs and properly test our understanding of dissolved nutrient processes. The increase in exports with expansion of fertiliser use was detectable so the corresponding reduction could be detectable as well where there are long records and no compounding factors. Efforts to do so will improve understanding of progress and what further actions need to be taken.

DIN may not be the only dissolved nutrient worthy of attention. Further assessment is needed on DON and P, particularly in the large dry tropic basins where DIN is not of concern as there is some evidence that exports may have accelerated in association with erosion and that at least some of this material is bioavailable. There is concern that the patterns of other bioavailable nutrient export may not just mirror overall patterns for sediment and DIN. The first test would be to better understand if DON and P are likely to be having marine impacts in addition to DIN. If so then the sources, types of DON and P, and transformations would need to be better understood to determine whether these nutrients need to be managed specifically instead of as a complimentary benefit of reducing erosion and DIN loss.

Both the export monitoring program and modelling programs have been improved in recent years. These programs are linked to policy and management. Continued focus on both of these and continued improvements are needed to increase confidence in the patterns of exports and their link to marine impacts, confidently assess management progress, monitor a wider range of conditions, and to provide warnings of any unforeseen patterns in exports.

4.2 Contextual variables influencing outcomes

Table 7 summarises contextual influences on material exports, as explained more fully in the summary of evidence.

Table 7. Summary of contextual variables for dissolved nutrient exports.

Contextual variables	Influence on question outcome or relationships
Flood variability	Very high year-to-year flood variability has some influence on exports (Khan et al., 2020; Liu et al., 2021a; Robson & Dourdet, 2015; Wang et al., 2011).
Land use	The area of fertiliser adding land use and the excess amount of fertiliser added have the strongest influence on DIN exports. The timing of fertiliser addition partly controls the timing of anthropogenic DIN exports (Bainbridge et al., 2009; Bartley et al., 2012; Brodie et al., 2015; Brodie & Mitchell, 2005;

Contextual variables	Influence on question outcome or relationships
	Connolly et al., 2015; Furnas, 2003; Hunter & Walton, 2008; Liu et al., 2018; Mitchell et al., 2009; Mitchell et al., 2005; Thorburn et al., 2013b; Thorburn & Wilkinson, 2013).
Climate	Wet tropic basins have naturally high dissolved N exports but also accelerated DIN losses because of large areas of sugarcane (Bainbridge et al., 2009; Brodie et al., 2015; Hunter & Walton, 2008; Mitchell et al., 2005; 2009).
Climate change	Changes to rainfall by 2050 are projected to be small compared to the current high annual variability of rainfall thus exports will continue to be dominated by climate and flood variability. Climate change impacts are also likely to be small compared to impacts from land use change (Alluvium, 2019; Lewis et al. 2021; Webster et al., 2009).
Basin/Catchment area	There is a huge range in area of basins exporting dissolved nutrients to the GBR. Large basins export more than small basins, but the export rate per unit area varies by an order of magnitude and is dependent upon climate and land use (Bartley et al., 2018; McCloskey et al., 2021).
Vegetation cover	Rainforests are naturally major sources of exported DON. Less is known about dissolved N losses from drier tropical forests (Bainbridge et al., 2009; Brodie et al., 2015; Brodie & Mitchell, 2005; Davies & Eyre, 2005; Hunter & Walton, 2008; Mitchell et al., 2009).
Groundwater	Some DIN export comes from groundwater sources rather than surface runoff, especially in the wet tropics, resulting in more chronic rather than acute peaks in anthropogenic exports (Connolly et al., 2015; Hunter, 2012; McCloskey et al. 2021; Rasiah et al., 2013; Thorburn et al., 2003).

4.3 Evidence appraisal

Relevance

The overall relevance of the body of evidence to the question was rated as High. The export of dissolved nutrients has been the topic of many studies of GBR rivers for a long time. Individual studies have focused on the large intensively used basins and those with the most intensive land use. These are the basins most likely to produce marine impacts. Basins not specifically studied by measurements are covered by several GBR wide assessments and modelling studies of exports so there is a high spatial completeness and relevance to the studies.

The temporal relevance of the body of evidence is rated as High with many studies examining exports but several also addressing pre-development exports, acceleration of exports over pre-development rates, variability with flood intensity, and changes with land use over time. There are now over 20 years of published catchment export monitoring data and there are a few longer-term proxy records of exports. The influence of climate change has not been investigated in detail but the understanding of the controls on exports suggests that until at least 2050 land use change will continue to be a stronger driver of exports. Land use change includes future improvements to land management to reach target export reductions and risks from changes to types and intensity of land use practice which have changed considerably in past decades.

DIN has been investigated in far more studies than other forms of N and P. These other forms should not be neglected in future as there are possibilities of anthropogenic increases to exports and marine impacts.

Because of the large body of directly relevant papers to exports, only highly relevant peer reviewed papers on GBR basins were reviewed.

Consistency, Quantity and Diversity

There were 61 papers that directly addressed the primary question in one or more GBR basins. It is the Authors' professional opinion that the searches represent the vast majority of relevant studies to the question. All aspects of the question were covered. A strong diversity of approaches are taken to exports including: direct measurements of discharge and constituent concentrations, annual export calculations from these, modelling of exports from all GBR basins by both statistical and material budget approaches, and occasional proxy records of exports over time in coral cores.

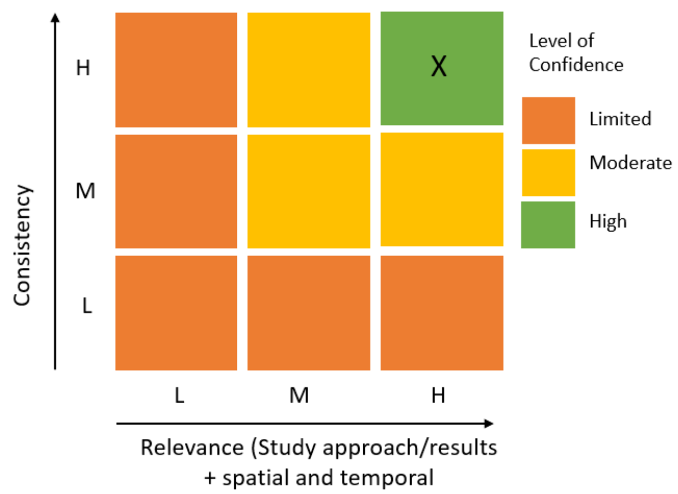
There is a high degree of consistency between independent types of studies on the patterns and sources of export. There is strong consistency and quantity of evidence over anthropogenic DIN exports but fewer and less consistent studies over other forms of N and over P. Early conclusions that P exports are not of concern may need to be revisited, starting from investigation of possible marine impacts.

In addition to the consistency of findings within studies of DIN exports they are consistent with upstream work on the drivers of nutrient loss (Question 4.5, Burford et al., this SCS) and work on marine distributions of nutrients (Question 4.1, Robson et al., this SCS).

Confidence

The confidence rating for the question is High as a result of the High consistency and the spatial and temporal relevance of a large number of studies. Overall, there is High confidence on the main exporting rivers, the land uses and types of dissolved nutrients. Confidence is higher for DIN than other species of nutrients where there are a lack of studies and uncertainties over key aspects of anthropogenic increases and their potential bioavailability.

Table 8. Summary of results for the evidence appraisal of the whole body of evidence in addressing Question 4.4. The overall measure of Confidence (i.e., Limited, Moderate and High) is represented by a matrix encompassing overall relevance and consistency.

<table>
<tr><th>Indicator</th><th>Rating</th><th>Overall measure of Confidence</th></tr>
<tr><td>Relevance (overall)</td><td>High</td><td rowspan="8">
</td></tr>
<tr><td>-To the Question</td><td>High</td></tr>
<tr><td>-Spatial</td><td>High</td></tr>
<tr><td>-Temporal</td><td>High</td></tr>
<tr><td>Consistency</td><td>High</td></tr>
<tr><td>Quantity</td><td>High
(61 GBR studies)</td></tr>
<tr><td>Diversity</td><td>High
(33 observational, 14 modelling, 7 combined, 7 secondary)</td></tr>
</table>

4.4 Indigenous engagement/participation within the body of evidence

There was no Indigenous engagement or participation described in the body of evidence. The topic of quantifying exports of particular nutrient constituents is probably more reductive than the overall systems frameworks of Indigenous knowledge.

4.5 Knowledge gaps

Overall there is a very good body of knowledge to support management of DIN exports and the focus on that species. Other forms of potentially bioavailable nutrients should be investigated further. There are some gaps in understanding which if filled would help reduce future pollution. These are outlined in Table 9.

Table 9. Summary of knowledge gaps for Question 4.4.

Gap in knowledge (based on what is presented in Section 4.1)	Possible research or Monitoring & Evaluation (M&E) question to be addressed	Potential outcome or Impact for management if addressed
Test model predictions of reduced DIN exports as a result of progress towards targets.	Measured reductions to DIN exports and DIN losses from land uses.	Proof of management effectiveness. Further steps if they are required to fill gaps in targets.
Temporal details of DIN exports used in marine impact modelling.	Better monitoring and transfer to better temporal modelling of DIN exports.	Better understanding of temporal patterns of DIN impacts and therefore how to manage them.
Understanding of the possible marine impacts, anthropogenic increases and sources of bioavailable nutrients other than DIN (e.g., DON and P).	Characterise other nutrient forms that could have impact and investigate their sources and transport pathways.	Ability to manage nutrient impacts additional to DIN.
Nutrient export characterisation outside of wet tropic basins.	Field investigation of nutrient processes in large dry tropic basins and Burnett Mary regions which have not been studied much.	Ability to manage nutrient impacts additional to DIN. Increased confidence of how to apply wet tropics knowledge elsewhere.

5. Evidence Statement

The synthesis of the evidence for **Question 4.4** was based on 61 studies undertaken mostly in the Great Barrier Reef and published between 1990 and 2022, including a *High* diversity of study types (54% observational, 23% modelling, 11.5% reviews and 11.5% combined), and with a *High* confidence rating (based on *High* consistency and *High* overall relevance of studies).

Summary of findings relevant to policy or management action

There is a strong body of evidence showing exports of anthropogenic[9] dissolved inorganic nitrogen are at least twice as high as pre-development rates, mainly as a result of fertiliser-adding land uses. Monitoring and modelling show that the Herbert, Burdekin, Fitzroy, Johnstone, Mulgrave-Russell, Tully and Haughton basins are the largest exporters of total dissolved inorganic nitrogen to the Great Barrier Reef, each exporting an annual average load of over 500 tonnes per year. Anthropogenic exports of dissolved inorganic nitrogen are greatest in basins dominated by sugarcane; these basins include those in the Wet Tropics, Burdekin and Mackay Whitsunday Natural Resource Management regions. Other land uses including urban, bananas and other horticulture contribute smaller amounts. Surface runoff, subsurface movement and groundwater are all significant transport pathways of dissolved nutrients to the Great Barrier Reef, however the spatial and temporal variation of these pathways has not been fully quantified. Most export occurs in the wet season, with chronic and continuously high exports in wet tropical catchments. Dissolved nutrient loads are less correlated with flood discharge than particulate nutrient loads. Most research has examined dissolved inorganic nitrogen, however the export of other dissolved nutrients including phosphorus may be substantial and this is an area that warrants further assessment.

Supporting points

- In 11 of the 35 Great Barrier Reef basins the current total dissolved inorganic nitrogen exports are estimated to be over double the pre-development rate. These basins are in the Wet Tropics, Burdekin, Mackay Whitsunday and Burnett Mary regions.
- There is strong and consistent evidence of high anthropogenic dissolved inorganic nitrogen exports from basins in the Wet Tropics, Burdekin and Mackay Whitsunday regions. These basins have substantial areas of fertiliser-adding land use. Sugarcane is the biggest fertiliser-adding land use in the Great Barrier Reef catchments, but bananas and other horticulture can be locally important. Basins in the Burnett Mary region also show high anthropogenic exports per unit area, with sugarcane a major land use, although the total anthropogenic loads are not as high as other regions.
- Sugarcane contributes 42% of total dissolved inorganic nitrogen export despite it occupying just 1.2% of the Great Barrier Reef catchment area, whereas urban land use contributes 7% from 0.7% of the area and bananas 1% from <0.1% of the area. Grazing lands contribute 22% of the total dissolved inorganic nitrogen export from 73% of the Great Barrier Reef catchment area, and conservation land contributes 24% from 15% of the area, but the latter is natural not anthropogenic export. Anthropogenic load contributions of agricultural and urban land uses are much higher than those of conservation areas.
- Dissolved inorganic phosphorus concentrations are low and greatly exceeded by particulate phosphorus.
- Exports of dissolved organic nitrogen are greater than dissolved inorganic nitrogen exports in areas that have limited fertiliser application.
- The focus of nutrient export research and management has been on dissolved inorganic nitrogen and is linked to knowledge in the marine systems where there is greater clarity of the

[9] The end-of-catchment anthropogenic load of dissolved nutrients is calculated as the current end-of-catchment load minus the predicted end-of-catchment pre-development load.

impacts of dissolved inorganic nutrient forms. However other nutrients may be important for Great Barrier Reef ecosystems. For example, dissolved organic and particulate nitrogen may also be adding to increased nutrient concentrations in the Great Barrier Reef. There is also evidence for substantially increased phosphorus exports from the Great Barrier Reef catchment area overall, and while most phosphorus is in the particulate form, it can become bioavailable in freshwater and marine environments. The impacts of these nutrient forms on Great Barrier Reef ecosystems are poorly understood, as is detailed knowledge of their anthropogenic sources.

- The Reef Water Quality Report Card 2020 estimates that 'Moderate' overall progress has been made toward meeting the dissolved inorganic nitrogen load reduction targets. The monitoring program should be able to start detecting improvements to export loads where long records and no compounding factors are present. For some management actions it may be several years until the benefits of management are fully realised.
- Significant improvements have been made to the Paddock to Reef Program's SedNet model (referred to as Source Catchments) in the last few years and it now better matches observed patterns of dissolved nutrients. It provides the best available estimates of dissolved nutrient exports as a result of the consistency in approach across all 35 basins as well as the wealth of information that can be extracted from the results.

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.

Body of Evidence

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Appendix 1: 2022 Scientific Consensus Statement author contributions to Question 4.4

Theme 4: Dissolved nutrients – catchment to reef

Question 4.4 How much anthropogenic dissolved nutrient (nitrogen and phosphorus species) is exported from Great Barrier Reef catchments (including the spatial and temporal variation in export), what are the most important characteristics of anthropogenic dissolved nutrients, and what are the primary sources?

Author team

Name	Organisation	Expertise	Role in addressing the Question	Sections/Topics involved
1. Ian P Prosser	University of Canberra CSIRO	Catchment sediment and nutrients	Lead author	All sections
2. Scott N Wilkinson	CSIRO	Catchment sediment and nutrients	Contributor	Background, Key Findings